A Laboratory Investigation of Radiative Transfer in Cloud Fields

By
James A. Kuenning
Thomas B. McKee
Stephen K. Cox

Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado

Colorado State University

Department of Atmospheric Science

Paper No. 286

A LABORATORY INVESTIGATION OF RADIATIVE TRANSFER IN CLOUD FIELDS

By

James A. Kuenning

Thomas B. McKee

Stephen K. Cox

The research reported here has been supported
by the Global Atmospheric Research Program,
National Science Foundation, and the
GATE Project Office, National Oceanic and Atmospheric
Administration under grants OCD-74-21678 and ATM-77-15369.

Department of Atmospheric Science
Colorado State University
Fort Collins. Colorado

April 1978

Atmospheric Science Paper No. 286

ABSTRACT

Finite clouds were simulated with laboratory models in an investigation of cloud interaction distances, variation of the cloud interaction distances as a function of cloud height, and radiative properties of cloud fields. Comparisons were made between laboratory data and Monte Carlo calculations.

The center cloud in a 3 x 3 array of modeled clouds was found to have a 5% increase in the top directional reflectance over the isolated cloud case at a separation of 2.5 cloud diameters, and increased to 30% at a separation of one cloud diameter. The increase of the top directional reflectance as the separation increased behaved similar to $1/S^2$ where S is the cloud separation. The cloud interaction distance was found to rapidly increase as the height to diameter ratio increased, but then leveled off as the optical thickness of the clouds got larger than about 100 to 125. It was concluded that cubic clouds separated by more than 2.5 cloud diameters could be treated as non-interacting clouds.

A comparison of calculated directional reflectances for cloud fields was done using the infinite cloud approximation, non-interacting cubes, slab clouds, and interacting cubic clouds for sky covers of 0% to 100% sun vertical. An error analysis between the infinite cloud approximation and the interacting cubic clouds shows a maximum relative error of 40% at cloud covers under 5% but the absolute error maximum was 5% directional reflectance at sky covers around 50%.

ACKNOWLEDGEMENTS

This research has been supported by the Global Atmospheric Research Program, National Science Foundation and the GATE Project Office, NOAA, under grants OCD-74-21678 and ATM-77-15369.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES Continued

LIST OF SYMBOLS

English Symbols

a	constant in multiple regression fit equation
A	ampere
b	constant for $1/S^2$ term in multiple regression fit equation
c	constant for $1/S^3$ term in multiple regression fit equation
C1	droplet distribution (Deirmendjian)
d	diameter of cloud
$d^2y.x$	deviations of the x and y product
D	distance that the centers are separated
g	grams
m	meter
S	separation (defined $S = \frac{D}{d}$)
$S_{\hat{y}}$	standard error
UT_j/UT_i	ratio or the currents (or voltage) at a given separation to current (or voltage) at maximum separation
VOM	Voltage-Ohm-Meter

Greek Symbols

θ	angle measured from vertical in x-z plane
ϕ	angle of rotation measured from +x in x-y plane
τ	optical thickness
μ	micron (10^{-6} meters) or mean of the sample

I. Introduction

In the real atmosphere, clouds take on many complex shapes. Small and large cumulus clouds exhibit complicated, fine structured detail as well as many various sizes on the larger scale. However, in global energy budget calculations (London and Sasamori, 1971; London, 1957), clouds are treated as semi-infinite homogeneous layers. In a satellite derived energy budget study by Vonder Haar and Hanson (1969), London's study (1957) was shown to overestimate the mean planetary albedo. The authors suggest this error may come from any one or a combination of the following: 1) an overestimate of the amount of types of clouds in the tropics; 2) the difficulty in computing solar energy transfer in cloudy, turbid atmosphere; 3) an improper knowledge of the total directional reflectance of major cloud types. Their other reasons involved error in the satellite system. Most of the reasons that London's study (1957) could be in error deal with the inability to handle radiative transfer in cloudy regions properly.

McKee and Cox (1974, 1976) showed large differences in the radiative characteristics between infinite and finite clouds. In their 1976 paper, they presented results dealing with the radiance patterns for finite cubic clouds. These results again showed dramatic differences between these two types of clouds. So, it seemed, to accurately evaluate energy budgets, the infinite cloud approximation could not be used. However, the complex shapes of clouds and their interaction with each other make modeling finite clouds difficult.

Aida (1976) presented results which dealt with the interaction of finite clouds using Monte Carlo techniques. His results indicate that this interaction cannot be neglected, since it leads to approximately a 40% increase in the upward-going radiance fields. A study by Barkstrom and Arduini (1976) dealt with the interaction problem by modeling the radiance field exiting a cloud as a diffusion problem. Both these studies dealt with individual clouds and their interaction using simple cloud and spatial geometries.

Wendling (1977) addressed the problem of cloud texture. He calculated albedos for semi-infinite clouds with grooves and ridges in the top of the cloud. He found significant decreases in the inhomogeneous cloud albedo when the sun was vertical compared to the semi-infinite cloud sun vertical.

Computational methods other than Monte Carlo cannot effectively deal with finite clouds. The Monte Carlo method can be used for finite clouds of simple geometries, though computer time can become quite large for optically thick clouds. Complex shaped clouds present problems even for the Monte Carlo technique. The complex geometries demand prohibitive proportions of computer time. Consequently, this paper is an attempt to model finite clouds in a laboratory with physical models which simulate radiative effects.

The first, most attractive, reason for trying to model radiative transfer in clouds with physical models is that it is relatively inexpensive compared to computer simulation. Another reason is that complex geometries can be modeled more simply with physical models than with computer models. There is also the need to verify if theoretical calculations compare with experimental results. A very basic question of whether the idea of physically modeling clouds is possible needs to be answered.

The idea of physical modeling is to select a material which, through its scattering properties, would resemble the scattering process inside a real water cloud. The material would have to be shapable into cloud-like forms and then illuminated under a columnated light source. With this set up, measurements would be made of the light fields which were scattered off the model cloud. There are several variables which will be used to describe the clouds and their placement, however, these will be explained later.

II. Experimental Procedure

II.1. Materials

Inside water clouds, the mode of scattering is Mie Scattering. Mie Scattering is characterized by the particle size in the scattering media being approximately the same size as the wavelength of light. Therefore, in selecting a material for the physical model, the particle size should be approximately the size of a cloud droplet, ranging from 0.2 microns up to 20 microns. Inside the water clouds the droplets are suspended by air. Therefore, in trying to find a material suited for physical modeling of the clouds, we need to find a material that has these scattering properties, but the media holding the objects must not interfere in the measurement by some other optical properties such as reflection.

Figure 1 gives the relationship between the optical depth and the liquid water content for a cumulus cloud with a C1 droplet distribution (Deirmendjian, 1969) and a geometric depth of 1.5 kilometers. For a cumulus cloud 1.5 kilometers deep, the optical depth ranges from around 40 for liquid water of 0.1 g/m^3 to around 80 for 0.2 g/m^3.

For modeling clouds one needs a material whose optical depth is large in a relatively small geometric distance. To model a water cloud perfectly, one would need a material that had tightly packed particles about 10 μm in size, held together by their own adhesion.

Many different types of materials were tried. The first material was cotton balls. Cotton is white, composed of small fibers and is shapeable. Initially, when this experiment was conceived, one of the main objectives was to model individual clouds. The cotton balls lent

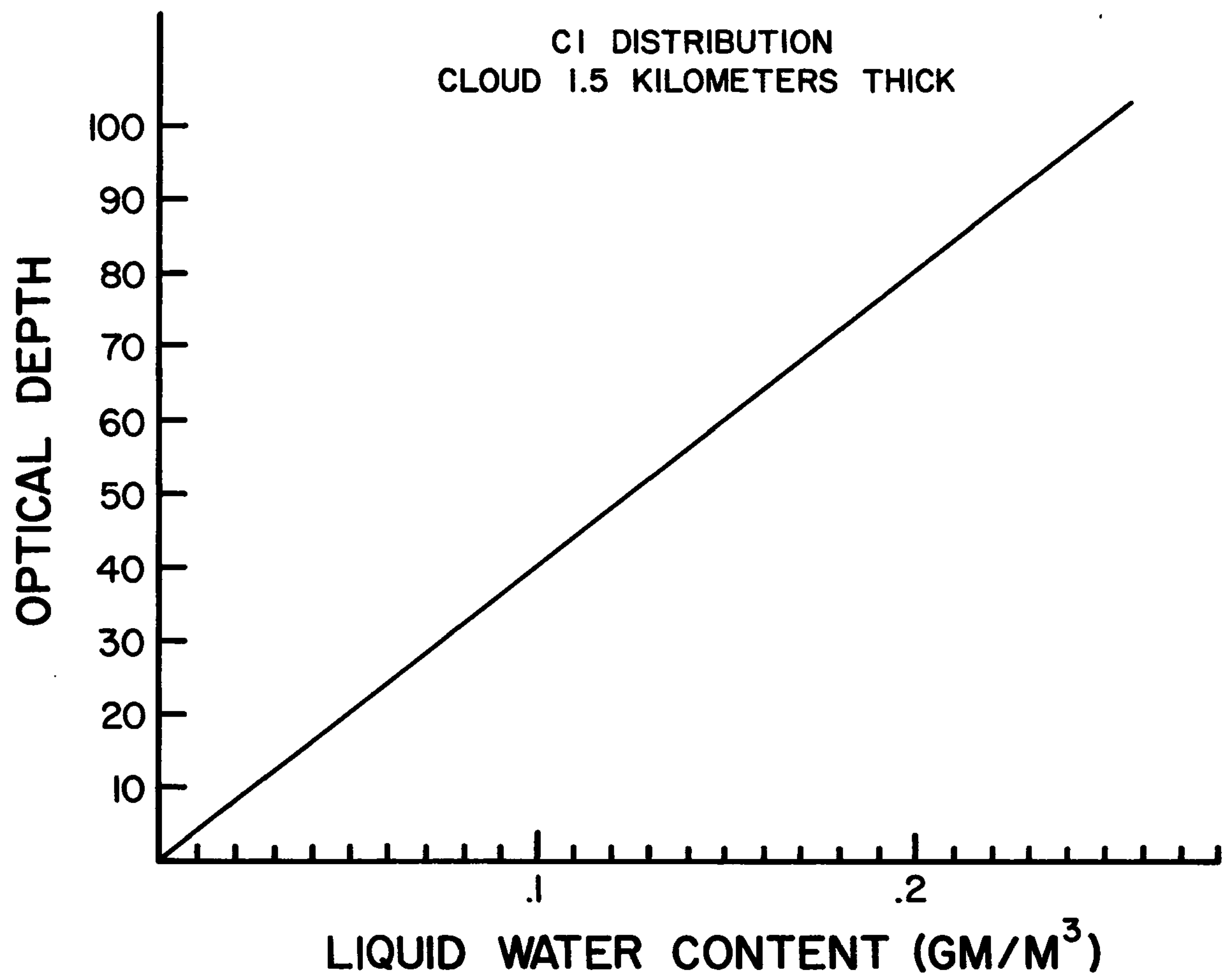

Figure 1. Optical thickness versus liquid water content for C1 droplet distribution.

themselves to be easily "stuck" together to form large complex shapes. The problem was that the boundaries between the discrete elements allowed light to funnel through the boundaries. Another problem with this approach was that the built up clouds were subject to constant change while being handled.

Styrofoam and sugar cubes were tried in an effort to find a medium whose shape was somewhat definable. Sugar cubes do show scattering properties but are optically very thick. Styrofoam is shapeable to various thickness, but has surface reflections which detract from its appearance as a cloud.

Another material tried was shredded paper, but it, too, was lacking in homogeneity and shapeability. Polyester fiber, the type used in aquarium filters, was tried and was very similar to cotton except for its pale yellow color. Resin formed insulation foams were tried but were too optically thick. Plastic with suspended particles was tried. These types of material were rejected because of the optical properties of the plastics themselves.

The material finally chosen was cotton. The scattering media is long 10 μm size fibers which are woven to hold the material together. These fibers are not independent spheres, as in the case of cloud droplets, but can be viewed as cloud particles lined up in rows. Since cloud fields were going to be modeled, cotton balls were chosen which had a mean diameter of two inches. If the cotton balls are physically examined under a columnated light source, they have a visual appearance similar to water clouds.

Of the materials examined, cotton balls exhibited reflective characteristics most similar to clouds. Since cloud fields were chosen to be modeled, the individual cloud elements needed to be approximately the same size. The material must retain its shape even though it is being handled as the cloud elements are moved around. The experiments need be repeatable so the material needs to retain its shape and optical thickness with time. So, given the constraints of where the experiment was to be set up and the equipment to be used, cotton balls were chosen as the principle material.

II.2. Experimental Setup

To model the scattering phenomenon in cloud fields, the incident light upon the clouds must first be modeled. The light received at Earth from the Sun is very nearly columnated with respect to the linear scales in the vertical associated with clouds. The experimental light source used was a 300 watt floodlamp housed inside a box used to columnate the light. The box was 60 centimeters long and the opening was 13 x 13 centimeters. The light was mounted in the back of the box. The inside was painted with a flat black paint and then lightly sanded to cut down on the surface reflections. This light box assembly was mounted on the ceiling and was pointed downward toward the floor. The clouds were placed on a surface 1.15 meters from the base of the light box, or 1.75 meters from the light itself. Figure 2 shows a photograph of the experimental setup.

The clouds were placed on a piece of particle board which was also painted flat black. The particle board was 76 x 76 centimeters and located on a stand which as approximately 60 centimeters off the floor. The clouds were placed on this particle board when measurements were being taken.

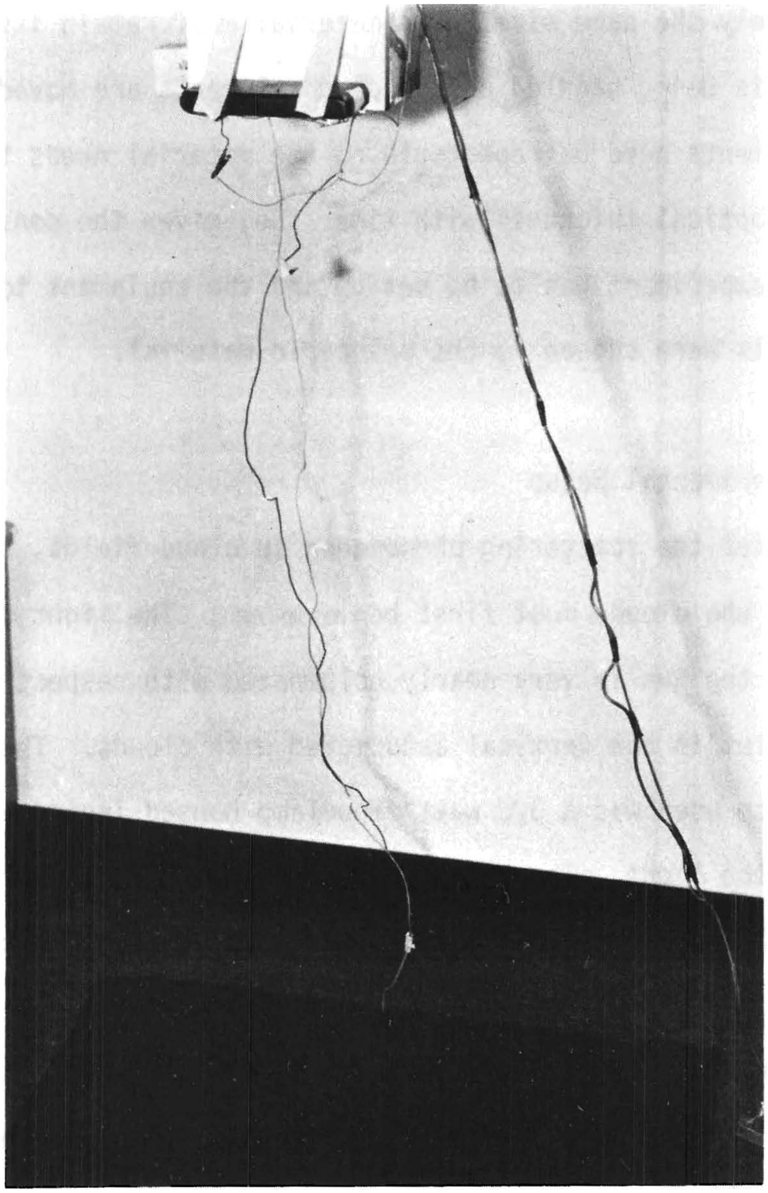

Figure 2. Photograph depicting experimental set-up.

Underneath the stand was a 4' x 8' sheet of plywood which was also painted flat black. All this material was painted flat black in order to minimize the amount of light entering the sensor which did not interact with the clouds in some manner. This was located in a room which could be darkened completely from outside light.

Measurement of the scattered light was accomplished by means of a photo voltaic cell which has a linear current output with increasing illumination. The current was measured with a voltage-ohm meter capable of measuring current with an absolute accuracy of ±1 μA and a resolution of 0.1 μA. At low input impedences, such as when measuring with a VOM, the photo voltaic cells will exhibit fatigue, that is, the output will decrease as a function of time under a given illumination. However, due to the low level of illumination involved in this experiment, this was not a problem. The output only decreased 0.5 μA under short circuit condition in fifteen minutes under the maximum illumination that was expected to be encountered.

Before looking at the results from the experimental modeling, several parameters need to be defined. The first is the sensor output. This is the current output from the sensor as measured by the VOM. The separation distance designated by S is defined as $S = \frac{D}{d}$ where d is the diameter of the cloud and D is the distance between the clouds measured from center to center (see Figure 3). This is a scaling parameter which is dimensionless and gives the number of cloud diameters by which the clouds are separated. The next parameter is designated by UT_j/UT_1 where j is the number of clouds in that particular model. This parameter is the ratio of the sensor output at a

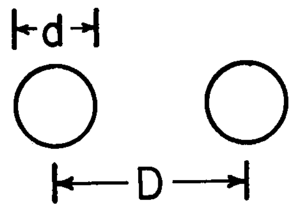

Figure 3. Figure showing how D and d are measured.

particular value of S to the sensor output at maximum separation where D = d. So, at maximum separation, this ratio is exactly 1.00. All the ratios are computed using the maximum separation current output from that individual run. This is done so that the ratio gives the percentage increase in sensor output for that certain run. Then these can be compared to different runs when the cloud fields have changed and the raw sensor currents are different. The use of these parameters will become clearer when some data have been studied. In all studies, except the five cloud model, the actual current (or voltage) values are listed in the appendix in table form.

III. Results

III.1. Cloud to Cloud Interaction

When the radiance field of a cloud under study is affected by the presence of an adjacent cloud, we shall refer to this as cloud to cloud interaction. This section presents the results obtained from the study of cloud to cloud interactions. Cloud to cloud interaction was modeled experimentally by placing a sensor on top of the center cloud. The total field of view of the sensor was filled by the cloud. In the five cloud arrays the sensor was always on top of the center cloud and the other four clouds initially were placed five diameters from the center cloud. A reading of the current produced by the sensor was observed and used as the base value to which all others were ratioed in that run. As the four clouds were moved symmetrically toward the center cloud, readings of the sensor current were taken at various separation distances. This process was continued until the clouds were touching. The series of steps were repeated three times for both the five cloud and the nine cloud models.

Figure 4 (a, b) depicts the nine cloud array configuration at maximum and minimum separation respectively, viewed as if one were looking at the cloud field from above. The five cloud array contained the center cloud and four corner clouds removed. The experimental five and nine cloud arrays were developed to compare with Monte Carlo results reported by Aida (1976). The five cloud array for the three individual runs are shown in Table 1 which includes the actual current and ratio values for the three runs. Figure 5 shows the data plotted with the separation distance on the ordinate and the ratio on the

Table 1. Data for five cloud model. The "FITTED" column is the values predicted by the regression curve.

S	Output (μAmp)	UT_5/UT_1	Output (μAmp)	UT_5/UT_1	Output (μAmp)	UT_5/UT_1	FITTED
5.0	32.2	1.000	32.1	1.000	32.2	1.000	.998
4.5	32.2	1.000	32.2	1.003	32.3	1.003	1.000
4.0	32.2	1.000	32.2	1.003	32.2	1.000	1.004
3.5	32.3	1.003	32.2	1.003	32.2	1.000	1.009
3.0	32.7	1.015	32.6	1.016	32.5	1.009	1.017
2.5	33.3	1.034	33.2	1.034	33.3	1.034	1.030
2.25	33.3	1.034	33.6	1.047	33.7	1.047	1.039
2.0	34.0	1.056	34.1	1.062	34.0	1.056	1.052
1.75	34.9	1.084	34.9	1.087	34.7	1.078	1.071
1.5	35.5	1.102	35.6	1.109	35.7	1.109	1.100
1.25	37.0	1.149	37.0	1.153	37.1	1.152	1.144
1.0	39.3	1.220	39.2	1.221	39.3	1.220	1.220

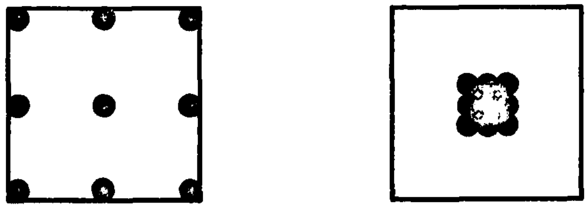

Figure 4. Nine cloud maximum and minimum separation configuration.

abcissa. The curve on the graph was obtained by fitting all the data to a multiple regression routine. The resulting best fit curve equation for the five cloud model is $\frac{UT_5}{UT_1} = .986 + \frac{.296}{S^2} - \frac{.061}{S^3}$ with a correlation coefficient of 0.975.

The physical process of cloud to cloud interactions may be described as light leaving an adjacent cloud in such a direction as to intercept the center cloud. If one assumes that the radiance fields are homogeneous, the interaction should depend on one over the distance squared. So for the interaction equation, one would expect a form like $\frac{UT_5}{UT_1} = a + \frac{b}{S^2}$. Since there are other factors determining how much light reaches the sensor (scattering and the radiance fields are not homogeneous) a correction term, namely $\frac{c}{S^3}$, was used to compensate for these other processes.

The nine cloud array is similar to the five except that the center cloud is surrounded by eight clouds instead of four. The same procedure was used in obtaining the data that was described earlier

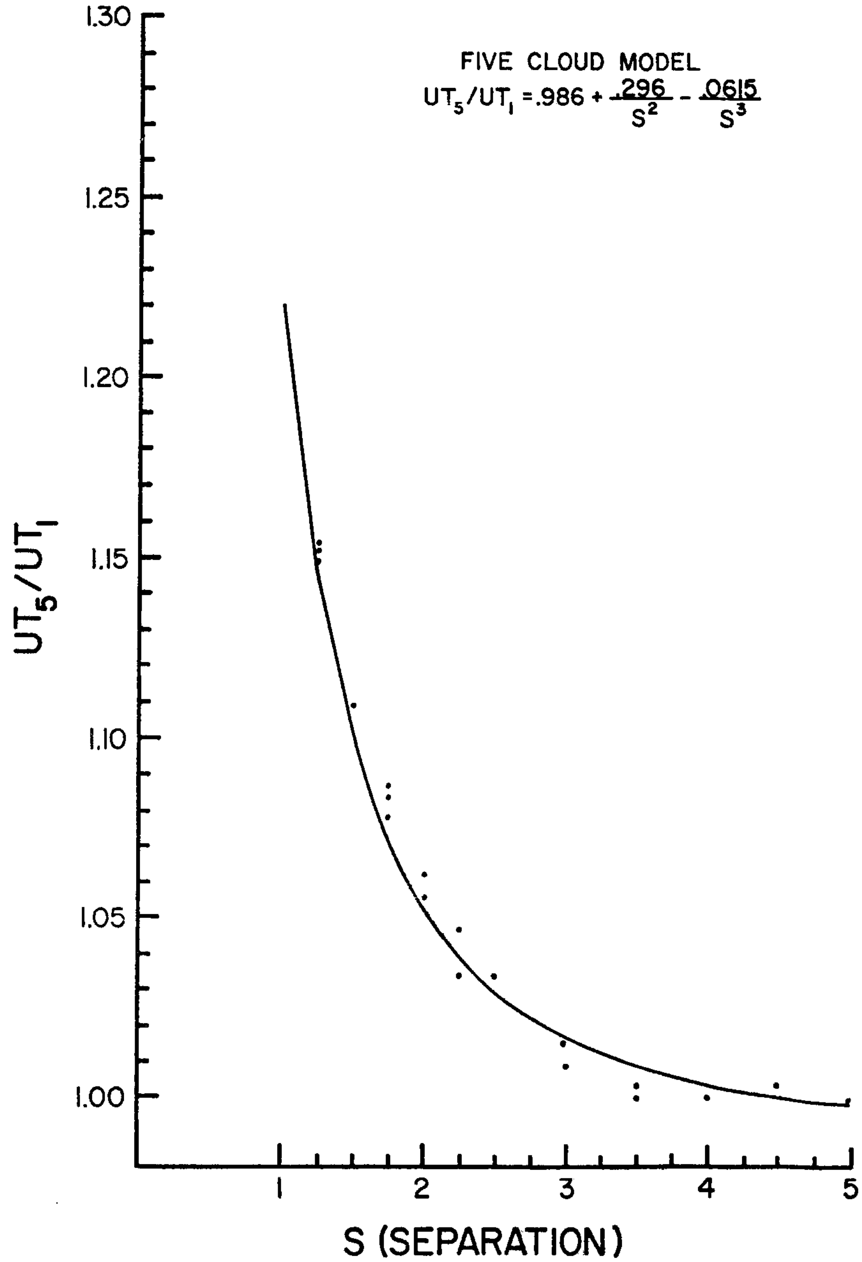

Figure 5. UT_5/UT_1 versus separation for five cloud model.

for the five cloud case. The data appears in graphical form in Figure 6. The curve again was produced by the multiple regression technique as before. The equation for nine cloud is as follows:

$$\frac{UT_9}{UT_1} = .984 + \frac{.557}{S^2} - \frac{.243}{S^3} .$$

The five cloud model has an increase of 22% over the value at maximum separation, while the nine cloud model has an increase of about 30% over maximum separation. Of the total change from maximum to minimum separation, 76% of that change takes place in going from two diameters' separation to one in the five cloud model and 68% in the nine cloud model.

The experimental models are similar to Aida's (1976) model. Aida (1976) let the photons enter only the central cloud and obtained a value for the total upward-going radiances which he called UT_1. Next he added four more clouds for his five cloud model. The photons could only enter the central cloud directly. If, through interaction in the center cloud, the photons entered the other four clouds, their interaction pattern was then computed to determine if they left in the upper or lower hemisphere. No futher interaction was permitted. The total upward-going radiance is then calculated for the entire cloud field. This value is then ratioed to the total upward radiance for a single isolated cloud. This was done for separations of 5, 2, 1.5, 1.0. The results of Aida (1976) that correspond to the experimental results are the five cloud and nine cloud models for optical depth of 49 and sun angle of $\theta = 0°$. Figure 7 shows Aida's results along with the best fit curve generated by the multiple regression routine for

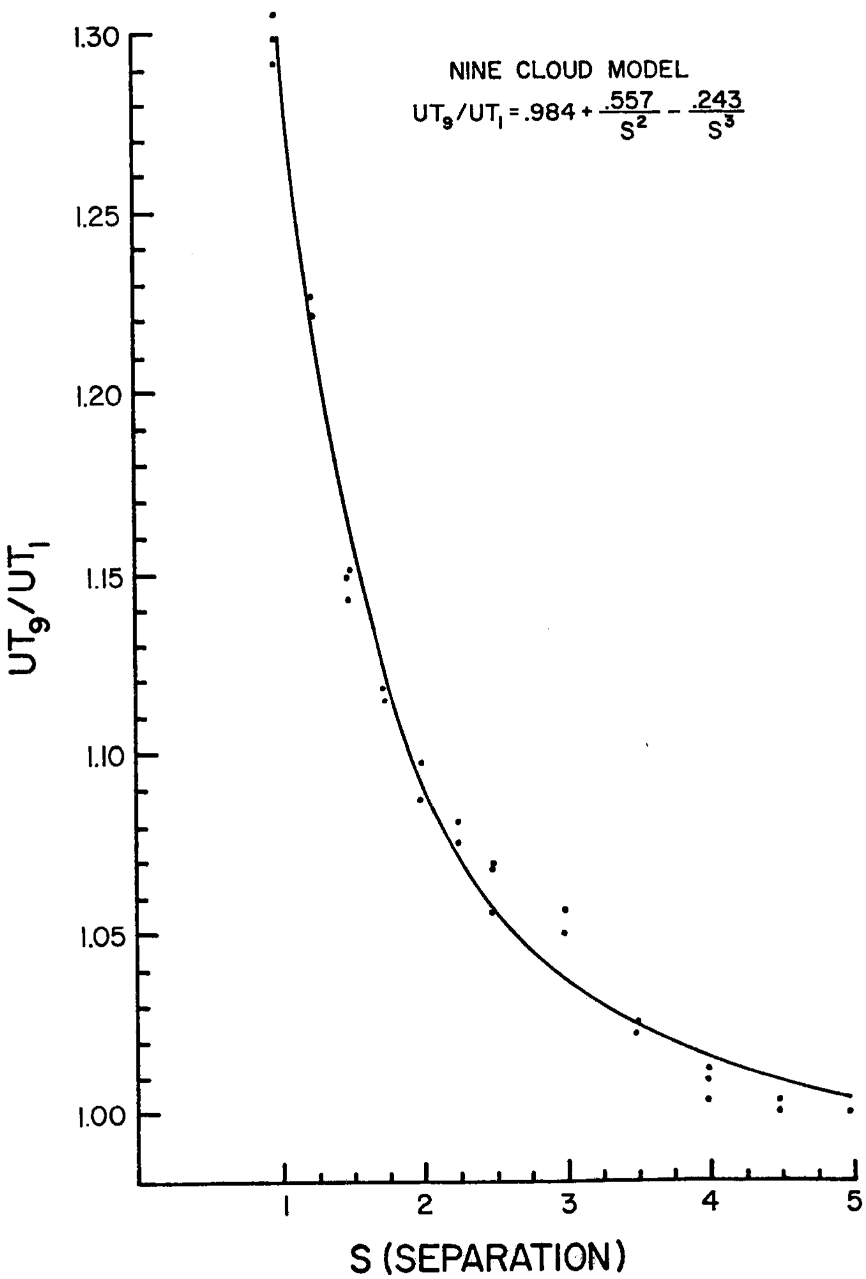

Figure 6. UT_9/UT_1 versus separation for nine cloud model.

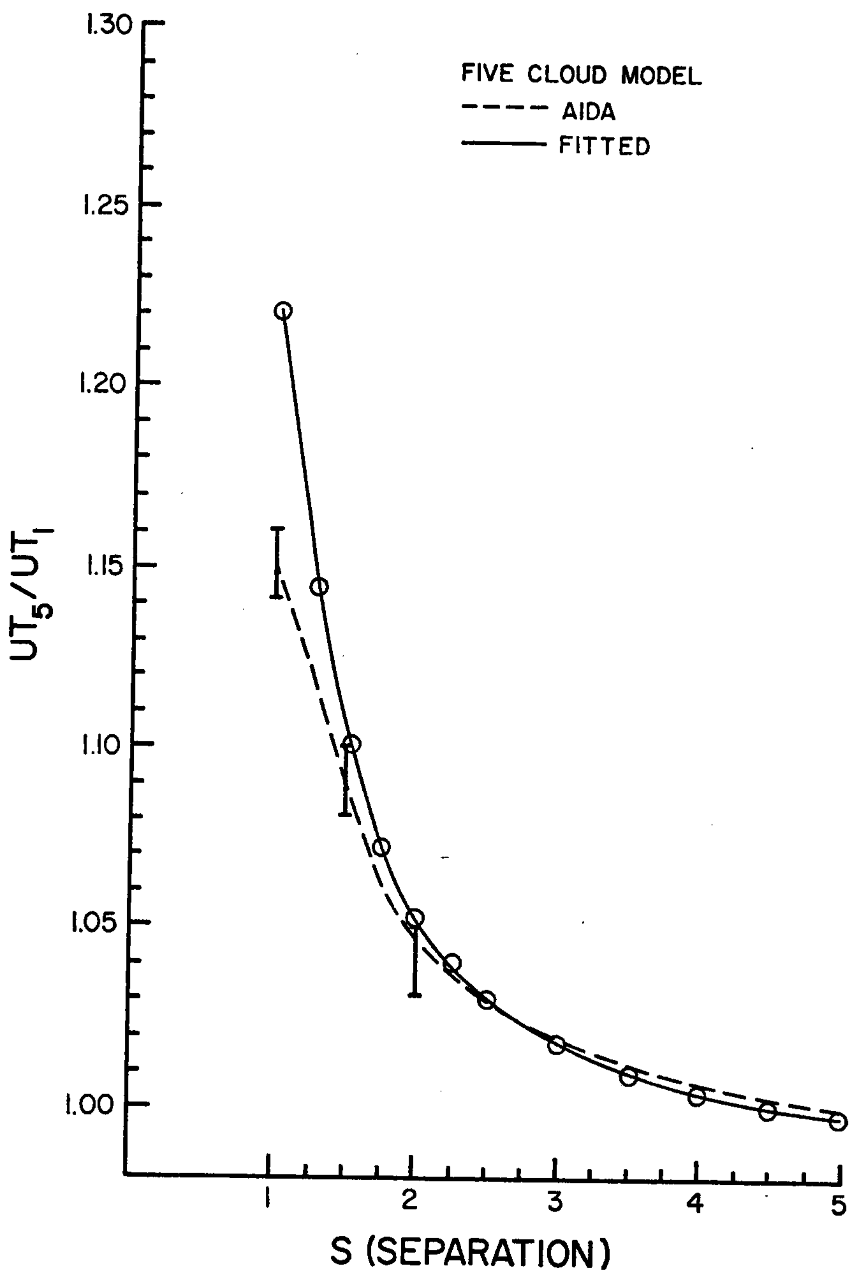

Figure 7. Aida versus experimental method for five cloud model.

the experimental five cloud model. The error bars on Aida's data are due to interpolation from a graph.

In the five cloud model, Aida's results are lower than the experimental method. This could be due to the sensor that was covering the central cloud. The sensor covering the cloud has the effect of decreasing the amount of upward-going light because the sensor blocks incident light. Another factor is that Aida is calculating the total upward-going radiance off the entire cloud field, though he is only letting photons enter the central cloud. In the experimental setup, light is entering all the clouds and is only being measured by what is coming off the central cloud top going up.

These two different methods may not appear to be similar at first. Aida is measuring an increase in reflected irradiance for the entire cloud field, while the experimental method is measuring the increase for only one cloud. Consider the following:

If one has five light bulbs and wishes to increase the total light output of the field by 10%, one would increase the individual bulb output by 10%. Aida is measuring the total increase while the experimental method is measuring the increase of the individual clouds.

Figure 8 shows the results of Aida's nine cloud model plotted along with the experimental results. The nine cloud model exhibits better agreement than did the five but still seems to be high at small separations. All the possible reasons for differences could apply in the nine cloud model also.

In summary, the two experimental models seem to agree with Aida's (1976) results quite well. But an important point needs to be noted.

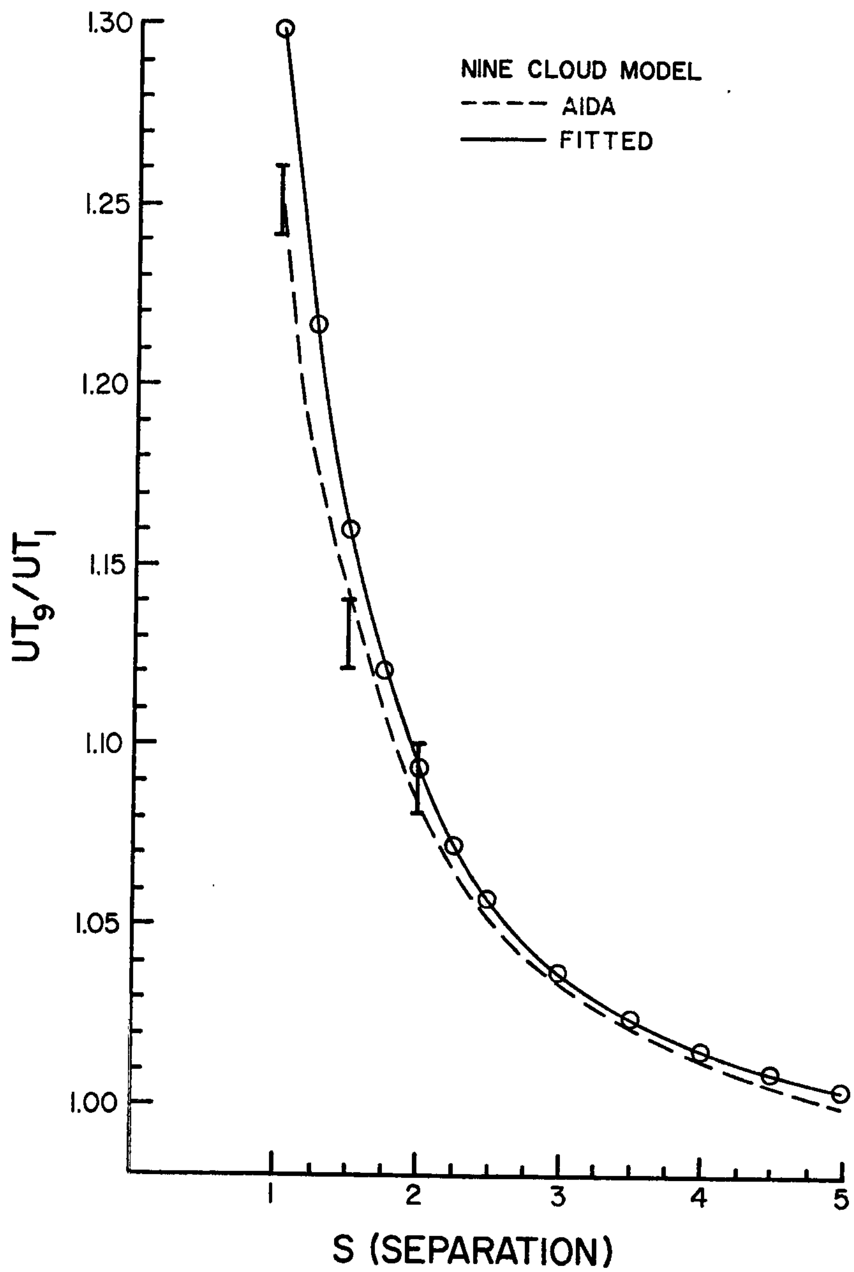

Figure 8. Aida versus experimental method for nine cloud model.

Aida's calculations are done using cubical clouds and calculating albedos. The experimental method uses spherical clouds and measures the light off the top of the cloud.

III.2. Cloud Height Versus Cloud Interaction Distance

The next area of research pursued was to determine how the interaction distance varied as a function of the height. The clouds used in the five cloud and nine cloud models were approximately .75 diameters high, due to the fact that they compress when they are placed onto the blackened surface. Styrofoam cut into 5.1 x 5.1 x 1.3 centimeter pieces was used for the layer model. The reasons for using "square" clouds are that they stack more easily and are different radiatively from the spherical clouds. McKee and Cox (1974, 1976) have investigated the radiative properties of cubical clouds of various optical thickness and solar angles. By using square clouds, the differences could be explored on how to relate the detailed work of the aforementioned authors to more realistic clouds found in the atmosphere.

The layer model runs were done by taking the five cloud array for one, two, three, four and five thicknesses of styrofoam. Each one of these was repeated three times, as previously done with the five and nine cotton cloud arrays. The sensor was again placed on top of the center cloud and the other four clouds were placed at maximum separation. A reading was taken at maximum separation and all other readings in that run were ratioed to the maximum separation reading. The height of the layer model is depicted on the graph as the solid blackened shape at the end of the title. Curves were fitted to all the different layer models using the same type routine as described previously. The equation for the best fit appears on the graph for each layer model.

Figure 9 shows data collected from the one layer, five cloud array run. The fitted curve shows a slight increase after reaching a minimum value due to the dominance of the cubic term. The low flat clouds show a very short interaction distance, a 5% increase at 1.3 diameter separation. The graph also shows at separation of one diameter an increase of 22% over maximum separation occurs. Figure 10 shows the five cloud, two layer array, along with the fitted curve. This shows almost a 40% increase over maximum separation and a 5% increase at 1.75 separation diameter.

Figure 11 shows the three layer, five cloud array with the fitted curve plotted and the equation in the upper right. The three layer shows a maximum increase at one separation diameter of almost 42%. This is a much smaller change than observed going from the one layer to the two layer model. A 5% increase is observed at a separation of 1.95 diameters. The four layer model is shown in Figure 12, with the best fit equation in the right hand corner. The square term has almost insignificant size. The maximum increase is 43% at one separation diameter, with the 5% increase occurring at two diameters. In the five layer model, which appears in Figure 13, the maximum increase is 42.5% and 5% increase occurs at 1.9 separation diameter, which is a decrease from the four cloud.

The reason for the large differences between the one layer and the two layer model is that it does increase the distance which the

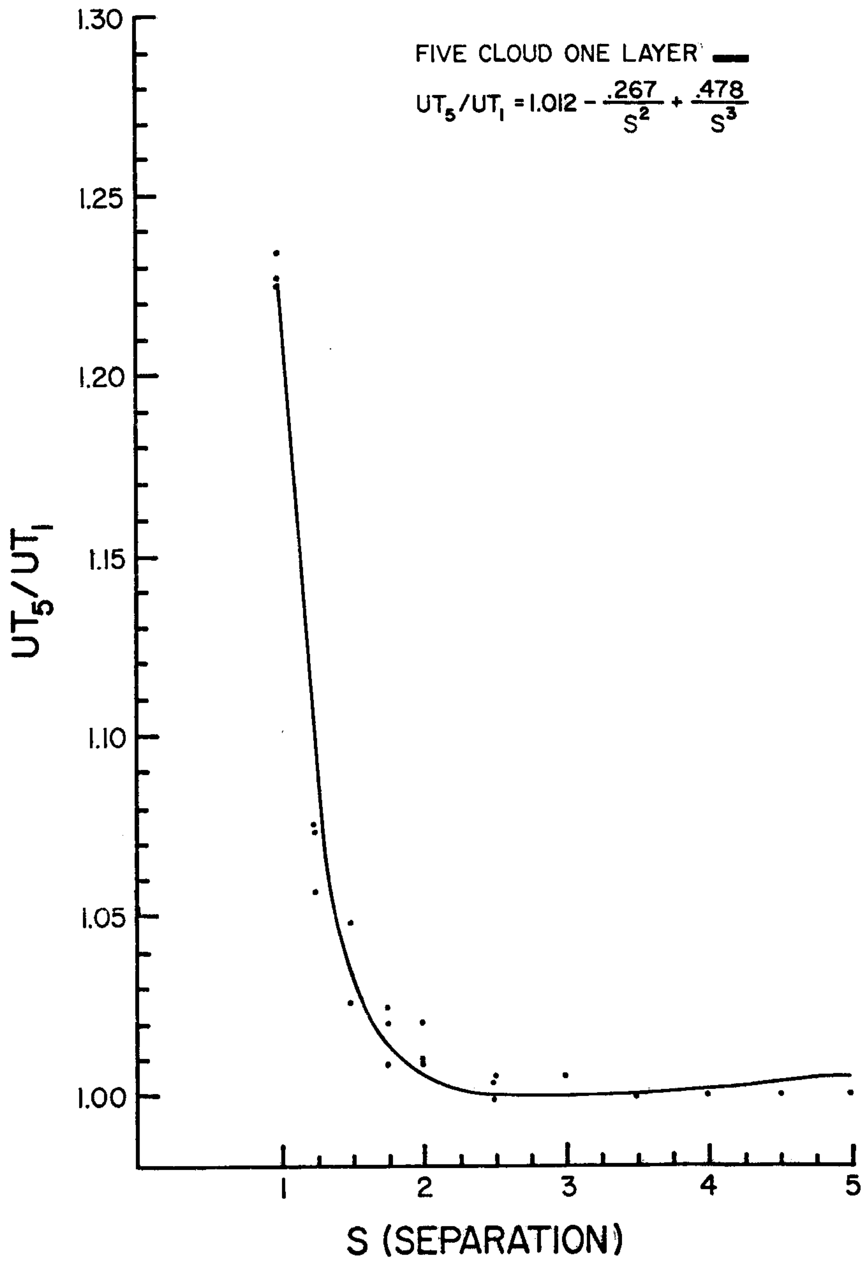

Figure 9. Five cloud one layer graph.

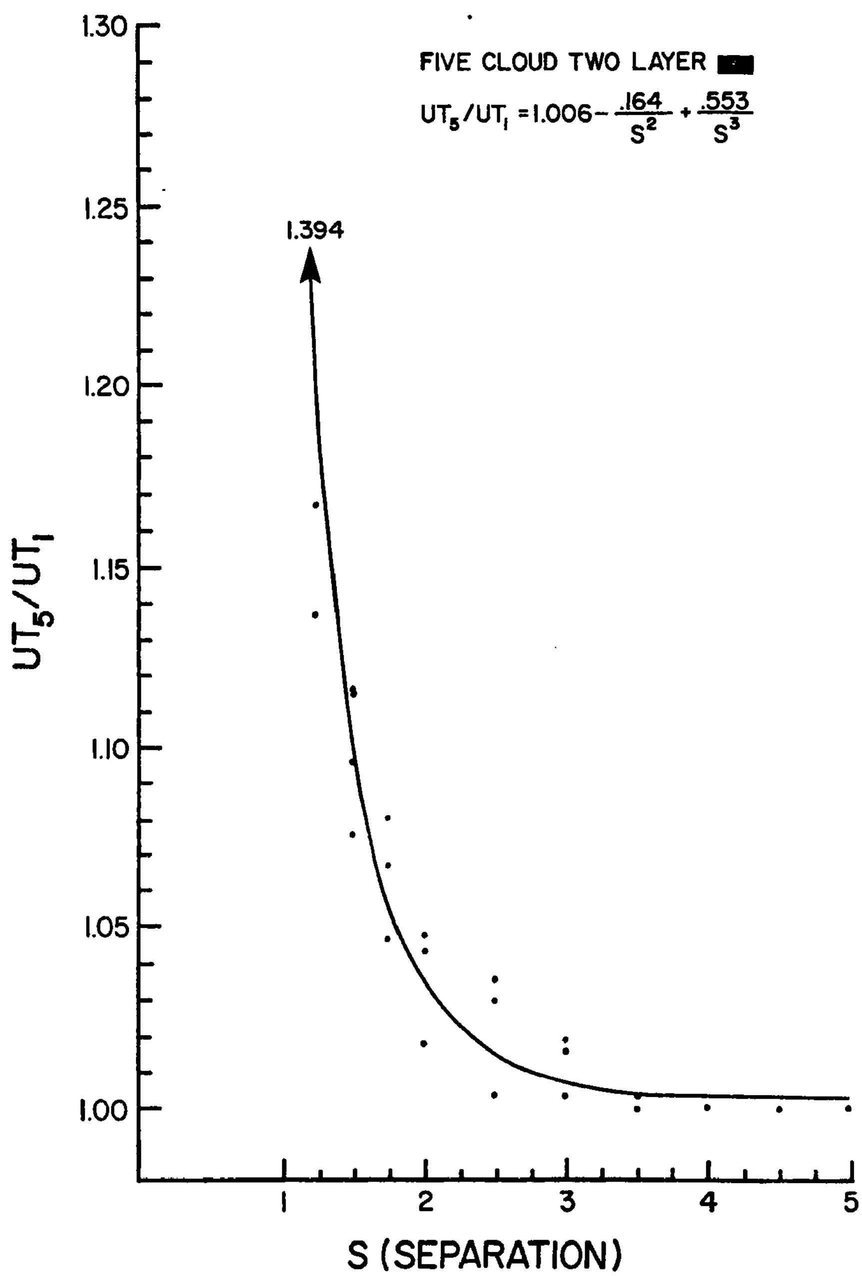

Figure 10. Five cloud two layer graph.

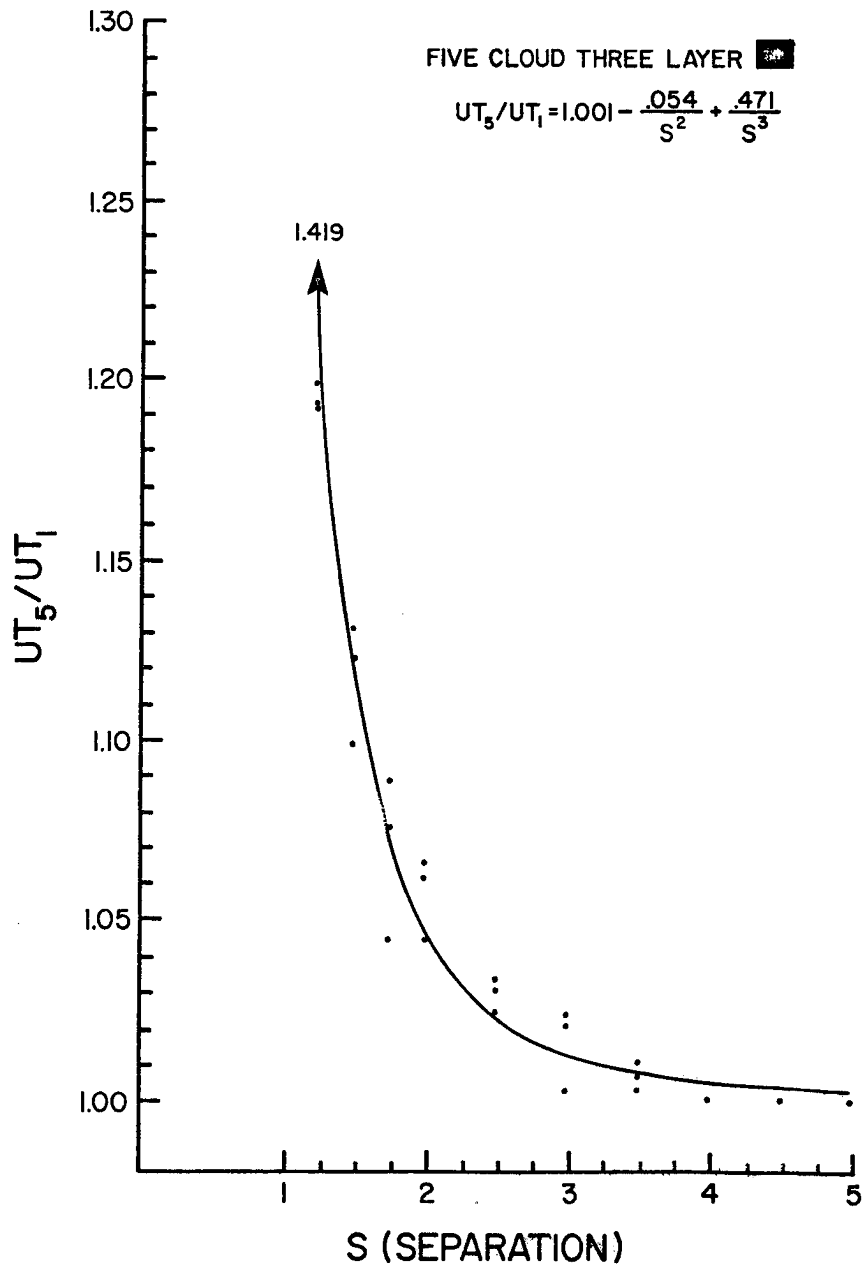

Figure 11. Five cloud three layer graph.

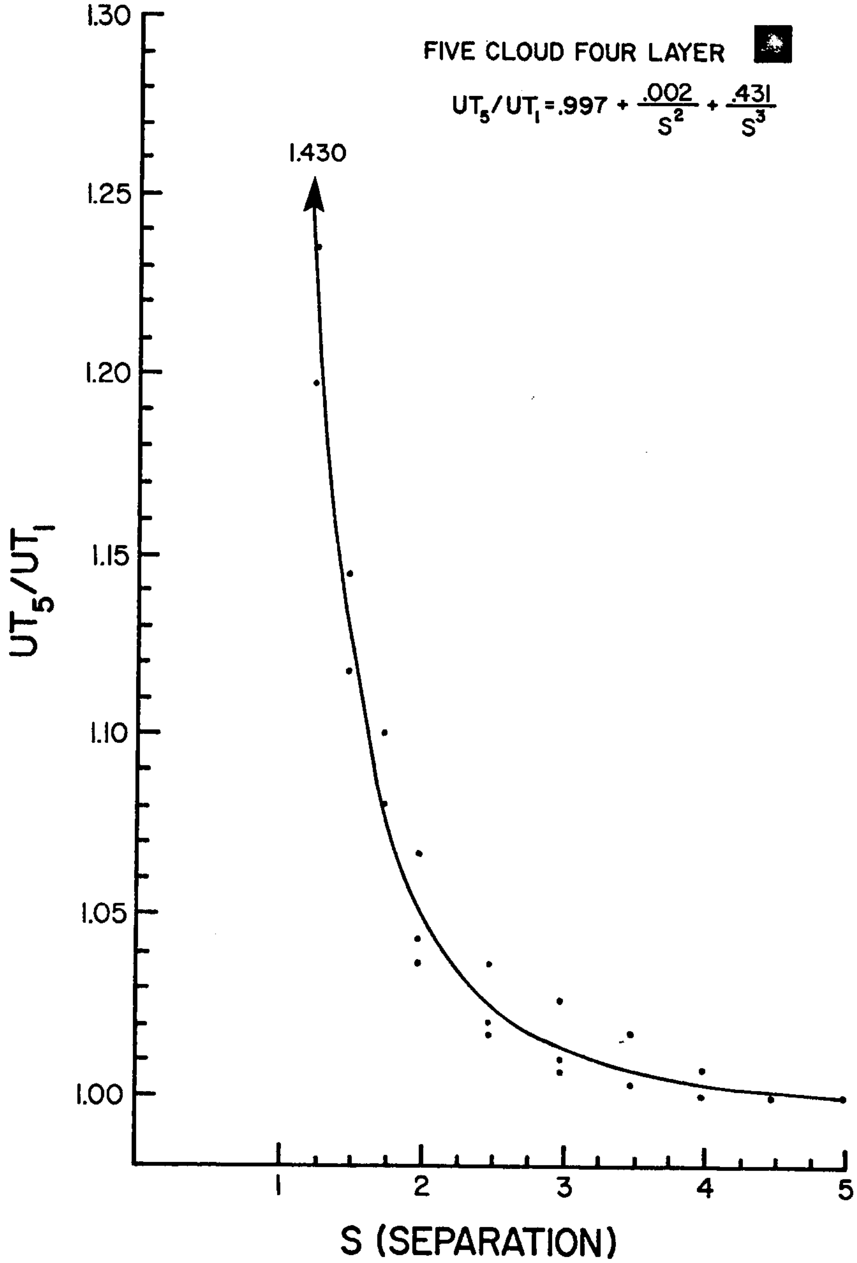

Figure 12. Five cloud four layer graph.

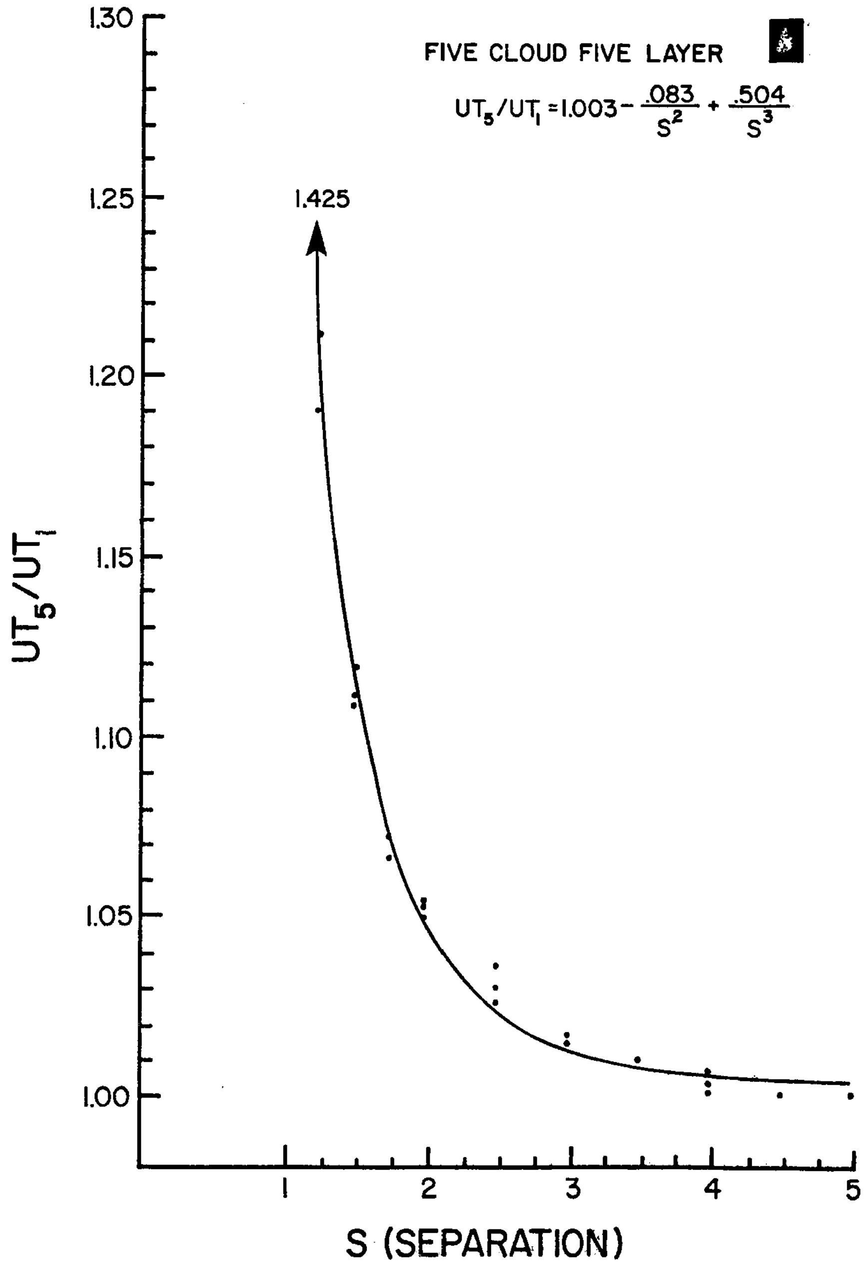

Figure 13. Five cloud five layer graph.

clouds interact by giving more distance for the light to scatter through the optical thickness. But as one increases the optical thickness even more, the interaction distance does not change much, because the interaction takes place mainly in the upper part of the cloud. In the lower parts of the cloud, the optical thickness is so large, the transmittance so small, that little of the light penetrates far into the cloud.

In an experiment to try to measure the optical depth of the styrofoam, it appears that a 2.5 centimeter thickness has an optical depth of approximately 50. This was deduced by measuring the reflected light as the depth of the foam was increased. This curve was then compared to a curve given by McKee and Cox (1976) which gave the increase in albedo as a function of the optical thickness of a cubic cloud (see Figure 14). So increasing the height of the clouds would not make a significant increase in the interaction distance, since most of the interaction takes place in the upper part of the clouds.

Consider some of the implications involved with the measurements given here. Below are the percent changes for the models presented so far. The percent changes are for how much the ratio decreased when going from a separation of one diameter to a separation of two diameters for each different model.

If one considers the magnitude of these percentage changes, it appears in most cases, except possibly the nine cloud cotton ball model, that if the clouds in the atmosphere are separated by more than two diameters, they could be treated as if they were finite non-interacting clouds, because any separation of larger than two diameters

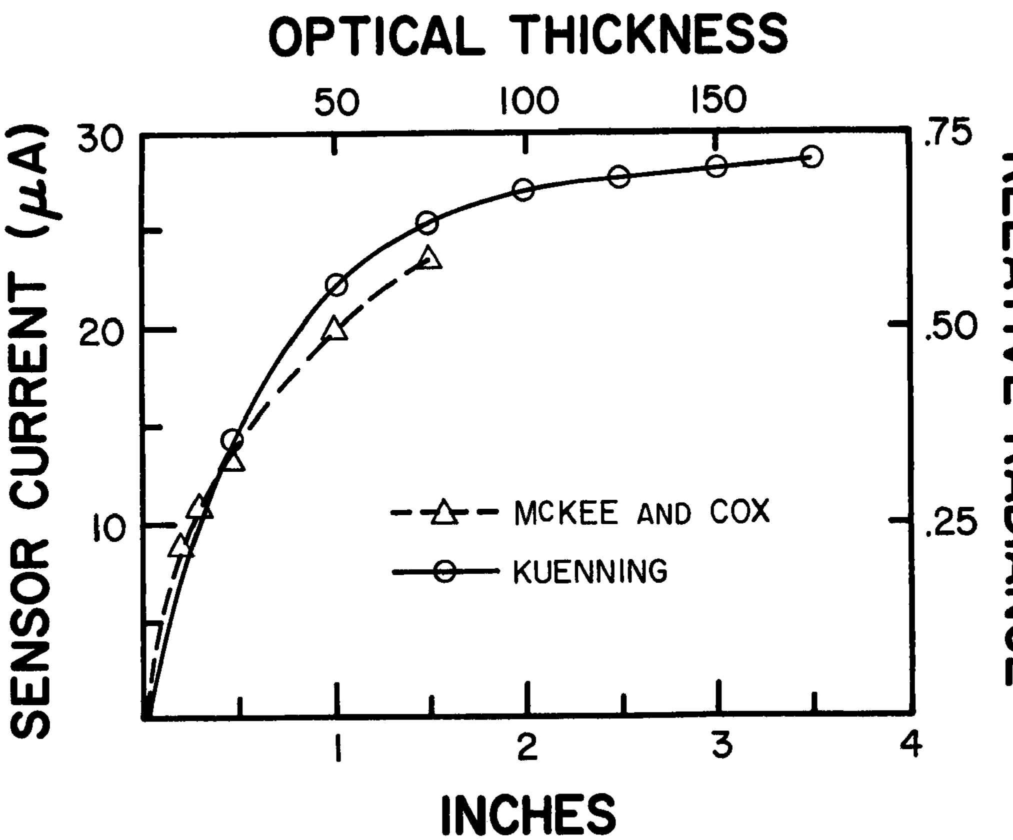

Figure 14. Graph shows the approximate optical depth of styrofoam plotted against a Monte Carlo generated graph from McKee and Cox (1976).

Table 2. Percent changes for models.

Model	Percentage
5 cloud cotton	76%
9 cloud cotton	68%
5 cloud styrofoam 1 layer	97%
5 cloud styrofoam 2 layer	91%
5 cloud styrofoam 3 layer	89%
5 cloud styrofoam 4 layer	88%
5 cloud styrofoam 5 layer	90%

does not significantly increase the upward-going radiance fields. At small separations, there is a very large change which could have a large impact on what one observes in the atmosphere.

Consider a semi-infinite cloud whose optical depth is around seventy. There are models available to calculate the albedo for this type of cloud. The Monte Carlo technique predicts an albedo of 91.7%. But measurements in our atmosphere seem to indicate that clouds seldom have albedos higher than 80%. So there arise some significant differences between theoretical calculations and observational data. Consider the following example as an explanation of the differences.

Suppose that a semi-infinite cloud is not horizontally homogeneous and is made up of 4 kilometer cubes with optical depths of 70. The cubes have a separation of 1.1 diameters or the edges are separated by 0.4 kilometers. This separation is below the resolution of most satellites used in the late 1960's and therefore would be difficult to discern whether it was one cloud or a bunch of small clouds close together. Using the results of the five-cloud, four-layer model (Figure 12), the value of UT_5/UT_1 at a separation of 1.00 is 1.43, while at a separation of 1.1 the ratio is 1.32. This means that in going from a maximum separation to a 1.1 separation, one would detect only 74% of the change in albedo from the maximum to minimum separation. A cubic cloud of optical depth 70 and sun vertical has an albedo of 70% while semi-infinite has an albedo of 91.7%. Therefore, the albedo of the semi-infinite composed of finite cubes would have an albedo of 86%. Larger separations than 1.1 would decrease the albedo.

While the previous argument does not explain all the differences between theoretical and observational results, it does explain a significant portion of the discrepancy. More generally, a semi-infinite cloud will lose its semi-infinite characteristics quickly when broken up into separate components, because of the rapid drop of the quantity UT_5/UT_1 as the separation is increased.

IV. Implications

IV.1. Discussion

Consider a single isolated cubic cloud and one wishes to study how the albedo of that cloud changes due to its interaction with the surrounding clouds. The nine cloud model, whose graph appears in Figure 6, is an example of what happens to a single cloud when eight other clouds are brought into the area. It shows an increase of about 30% at minimum separation. At first glance, this might be termed as a 30% increase in the albedo of the center cloud. But albedo is defined as ratio of all energy at all wave lengths leaving the system in the upper hemisphere to that which is incident on the system at all wave lengths and all angles. Normally in our atmosphere, there is one primary source of energy confined to a relatively small solid angle. However, when considering the interaction of clouds, energy enters the cloud from the adjacent clouds through the scattering process.

It seems plausible that most of the apparent increase in albedo is only due to the increase in energy incident on the sides of the cloud. Directional reflectance is defined as the ratio of all energy at all wave lengths leaving the system going upward to that energy which is incident at all wave lengths and just one angle. If one considers directional reflectance as a variable measuring the cloud radiance fields, the directional reflectance does change value as the clouds are moved in closer together. Normally in our atmosphere, albedo and directional reflectance are considered to be equal. This is not true when dealing with multi-directional energy incident upon the cloud. In this case if one uses directional reflectance it does change, since the light coming from the adjacent clouds adds to the energy leaving in the upper hemisphere. This reasoning does not apply when one considers the entire field as a unit, since the energy incident on the field is constant.

If one envisions an instrument capable of measuring the albedo of a cloud field instantaneously, one would expect an actual increase in the cloud field albedo as the cloud separation becomes smaller. The amount of incident energy does not change with decreasing separation, but the total upward-going radiances do change, due to the interaction. The interaction among the clouds permits energy that would have exited going downward from the clouds to interact further with the adjacent clouds and possibly exit going in the upward direction, adding to the albedo of the cloud field.

The separation among the clouds may be decreased by simply moving the clouds closer together or by adding more clouds to a given size of area, increasing the sky cover. When increasing the sky cover, the albedo will increase according to the formula $A_s = a_s SC$ where a_c is cloud albedo and SC is sky cover, but it will also increase because of the smaller separation distances. In the nine cloud model, the amount that the directional reflectance increased was found for various separations. These correction factors can be applied to the cloud field if the separation among the clouds is known.

IV.2. Comparison of Finite to Infinite

If one defines an area that will be considered as the entire sky cover, calculations can be done using the Monte Carlo program and data from the nine cloud model to calculate the albedo of the entire system as a function of sky cover for various cases. The area which represented 100% sky cover was 20 x 20 kilometers.

The first case is what will be called the "Basic Cube". The Monte Carlo program was used to calculate the albedo of a single cubic cloud 1.5 x 1.5 x 1.5 kilometers for the sun vertical and an optical thickness of 73.5. The scattering is conservative with the C1 (Deirmendjian) cloud droplet distribution. The albedo calculated was .700. By using the formula $A_s = a_c SC$, where A_s is the system albedo, a_c is the cloud albedo, and SC is the sky cover, one can generate the system albedo for sky covers from 0% to 100%. This relationship is linear and appears in Figure 15 labeled as "Basic Cubic". Physically what is happening is that more and more cubic clouds are being placed inside the area, but they are not permitted to interact. Their placement in the cloud field and with respect to each other is not critical, since only the area covered by them increases the system albedo.

The second is the opposite of the first and will be called the "Slab". In this case, we place the cubic clouds so that they are touching and therefore may be treated as one large cloud. The Monte Carlo program may be made to expand the cubic cloud out to a slab maintaining the same vertical optical depth. This was done for slabs of the following horizontal dimensions: 1.5 x 1.5, 3 x 3, 4.5 x 4.5, 6 x 6, 9 x 9, 15 x 15, and 18 x 18 kilometers. For each slab cloud, an albedo was calculated by the program and then multiplied by the sky cover they represent in the area. The slab runs are graphed in Figure 15 and labeled "Slab". This slab run represents the maximum

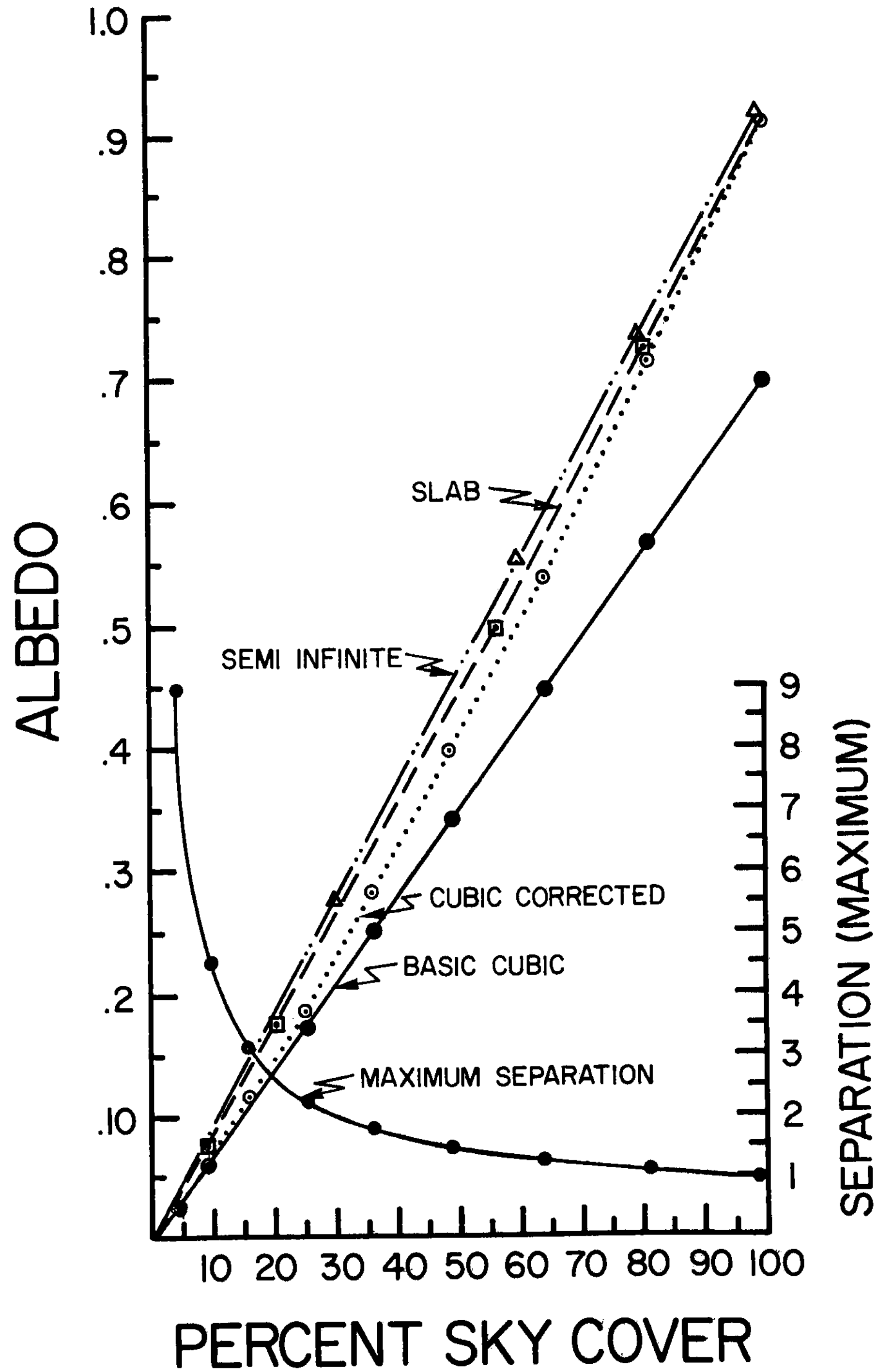

Figure 15. Graph showing the different cloud field albedoes for non-interacting cubic, semi-infinite, slab, and interacting cubic clouds for sky covers from 0% to 100% for optical thickness of 73.5.

possible albedo for finite clouds. Another case that can be studied is how the infinite cloud fits in with the other two cases.

The third case will be called the "Semi-infinite" case. This consists of calculating the albedo of an infinite cloud, using the Monte Carlo program, and multiplying the albedo by the sky cover. This is similar to the "Basic Cubic" case, only a different cloud albedo, namely the infinite cloud, is used in the formula. The graphic results of this case appear in Figure 15 and are labeled "Semi-infinite".

The fourth case deals with allowing the finite cubic clouds to interact to a lesser extent than the slab. This case is called the "Cubic Corrected." Recall that the "Basic Cubic" case is just finite clouds which are not permitted to interact. Now as the sky cover increases, the finite clouds get closer and closer together. Therefore, the constraint that the clouds not interact is unreasonable. But the case entitled "Slab" confines the finite clouds to be touching, which is only realistic at 100% sky cover. So the fourth case is the opposite of the "Slab" case in that it minimizes the interaction, but still allows the clouds to interact.

To compute the minimum interaction, one must first calculate the maximum separation the clouds could have for a given sky cover. If one uses only the symmetric cloud array, a formula can be developed to calculate the maximum separation. The formula is $S_{max} = \frac{\Delta x - D}{D(\sqrt{N}-1)}$ where ΔX is the width of the area, D is diameter of the clouds and N is the number of clouds in the area. The maximum separation was calculated for various sky covers and appears in Figure 15 labeled "Maximum Separation".

Recall that Figure 6 which is the nine cloud model gives the increase in the direction reflectance of the top of the cloud. With this data and the maximum separation, the "Basic Cube" case can be corrected for the interaction. At each step of the sky cover, a maximum separation is calculated. With this maximum separation, a correction factor may be obtained from the nine cloud model. This correction factor is multiplied by the respective albedo from the "Basic Cube" to obtain the corrected albedo. The results are shown in Figure 15 and labeled "Cubic Corrected".

The results of Figure 15 have some rather interesting implications about how one should treat the cloud fields when trying to model their radiative characteristics. Classically, in the past, large global climate models or energy budget computations, in attempting to model the radiative transfer in cloud fields, have used the infinite cloud assumption for calculating the transfer. This method takes the calculated albedo and reduces it for the sky cover. McKee and Cox (1974) disputed this almost universal application of this semi-infinite approximation, saying that radiatively the finite clouds are much different from the infinite clouds. Since the finite clouds had much lower albedos than the infinite clouds, it was assumed that the infinite cloud approximation could lead to erroneous results. However, finite clouds lead to the complication of interaction and how the interaction could be treated.

Many studies have dealt with this problem. Aida (1976) used Monte Carlo techniques and some of his results have been presented. Barkstrom (1976) used a diffusion model equation to study its effect.

The author's results and the aforementioned papers all seem to indicate that this interaction is very significant when the clouds are within 2.5 separation diameters.

In Figure 15 the curve marked "Cubic Corrected" is a curve showing the minimum albedo that a field of cubic clouds would have. This is because the clouds are as far apart as possible for the particular sky cover. The curve marked "Semi-Infinite" would be the albedo for the infinite cloud approximation. As can be seen, the semi-infinite does not differ much from the corrected cubic.

One point to make is that where the "Cubic Corrected" albedo exceeds the "Slab" albedo, the experimental results in this paper have overestimated the interaction, since the "Cubic Corrected" should only equal the "Slab" at 0% and 100% sky cover and in between those two points, it should always be less.

The most important thing about the "Cubic Corrected" and the "Slab" is that any cloud field composed of single sized cubic clouds with the same optical depth must have an albedo that is greater than or equation to the "Cubic Corrected", but less than or equal to that of the "Slab". Any cloud field, no matter if the placement is random or symmetric, must fall between these two limits for all sky covers. As can be seen from Figure 15 the infinite is in fairly close agreement to the slab case. Hence, the infinite approximation has a maximum known amount of error from the "Cubic Corrected".

Figure 16 shows the same type results for an optical depth of twenty. Analyzing the results for a smaller optical depth will give an indication as to whether these results change drastically for

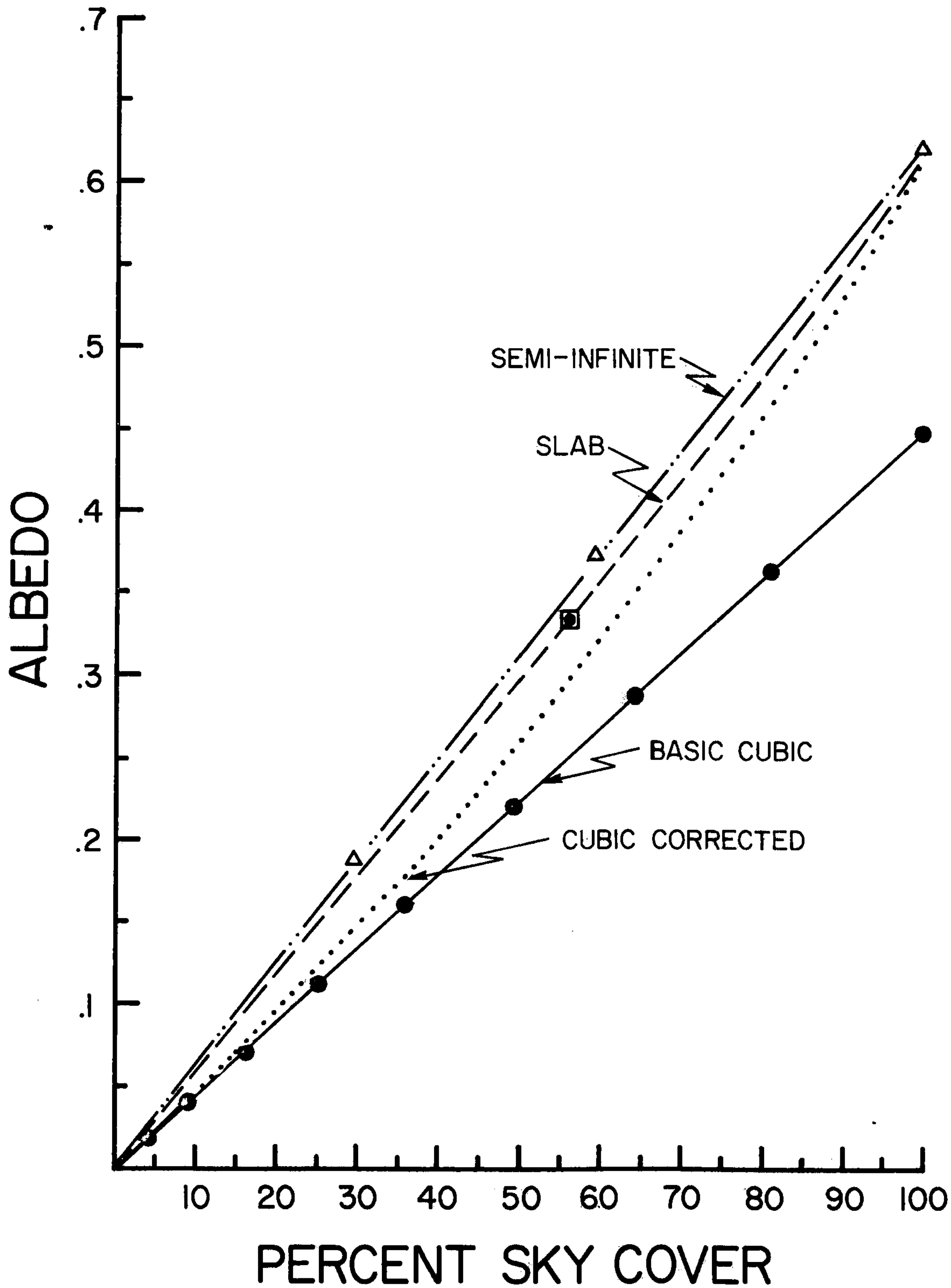

Figure 16. Same as Figure 15 except the optical thickness is 20.

different optical depth. One thing quite different about this graph for optical depth of twenty is that while the "Basic Cubic", "Semi-infinite", and "Slab" cases are all generated from Monte Carlo programs, the "Cubic Corrected" is placed in by simply knowing the two end points and basically following the same shape as the bigger optical depth case. The only reason the "Cubic Corrected" could be in large error is that if the interaction distance changed for the optical depth to be much smaller, the "Cubic Corrected" might not diverge from the "Basic Cubic" until a sky cover of, for instance, 30%, where maximum separation is two diameters. Again this shows the infinite cloud approximation to be in error at most of 5% in albedo. This is deceptive in nature because this occurs in small albedos.

A better analysis of how much the infinite cloud could vary from the "Cubic Corrected" was done. A percent error was defined to evaluate the difference between the infinite and "Cubic Corrected". It was defined as

$$\text{Percent Error (SC)} = \frac{\text{INF(SC)} - \text{CC(SC)} \times 100}{\text{CC(SC)}}$$

where INF is the infinite cloud albedo at some sky cover and CC is the Cubic Corrected albedo at the same sky cover. CC(SC) and INF(SC) only denote that these are functions of sky cover. This percent error represents the largest amount the infinite cloud approximation could overpredict the system albedo.

Figure 17 shows the results for both optical depths. The smaller the optical depth, the larger the possible error. Small sky covers lead to larger maximum errors. Recall that this error is the largest

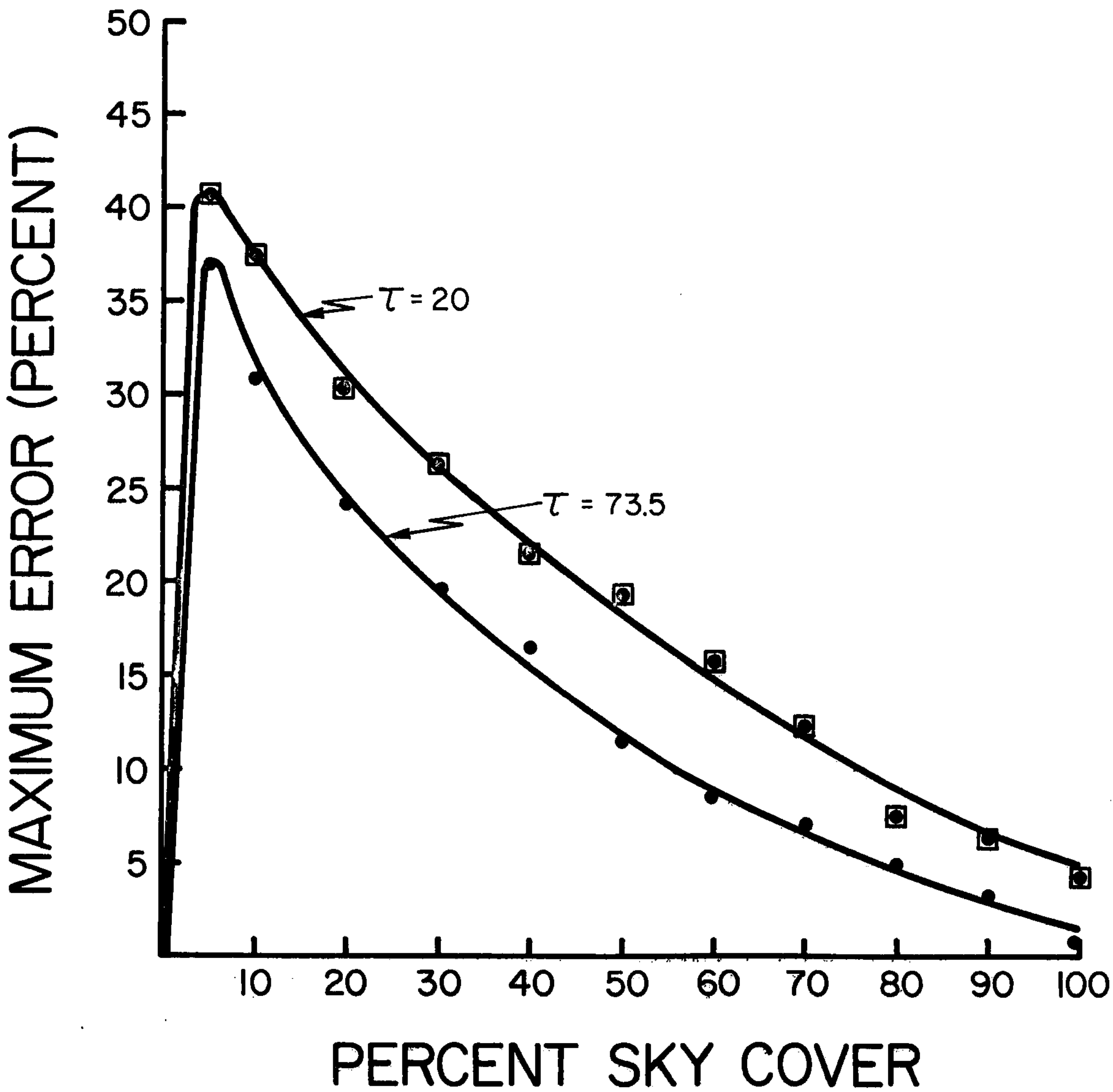

Figure 17. Maximum error versus sky cover for optical thickness of 20 and 70.

amount of error the infinite cloud model would overpredict a field of interacting cubic clouds. The relative error analysis is helpful in some applications but can be misleading. In the small sky cover regime, even though the percent errors are on the order or 40%, the absolute errors are only 0.8%. It would be instructive to look at the albedo differences between the "Infinite" and the "Corrected Cubic" as a function of sky cover.

Figure 18 shows the "Infinite" and "Corrected Cubic" albedo errors as a function of sky cover for an optical thickness of 73.5. It is interesting to note that the maximum error occurs at approximately 50% sky cover and is of apparent symmetric bell shaped curve. It is estimated that the average global cloud cover is on the order of 50% also. These two facts indicate that global energy budget calculations, using an infinite cloud approximation, are modeling cloudiness in a regime where the maximum albedo differences occur. What is not known is where the finite cloud regime ends and semi-infinite begins. If at 50% sky cover clouds are not finite clouds but more slab in nature one would expect a smaller difference between the interacting cubic and infinite cloud models. There is presently no detailed data available presenting average cloud diameter for sky covers from 5% to 95%.

All of the results in this paper are based on sun vertical and optically thick clouds. Figures 15 and 16 show the infinite cloud approximation overpredicting the directional reflectance. These results could change for large zenith angles where the infinite cloud model actually underpredicts the directional reflectance.

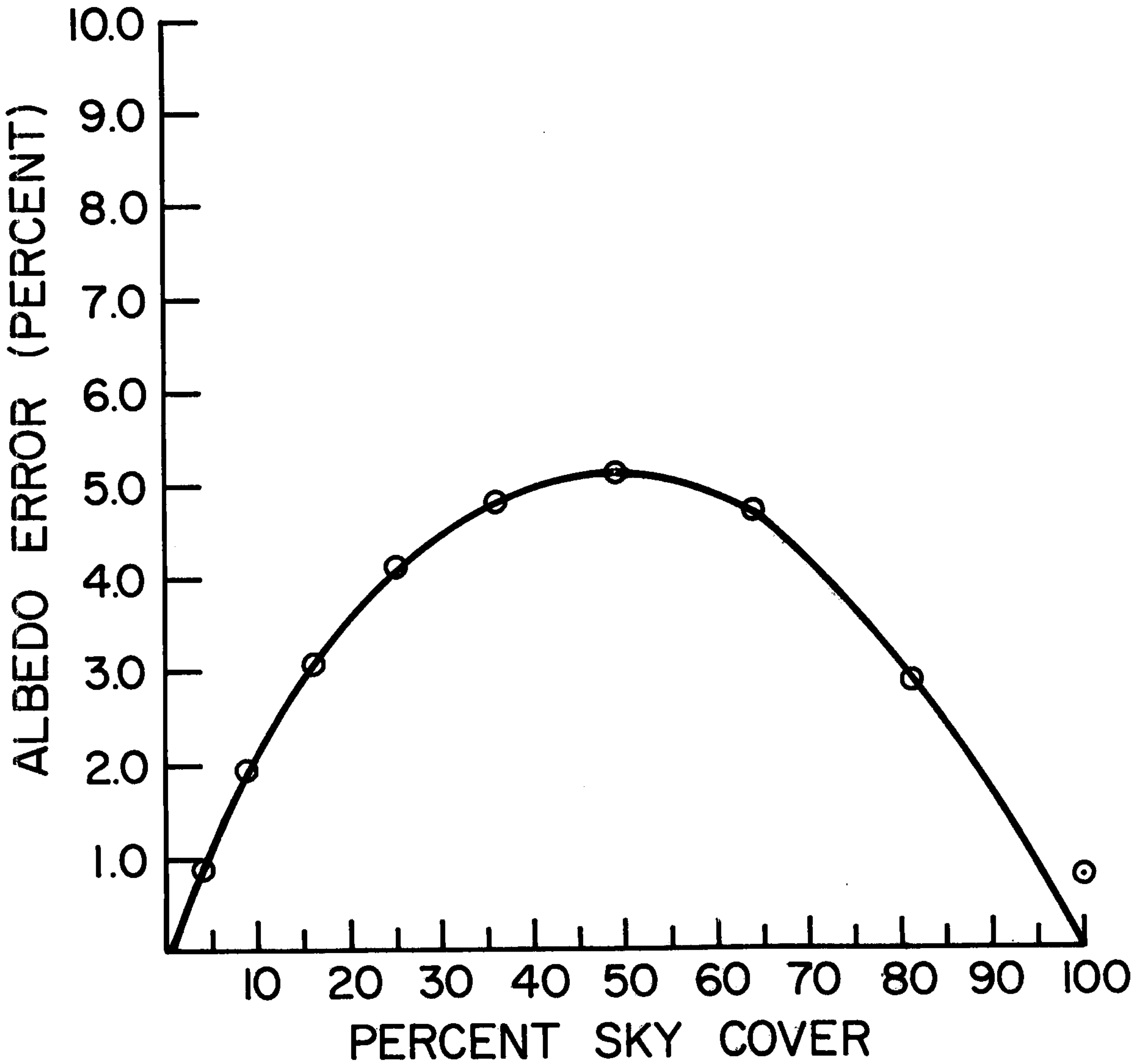

Figure 18. Absolute error between infinite and corrected cubic cloud field albedoes for an optical depth 73.5.

V. Suggestions for Future Research

During the experiment randomly placed cloud fields were investigated. The clouds were placed randomly into the coordinate system to simulate possible configurations of real cloud fields in the atmosphere. The sensors were placed high above the cloud fields in order to get a total view of the field. Unfortunately there were errors in this logic since the background signal was far too large compared to the signal received from the clouds. The problem was not discovered until too late, so no data of these experiments are included in this paper. However it is the opinion of the author that this would be a productive pursuit for further research and is included below. Several improvements in the experimental design are desirable and include the following:

1) To develop a better system of measuring the albedo;
2) To develop a method of calibration of the system against a known;
3) To develop a method of accurately controlling and measuring the optical depth;
4) To have a larger working area.

Future areas of research that would be most productive relating to the work done here are as follows:

1) To measure the entire albedo for cubic and spherical clouds undergoing interaction;
2) To measure the albedo of the random placement;
3) To extend the random cloud placement into larger cloud covers to complete the picture;

4) To study interaction distance and magnitudes of it as a function of optical depth;

5) To study the effect of using a size spectrum in the cloud fields according to know distributions of Planck;

6) To study the height versus interaction in greater detail using material whose geometric thickness is larger to its optical depth than the material used in this study;

7) To incorporate the random placement into the comparison of infinite to corrected cubic to better evaluate the possible error using the infinite cloud model.

VI. Concluding Remarks

The most important conclusion from this research is that useful data can be obtained from the physical modeling of clouds. Radiance patterns from complex cloud structures may be too difficult to calculate theoretically, whereas physical modeling may be the simplest means to approach the problem.

The center cloud in a 3 x 3 array of modeled clouds was found to have a 5% increase in the top directional reflectance over the isolated cloud case at a separation of 2.5 cloud diameters, and increased to 30% at a separation of one cloud diameter. The increase of the top directional reflectance as the separation increased behaved similar to $1/S^2$ where S is the cloud separation. The cloud interaction distance was found to rapidly increase as the height to diameter ratio increased, but then leveled off as the optical thickness of the clouds got larger than about 100 to 125. It was concluded that cubic clouds separated by more than 2.5 cloud diameters could be treated as non-interacting clouds.

A comparison of calculated directional reflectances for cloud fields was done using the infinite cloud approximation, non-interacting cubes, slab clouds, and interacting cubic clouds for sky covers of 0% to 100% sun vertical. An error analysis between the infinite cloud approximation and the interacting cubic clouds showed a maximum relative error of 40% at cloud covers under 5% but the absolute error maximum was 5% directional reflectance at sky covers around 50%.

REFERENCES

Aida, B., 1976: Transfer of solar radiation in an array of cumuli. Paper delivered at Symposium on Radiation in the Atmosphere, Garmisch-Partenkirchen, Germany, held 19-28 August, 1976.

Barkstron, B. R. and R. F. Arduini, 1976: The effect of finite horizontal size of clouds upon the visual albedo of the earth. Paper delivered at Symposium on Radiation in the Atmosphere, Garmisch-Partenkirchen, Germany, held 19-28 August, 1976.

Deirmendjian, D., 1969: Electromagnetic scattering on spherical polydispersions. Elsevier, 78 pp.

London, J., 1957: A study of the atmospheric heat balance. Final Rept. Contract AF19 (122)-165, College of Engineering, New York University, (ASTIA No. 117227), 98 pp.

London, J. and T. Sasamori, 1971: Radiative Energy Budget of the Atmosphere. Space Research XI, Akademic-Verlag, Berlin, 639-649.

McKee, T. B. and S. K. Cox, 1974: Scattering of visible radiation by finite clouds. J. Atmos. Sci., 31, 1885-1892.

McKee, T. B. and S. K. Cox, 1976: Simulated radiance patterns for finite cubic clouds. J. Atmos. Sci., 31, 2014-2020.

Plant, V. G., 1969: The size distribution of cumulus clouds in representative Florida populations. J. App. Met., 8, 46-67.

Rasche, E. and W. R. Bandeen, 1970: The radiation balance of the planet Earth from radiation measurements of the satellite Nimbus II. J. App. Met., 9, 215-238.

Snedecor, George W. and William G. Cochran, 1971: Statistical methods, sixth edition. Iowa State University Press, Ames, Iowa.

Vonder Haar, T. H. and K. J. Hanson, 1969: Absorption of solar radiation in the tropical regions. J. Atmos. Sci., 26, 652-655.

Wendling, P., 1977: Albedo and reflected radiance of horizontally inhomogeneous clouds. J. Atmos. Sci., 34, 642-650.

APPENDIX A.

The appendix contains the data for the figures presented in the text. The tables are arranged in the same order as the figures in the text.

Table A1. Data for nine cloud model.

S	Output (μAmp)	UT_9/UT_1	Output (μAmp)	UT_9/UT_1	Output (μAmp)	UT_9/UT_1	FITTED
5.0	32.2	1.000	32.2	1.000	32.1	1.000	1.004
4.5	32.2	1.000	32.3	1.003	32.2	1.003	1.009
4.0	32.3	1.003	32.6	1.012	32.4	1.009	1.015
3.5	32.9	1.022	33.0	1.025	32.9	1.025	1.024
3.0	34.0	1.056	33.8	1.050	33.9	1.056	1.037
2.5	34.4	1.068	34.0	1.056	34.3	1.069	1.057
2.25	34.6	1.075	34.5	1.071	34.7	1.081	1.072
2.0	35.0	1.087	35.0	1.087	35.2	1.097	1.093
1.75	35.9	1.115	36.0	1.118	36.1	1.125	1.120
1.5	37.0	1.149	36.8	1.143	36.9	1.150	1.159
1.25	39.1	1.214	39.5	1.227	39.2	1.221	1.216
1.0	41.6	1.292	41.8	1.298	41.9	1.305	1.298

Table A2. Data for five cloud layer models.

ONE LAYER

S	Output (μAmp)	UT_5/UT_1	Output (μAmp)	UT_5/UT_1	Output (μAmp)	UT_5/UT_1
5.0	20.4	1.000	22.8	1.000	20.3	1.000
4.5	20.4	1.000	22.8	1.000	20.3	1.000
4.0	20.4	1.000	22.8	1.000	20.3	1.000
3.5	20.4	1.000	22.8	1.000	20.3	1.000
3.0	20.5	1.005	22.8	1.000	20.4	1.005
2.5	20.5	1.005	22.9	1.004	20.4	1.005
2.0	20.6	1.010	23.0	1.009	20.7	1.020
1.75	20.8	1.020	23.0	1.009	20.8	1.025
1.5	21.1	1.034	23.4	1.026	21.3	1.049
1.25	21.9	1.074	24.1	1.057	21.8	1.074
1.0	25.9	1.225	28.2	1.257	24.9	1.227

TWO LAYER

S	Output (μAmp)	UT_5/UT_1	Output (μAmp)	UT_5/UT_1	Output (μAmp)	UT_5/UT_1
5.0	27.7	1.000	27.0	1.000	25.0	1.000
4.5	27.7	1.000	27.0	1.000	25.0	1.000
4.0	27.7	1.000	27.0	1.000	25.0	1.000
3.5	27.7	1.000	27.0	1.000	25.1	1.004
3.0	27.8	1.004	27.5	1.019	25.4	1.016
2.5	27.8	1.004	27.8	1.030	25.9	1.036
2.0	28.2	1.018	28.2	1.044	26.2	1.048
1.75	29.0	1.047	28.8	1.067	27.0	1.080
1.5	29.8	1.076	29.7	1.100	27.9	1.116
1.25	31.5	1.137	31.5	1.167	29.8	1.192
1.0	37.2	1.343	37.8	1.400	36.5	1.460

Table A2. Continued.

THREE LAYER						
S	Output (μAmp)	UT_5/UT_1	Output (μAmp)	UT_5/UT_1	Output (μAmp)	UT_5/UT_1
5.0	29.2	1.000	29.0	1.000	29.2	1.000
4.5	29.2	1.000	29.0	1.000	29.2	1.000
4.0	29.2	1.000	29.0	1.000	29.2	1.000
3.5	29.4	1.007	29.1	1.003	29.5	1.010
3.0	29.9	1.024	29.1	1.003	29.8	1.021
2.5	30.2	1.034	29.9	1.031	30.1	1.031
2.0	30.5	1.045	30.9	1.066	31.0	1.062
1.75	30.5	1.045	31.2	1.076	31.8	1.089
1.5	32.1	1.099	32.8	1.131	32.8	1.123
1.25	34.8	1.192	34.6	1.193	35.0	1.199
1.0	41.5	1.421	41.0	1.414	42.0	1.438

FOUR LAYER						
S	Output (μAmp)	UT_5/UT_1	Output (μAmp)	UT_5/UT_1	Output (μAmp)	UT_5/UT_1
5.0	29.9	1.000	30.0	1.000	29.9	1.000
4.5	29.9	1.000	30.0	1.000	29.9	1.000
4.0	29.9	1.000	30.2	1.007	29.9	1.000
3.5	30.0	1.003	30.5	1.017	30.0	1.003
3.0	30.1	1.007	30.8	1.027	30.2	1.010
2.5	30.4	1.017	31.1	1.037	30.5	1.020
2.0	31.2	1.043	22.0	1.067	31.0	1.037
1.75	32.3	1.080	33.0	1.100	32.2	1.077
1.5	33.4	1.117	33.8	1.127	34.2	1.144
1.25	35.8	1.197	35.9	1.197	36.9	1.234
1.0	42.9	1.435	42.8	1.427	43.0	1.438

Table A2. Continued.

FIVE LAYER						
S	Output (μAmp)	UT_5/UT_1	Output (μAmp)	UT_5/UT_1	Output (μAmp)	UT_5/UT_1
5.0	30.5	1.000	30.5	1.000	30.4	1.000
4.5	30.5	1.000	30.5	1.000	30.4	1.000
4.0	30.5	1.000	30.6	1.003	30.6	1.007
3.5	30.7	1.007	30.8	1.010	30.7	1.010
3.0	30.9	1.013	30.9	1.013	30.9	1.016
2.5	31.3	1.026	31.4	1.030	31.5	1.036
2.0	32.0	1.049	32.1	1.052	32.0	1.058
1.75	32.5	1.066	32.7	1.072	32.6	1.072
1.5	33.8	1.108	33.9	1.111	34.0	1.118
1.25	36.3	1.190	36.7	1.203	36.8	1.211
1.0	43.8	1.436	44.0	1.443	44.0	1.447

A Laboratory Investigation of Radiative Transfer in Cloud Fields

By
James A. Kuenning
Thomas B. McKee
Stephen K. Cox

Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado

Colorado State University

Department of Atmospheric Science

Paper No. 286

A LABORATORY INVESTIGATION OF RADIATIVE TRANSFER IN CLOUD FIELDS

By

James A. Kuenning

Thomas B. McKee

Stephen K. Cox

The research reported here has been supported
by the Global Atmospheric Research Program,
National Science Foundation, and the
GATE Project Office, National Oceanic and Atmospheric
Administration under grants OCD-74-21678 and ATM-77-15369.

Department of Atmospheric Science
Colorado State University
Fort Collins. Colorado

April 1978

Atmospheric Science Paper No. 286

ABSTRACT

Finite clouds were simulated with laboratory models in an investigation of cloud interaction distances, variation of the cloud interaction distances as a function of cloud height, and radiative properties of cloud fields. Comparisons were made between laboratory data and Monte Carlo calculations.

The center cloud in a 3 x 3 array of modeled clouds was found to have a 5% increase in the top directional reflectance over the isolated cloud case at a separation of 2.5 cloud diameters, and increased to 30% at a separation of one cloud diameter. The increase of the top directional reflectance as the separation increased behaved similar to $1/S^2$ where S is the cloud separation. The cloud interaction distance was found to rapidly increase as the height to diameter ratio increased, but then leveled off as the optical thickness of the clouds got larger than about 100 to 125. It was concluded that cubic clouds separated by more than 2.5 cloud diameters could be treated as non-interacting clouds.

A comparison of calculated directional reflectances for cloud fields was done using the infinite cloud approximation, non-interacting cubes, slab clouds, and interacting cubic clouds for sky covers of 0% to 100% sun vertical. An error analysis between the infinite cloud approximation and the interacting cubic clouds shows a maximum relative error of 40% at cloud covers under 5% but the absolute error maximum was 5% directional reflectance at sky covers around 50%.

ACKNOWLEDGEMENTS

This research has been supported by the Global Atmospheric Research Program, National Science Foundation and the GATE Project Office, NOAA, under grants OCD-74-21678 and ATM-77-15369.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES Continued

LIST OF SYMBOLS

English Symbols

a	constant in multiple regression fit equation
A	ampere
b	constant for $1/S^2$ term in multiple regression fit equation
c	constant for $1/S^3$ term in multiple regression fit equation
C1	droplet distribution (Deirmendjian)
d	diameter of cloud
$d^2y.x$	deviations of the x and y product
D	distance that the centers are separated
g	grams
m	meter
S	separation (defined $S = \frac{D}{d}$)
$S_{\hat{y}}$	standard error
UT_j/UT_i	ratio or the currents (or voltage) at a given separation to current (or voltage) at maximum separation
VOM	Voltage-Ohm-Meter

Greek Symbols

θ	angle measured from vertical in x-z plane
ϕ	angle of rotation measured from +x in x-y plane
τ	optical thickness
μ	micron (10^{-6} meters) or mean of the sample

I. Introduction

In the real atmosphere, clouds take on many complex shapes. Small and large cumulus clouds exhibit complicated, fine structured detail as well as many various sizes on the larger scale. However, in global energy budget calculations (London and Sasamori, 1971; London, 1957), clouds are treated as semi-infinite homogeneous layers. In a satellite derived energy budget study by Vonder Haar and Hanson (1969), London's study (1957) was shown to overestimate the mean planetary albedo. The authors suggest this error may come from any one or a combination of the following: 1) an overestimate of the amount of types of clouds in the tropics; 2) the difficulty in computing solar energy transfer in cloudy, turbid atmosphere; 3) an improper knowledge of the total directional reflectance of major cloud types. Their other reasons involved error in the satellite system. Most of the reasons that London's study (1957) could be in error deal with the inability to handle radiative transfer in cloudy regions properly.

McKee and Cox (1974, 1976) showed large differences in the radiative characteristics between infinite and finite clouds. In their 1976 paper, they presented results dealing with the radiance patterns for finite cubic clouds. These results again showed dramatic differences between these two types of clouds. So, it seemed, to accurately evaluate energy budgets, the infinite cloud approximation could not be used. However, the complex shapes of clouds and their interaction with each other make modeling finite clouds difficult.

Aida (1976) presented results which dealt with the interaction of finite clouds using Monte Carlo techniques. His results indicate that this interaction cannot be neglected, since it leads to approximately a 40% increase in the upward-going radiance fields. A study by Barkstrom and Arduini (1976) dealt with the interaction problem by modeling the radiance field exiting a cloud as a diffusion problem. Both these studies dealt with individual clouds and their interaction using simple cloud and spatial geometries.

Wendling (1977) addressed the problem of cloud texture. He calculated albedos for semi-infinite clouds with grooves and ridges in the top of the cloud. He found significant decreases in the inhomogeneous cloud albedo when the sun was vertical compared to the semi-infinite cloud sun vertical.

Computational methods other than Monte Carlo cannot effectively deal with finite clouds. The Monte Carlo method can be used for finite clouds of simple geometries, though computer time can become quite large for optically thick clouds. Complex shaped clouds present problems even for the Monte Carlo technique. The complex geometries demand prohibitive proportions of computer time. Consequently, this paper is an attempt to model finite clouds in a laboratory with physical models which simulate radiative effects.

The first, most attractive, reason for trying to model radiative transfer in clouds with physical models is that it is relatively inexpensive compared to computer simulation. Another reason is that complex geometries can be modeled more simply with physical models than with computer models. There is also the need to verify if theoretical calculations compare with experimental results. A very basic question of whether the idea of physically modeling clouds is possible needs to be answered.

The idea of physical modeling is to select a material which, through its scattering properties, would resemble the scattering process inside a real water cloud. The material would have to be shapable into cloud-like forms and then illuminated under a columnated light source. With this set up, measurements would be made of the light fields which were scattered off the model cloud. There are several variables which will be used to describe the clouds and their placement, however, these will be explained later.

II. Experimental Procedure

II.1. Materials

Inside water clouds, the mode of scattering is Mie Scattering. Mie Scattering is characterized by the particle size in the scattering media being approximately the same size as the wavelength of light. Therefore, in selecting a material for the physical model, the particle size should be approximately the size of a cloud droplet, ranging from 0.2 microns up to 20 microns. Inside the water clouds the droplets are suspended by air. Therefore, in trying to find a material suited for physical modeling of the clouds, we need to find a material that has these scattering properties, but the media holding the objects must not interfere in the measurement by some other optical properties such as reflection.

Figure 1 gives the relationship between the optical depth and the liquid water content for a cumulus cloud with a C1 droplet distribution (Deirmendjian, 1969) and a geometric depth of 1.5 kilometers. For a cumulus cloud 1.5 kilometers deep, the optical depth ranges from around 40 for liquid water of 0.1 g/m^3 to around 80 for 0.2 g/m^3.

For modeling clouds one needs a material whose optical depth is large in a relatively small geometric distance. To model a water cloud perfectly, one would need a material that had tightly packed particles about 10 μm in size, held together by their own adhesion.

Many different types of materials were tried. The first material was cotton balls. Cotton is white, composed of small fibers and is shapeable. Initially, when this experiment was conceived, one of the main objectives was to model individual clouds. The cotton balls lent

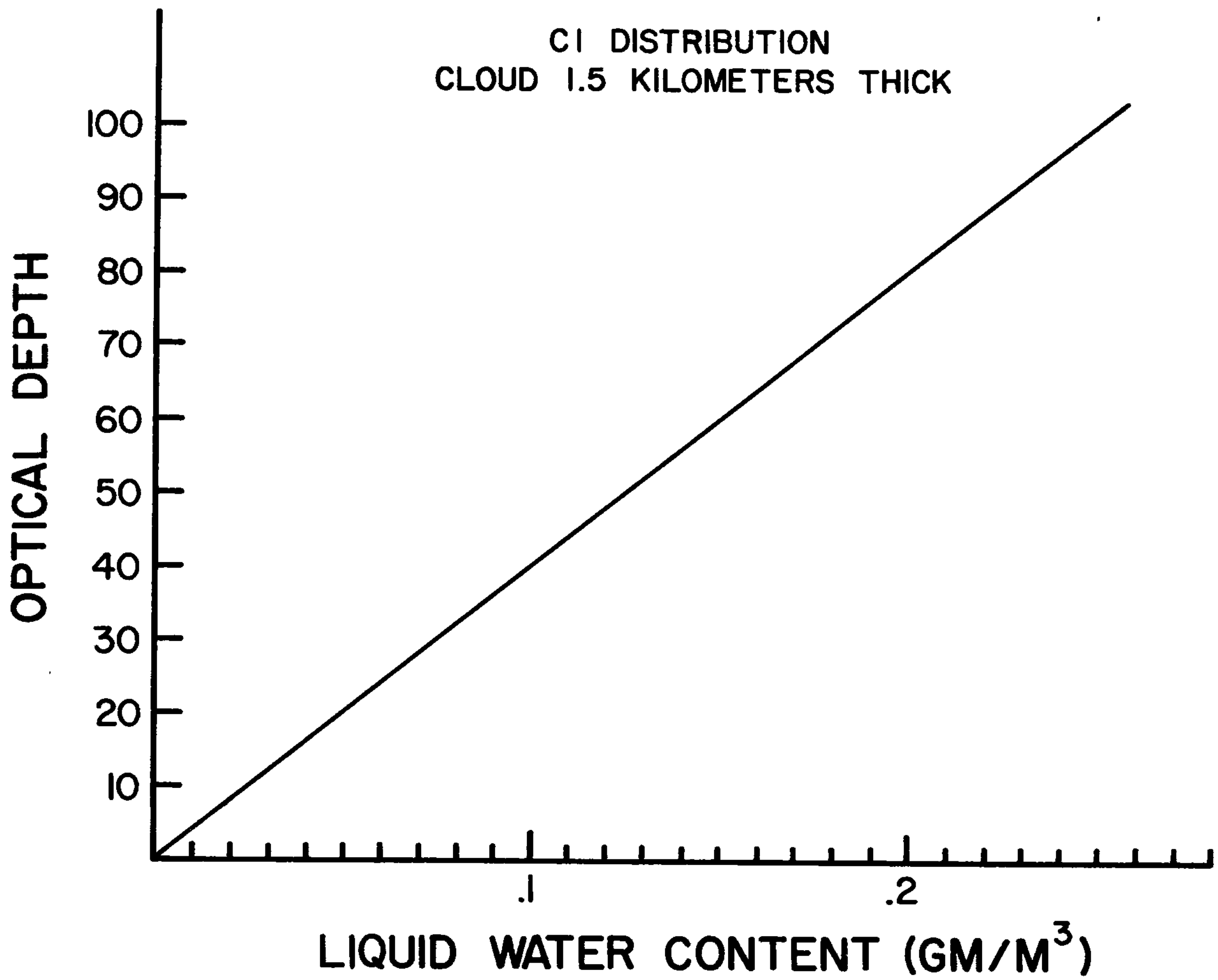

Figure 1. Optical thickness versus liquid water content for C1 droplet distribution.

themselves to be easily "stuck" together to form large complex shapes. The problem was that the boundaries between the discrete elements allowed light to funnel through the boundaries. Another problem with this approach was that the built up clouds were subject to constant change while being handled.

Styrofoam and sugar cubes were tried in an effort to find a medium whose shape was somewhat definable. Sugar cubes do show scattering properties but are optically very thick. Styrofoam is shapeable to various thickness, but has surface reflections which detract from its appearance as a cloud.

Another material tried was shredded paper, but it, too, was lacking in homogeneity and shapeability. Polyester fiber, the type used in aquarium filters, was tried and was very similar to cotton except for its pale yellow color. Resin formed insulation foams were tried but were too optically thick. Plastic with suspended particles was tried. These types of material were rejected because of the optical properties of the plastics themselves.

The material finally chosen was cotton. The scattering media is long 10 μm size fibers which are woven to hold the material together. These fibers are not independent spheres, as in the case of cloud droplets, but can be viewed as cloud particles lined up in rows. Since cloud fields were going to be modeled, cotton balls were chosen which had a mean diameter of two inches. If the cotton balls are physically examined under a columnated light source, they have a visual appearance similar to water clouds.

Of the materials examined, cotton balls exhibited reflective characteristics most similar to clouds. Since cloud fields were chosen to be modeled, the individual cloud elements needed to be approximately the same size. The material must retain its shape even though it is being handled as the cloud elements are moved around. The experiments need be repeatable so the material needs to retain its shape and optical thickness with time. So, given the constraints of where the experiment was to be set up and the equipment to be used, cotton balls were chosen as the principle material.

II.2. Experimental Setup

To model the scattering phenomenon in cloud fields, the incident light upon the clouds must first be modeled. The light received at Earth from the Sun is very nearly columnated with respect to the linear scales in the vertical associated with clouds. The experimental light source used was a 300 watt floodlamp housed inside a box used to columnate the light. The box was 60 centimeters long and the opening was 13 x 13 centimeters. The light was mounted in the back of the box. The inside was painted with a flat black paint and then lightly sanded to cut down on the surface reflections. This light box assembly was mounted on the ceiling and was pointed downward toward the floor. The clouds were placed on a surface 1.15 meters from the base of the light box, or 1.75 meters from the light itself. Figure 2 shows a photograph of the experimental setup.

The clouds were placed on a piece of particle board which was also painted flat black. The particle board was 76 x 76 centimeters and located on a stand which as approximately 60 centimeters off the floor. The clouds were placed on this particle board when measurements were being taken.

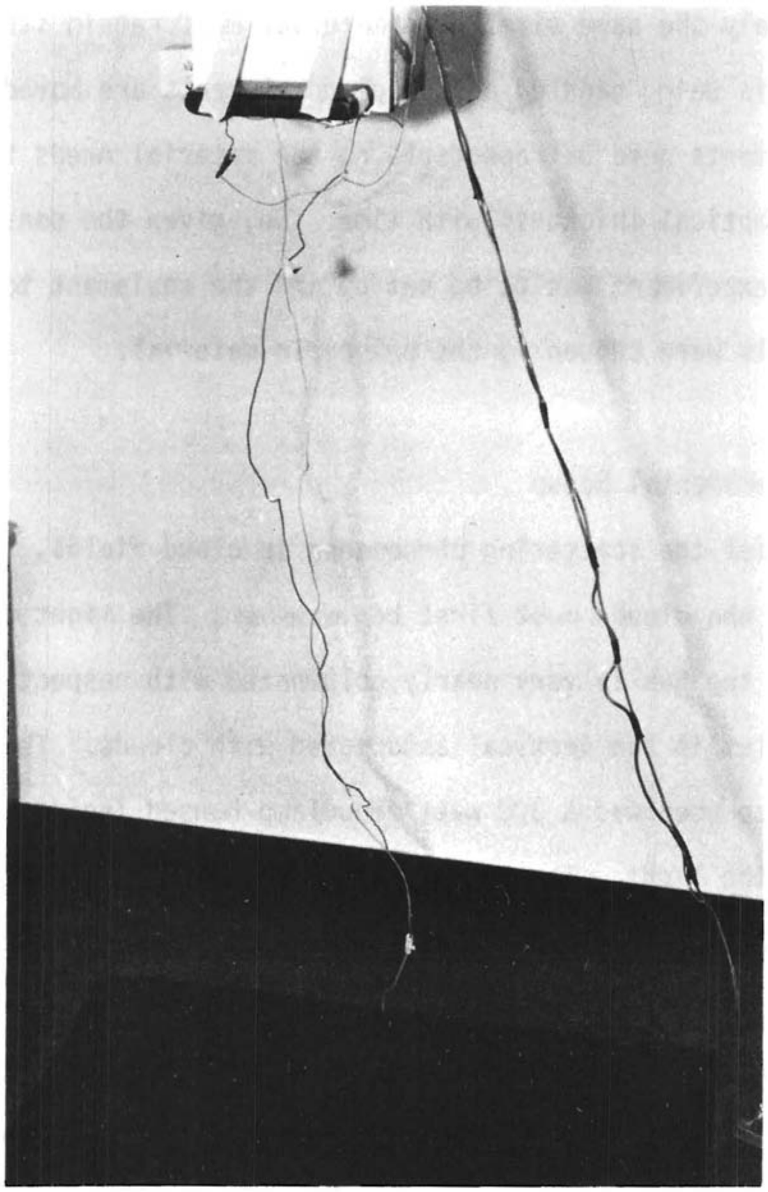

Figure 2. Photograph depicting experimental set-up.

Underneath the stand was a 4' x 8' sheet of plywood which was also painted flat black. All this material was painted flat black in order to minimize the amount of light entering the sensor which did not interact with the clouds in some manner. This was located in a room which could be darkened completely from outside light.

Measurement of the scattered light was accomplished by means of a photo voltaic cell which has a linear current output with increasing illumination. The current was measured with a voltage-ohm meter capable of measuring current with an absolute accuracy of ±1 μA and a resolution of 0.1 μA. At low input impedences, such as when measuring with a VOM, the photo voltaic cells will exhibit fatigue, that is, the output will decrease as a function of time under a given illumination. However, due to the low level of illumination involved in this experiment, this was not a problem. The output only decreased 0.5 μA under short circuit condition in fifteen minutes under the maximum illumination that was expected to be encountered.

Before looking at the results from the experimental modeling, several parameters need to be defined. The first is the sensor output. This is the current output from the sensor as measured by the VOM. The separation distance designated by S is defined as $S = \frac{D}{d}$ where d is the diameter of the cloud and D is the distance between the clouds measured from center to center (see Figure 3). This is a scaling parameter which is dimensionless and gives the number of cloud diameters by which the clouds are separated. The next parameter is designated by UT_j/UT_1 where j is the number of clouds in that particular model. This parameter is the ratio of the sensor output at a

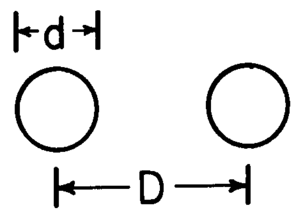

Figure 3. Figure showing how D and d are measured.

particular value of S to the sensor output at maximum separation where D = d. So, at maximum separation, this ratio is exactly 1.00. All the ratios are computed using the maximum separation current output from that individual run. This is done so that the ratio gives the percentage increase in sensor output for that certain run. Then these can be compared to different runs when the cloud fields have changed and the raw sensor currents are different. The use of these parameters will become clearer when some data have been studied. In all studies, except the five cloud model, the actual current (or voltage) values are listed in the appendix in table form.

III. Results

III.1. Cloud to Cloud Interaction

When the radiance field of a cloud under study is affected by the presence of an adjacent cloud, we shall refer to this as cloud to cloud interaction. This section presents the results obtained from the study of cloud to cloud interactions. Cloud to cloud interaction was modeled experimentally by placing a sensor on top of the center cloud. The total field of view of the sensor was filled by the cloud. In the five cloud arrays the sensor was always on top of the center cloud and the other four clouds initially were placed five diameters from the center cloud. A reading of the current produced by the sensor was observed and used as the base value to which all others were ratioed in that run. As the four clouds were moved symmetrically toward the center cloud, readings of the sensor current were taken at various separation distances. This process was continued until the clouds were touching. The series of steps were repeated three times for both the five cloud and the nine cloud models.

Figure 4 (a, b) depicts the nine cloud array configuration at maximum and minimum separation respectively, viewed as if one were looking at the cloud field from above. The five cloud array contained the center cloud and four corner clouds removed. The experimental five and nine cloud arrays were developed to compare with Monte Carlo results reported by Aida (1976). The five cloud array for the three individual runs are shown in Table 1 which includes the actual current and ratio values for the three runs. Figure 5 shows the data plotted with the separation distance on the ordinate and the ratio on the

Table 1. Data for five cloud model. The "FITTED" column is the values predicted by the regression curve.

S	Output (μAmp)	UT_5/UT_1	Output (μAmp)	UT_5/UT_1	Output (μAmp)	UT_5/UT_1	FITTED
5.0	32.2	1.000	32.1	1.000	32.2	1.000	.998
4.5	32.2	1.000	32.2	1.003	32.3	1.003	1.000
4.0	32.2	1.000	32.2	1.003	32.2	1.000	1.004
3.5	32.3	1.003	32.2	1.003	32.2	1.000	1.009
3.0	32.7	1.015	32.6	1.016	32.5	1.009	1.017
2.5	33.3	1.034	33.2	1.034	33.3	1.034	1.030
2.25	33.3	1.034	33.6	1.047	33.7	1.047	1.039
2.0	34.0	1.056	34.1	1.062	34.0	1.056	1.052
1.75	34.9	1.084	34.9	1.087	34.7	1.078	1.071
1.5	35.5	1.102	35.6	1.109	35.7	1.109	1.100
1.25	37.0	1.149	37.0	1.153	37.1	1.152	1.144
1.0	39.3	1.220	39.2	1.221	39.3	1.220	1.220

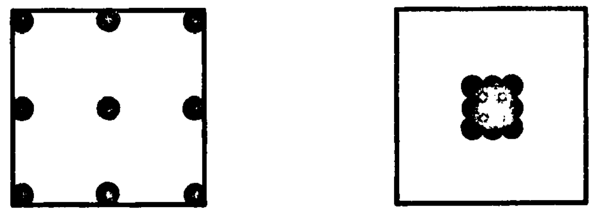

Figure 4. Nine cloud maximum and minimum separation configuration.

abcissa. The curve on the graph was obtained by fitting all the data to a multiple regression routine. The resulting best fit curve equation for the five cloud model is $\frac{UT_5}{UT_1} = .986 + \frac{.296}{S^2} - \frac{.061}{S^3}$ with a correlation coefficient of 0.975.

The physical process of cloud to cloud interactions may be described as light leaving an adjacent cloud in such a direction as to intercept the center cloud. If one assumes that the radiance fields are homogeneous, the interaction should depend on one over the distance squared. So for the interaction equation, one would expect a form like $\frac{UT_5}{UT_1} = a + \frac{b}{S^2}$. Since there are other factors determining how much light reaches the sensor (scattering and the radiance fields are not homogeneous) a correction term, namely $\frac{C}{S^3}$, was used to compensate for these other processes.

The nine cloud array is similar to the five except that the center cloud is surrounded by eight clouds instead of four. The same procedure was used in obtaining the data that was described earlier

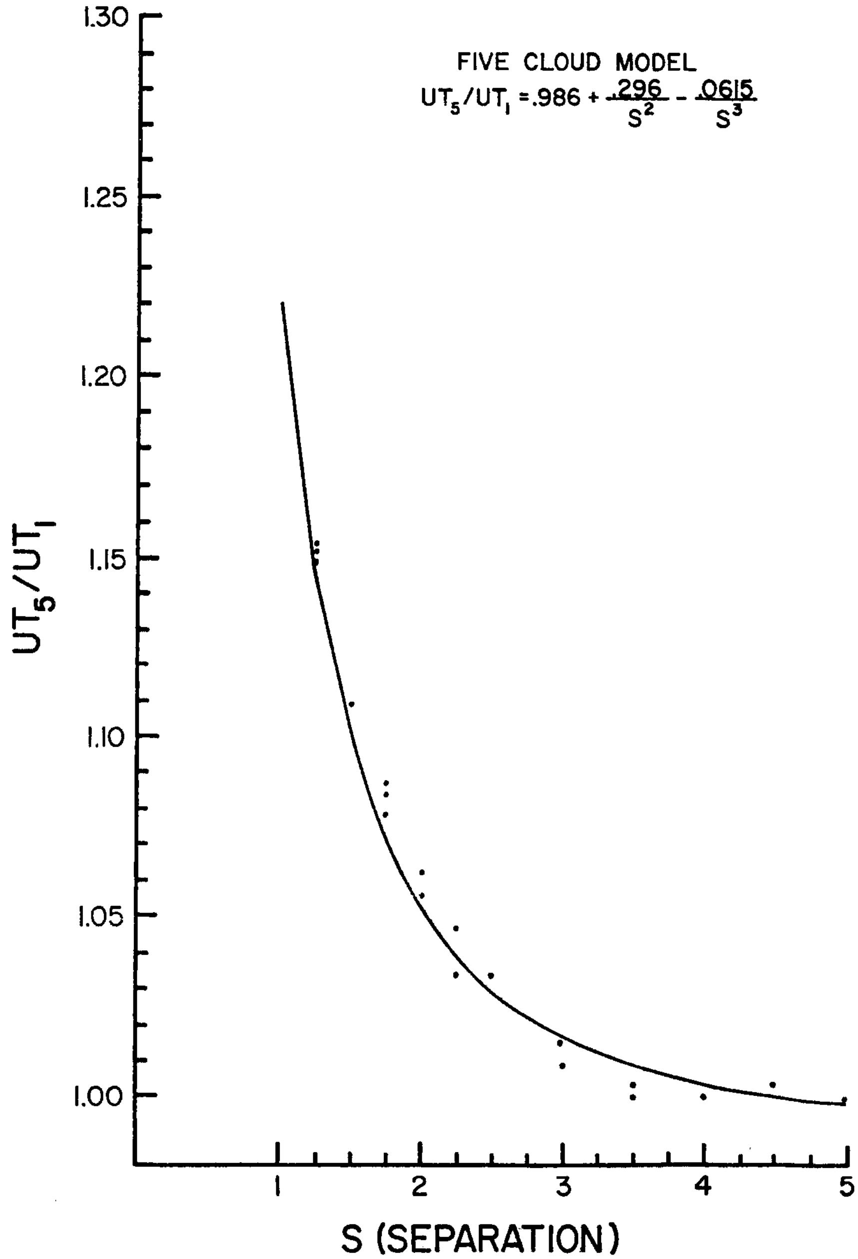

Figure 5. UT_5/UT_1 versus separation for five cloud model.

for the five cloud case. The data appears in graphical form in Figure 6. The curve again was produced by the multiple regression technique as before. The equation for nine cloud is as follows:

$$\frac{UT_9}{UT_1} = .984 + \frac{.557}{S^2} - \frac{.243}{S^3} .$$

The five cloud model has an increase of 22% over the value at maximum separation, while the nine cloud model has an increase of about 30% over maximum separation. Of the total change from maximum to minimum separation, 76% of that change takes place in going from two diameters' separation to one in the five cloud model and 68% in the nine cloud model.

The experimental models are similar to Aida's (1976) model. Aida (1976) let the photons enter only the central cloud and obtained a value for the total upward-going radiances which he called UT_1. Next he added four more clouds for his five cloud model. The photons could only enter the central cloud directly. If, through interaction in the center cloud, the photons entered the other four clouds, their interaction pattern was then computed to determine if they left in the upper or lower hemisphere. No futher interaction was permitted. The total upward-going radiance is then calculated for the entire cloud field. This value is then ratioed to the total upward radiance for a single isolated cloud. This was done for separations of 5, 2, 1.5, 1.0. The results of Aida (1976) that correspond to the experimental results are the five cloud and nine cloud models for optical depth of 49 and sun angle of $\theta = 0°$. Figure 7 shows Aida's results along with the best fit curve generated by the multiple regression routine for

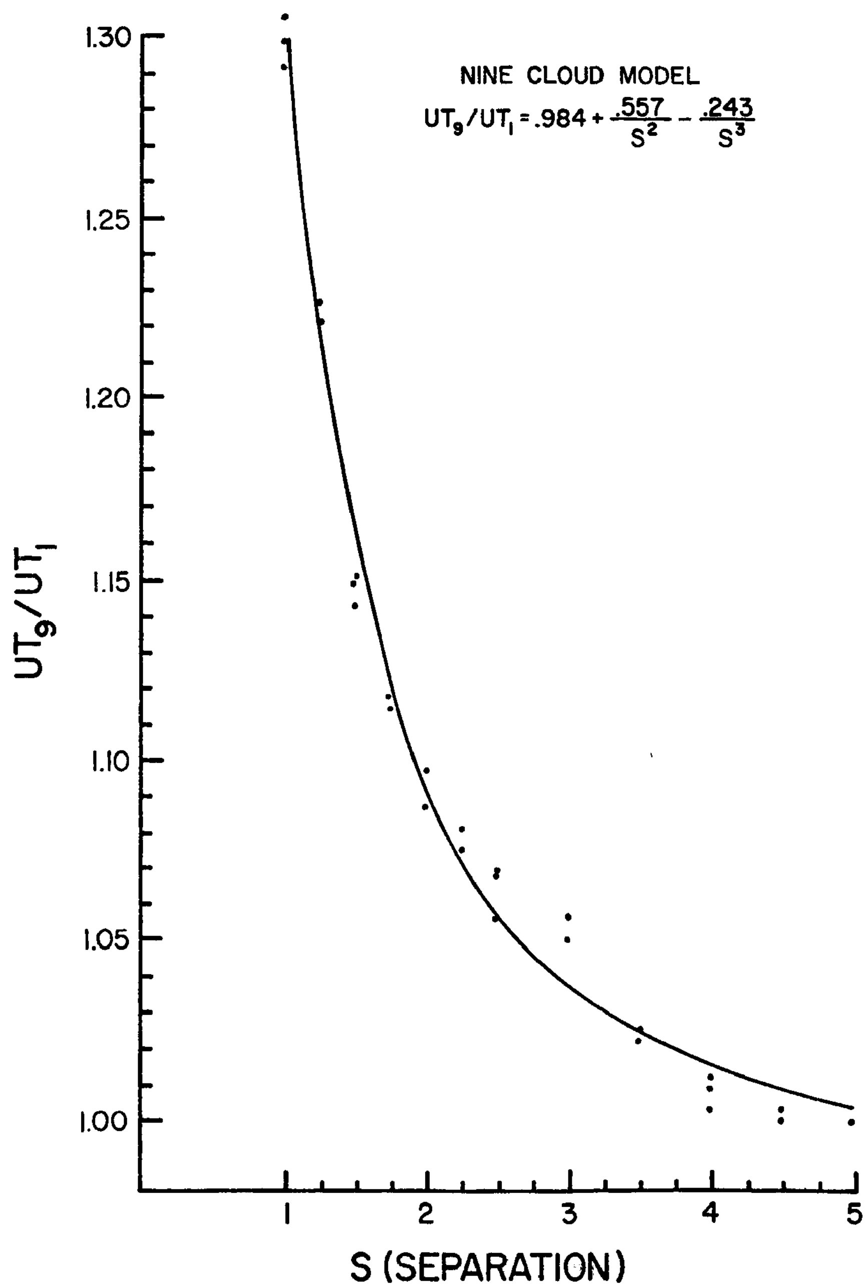

Figure 6. UT_9/UT_1 versus separation for nine cloud model.

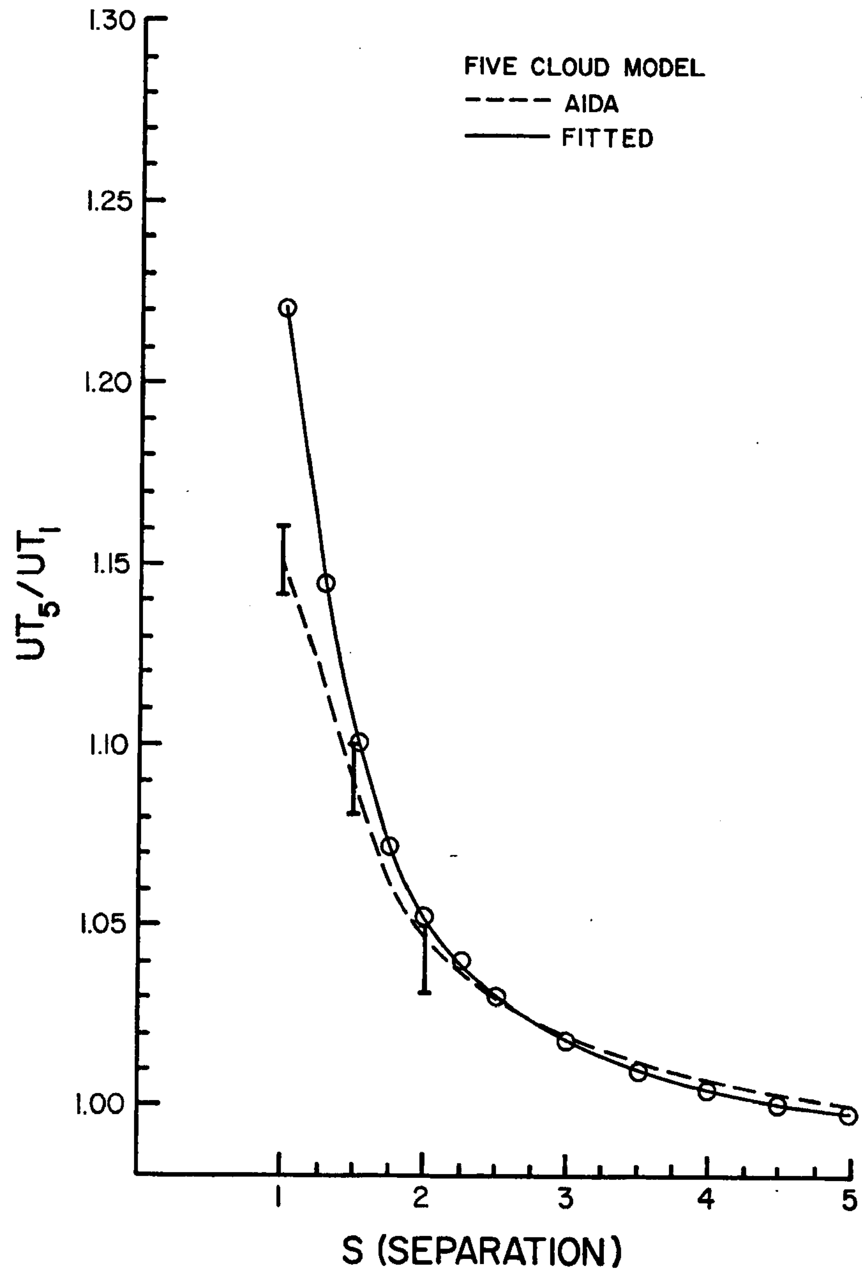

Figure 7. Aida versus experimental method for five cloud model.

the experimental five cloud model. The error bars on Aida's data are due to interpolation from a graph.

In the five cloud model, Aida's results are lower than the experimental method. This could be due to the sensor that was covering the central cloud. The sensor covering the cloud has the effect of decreasing the amount of upward-going light because the sensor blocks incident light. Another factor is that Aida is calculating the total upward-going radiance off the entire cloud field, though he is only letting photons enter the central cloud. In the experimental setup, light is entering all the clouds and is only being measured by what is coming off the central cloud top going up.

These two different methods may not appear to be similar at first. Aida is measuring an increase in reflected irradiance for the entire cloud field, while the experimental method is measuring the increase for only one cloud. Consider the following:

If one has five light bulbs and wishes to increase the total light output of the field by 10%, one would increase the individual bulb output by 10%. Aida is measuring the total increase while the experimental method is measuring the increase of the individual clouds.

Figure 8 shows the results of Aida's nine cloud model plotted along with the experimental results. The nine cloud model exhibits better agreement than did the five but still seems to be high at small separations. All the possible reasons for differences could apply in the nine cloud model also.

In summary, the two experimental models seem to agree with Aida's (1976) results quite well. But an important point needs to be noted.

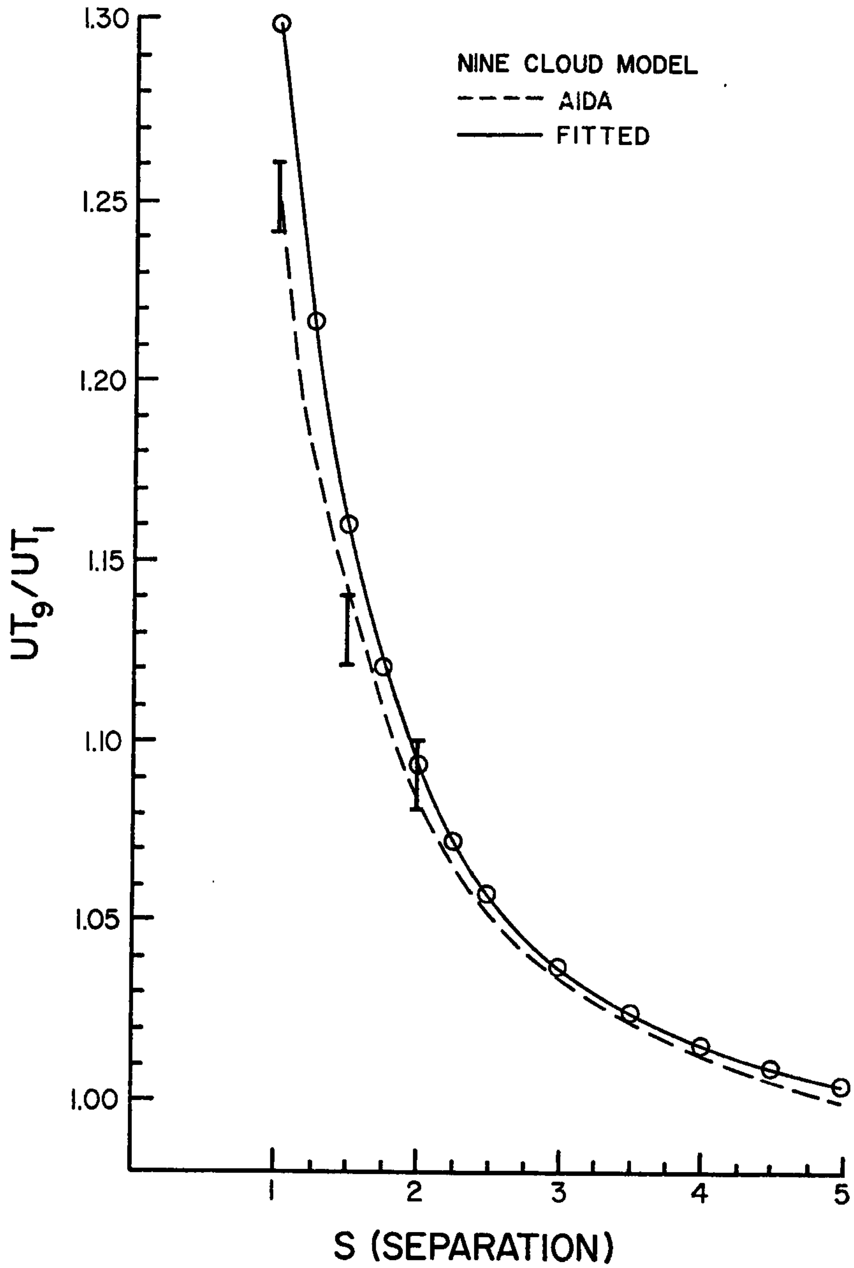

Figure 8. Aida versus experimental method for nine cloud model.

Aida's calculations are done using cubical clouds and calculating albedos. The experimental method uses spherical clouds and measures the light off the top of the cloud.

III.2. Cloud Height Versus Cloud Interaction Distance

The next area of research pursued was to determine how the interaction distance varied as a function of the height. The clouds used in the five cloud and nine cloud models were approximately .75 diameters high, due to the fact that they compress when they are placed onto the blackened surface. Styrofoam cut into 5.1 x 5.1 x 1.3 centimeter pieces was used for the layer model. The reasons for using "square" clouds are that they stack more easily and are different radiatively from the spherical clouds. McKee and Cox (1974, 1976) have investigated the radiative properties of cubical clouds of various optical thickness and solar angles. By using square clouds, the differences could be explored on how to relate the detailed work of the aforementioned authors to more realistic clouds found in the atmosphere.

The layer model runs were done by taking the five cloud array for one, two, three, four and five thicknesses of styrofoam. Each one of these was repeated three times, as previously done with the five and nine cotton cloud arrays. The sensor was again placed on top of the center cloud and the other four clouds were placed at maximum separation. A reading was taken at maximum separation and all other readings in that run were ratioed to the maximum separation reading. The height of the layer model is depicted on the graph as the solid blackened shape at the end of the title. Curves were fitted to all the different layer models using the same type routine as described previously. The equation for the best fit appears on the graph for each layer model.

Figure 9 shows data collected from the one layer, five cloud array run. The fitted curve shows a slight increase after reaching a minimum value due to the dominance of the cubic term. The low flat clouds show a very short interaction distance, a 5% increase at 1.3 diameter separation. The graph also shows at separation of one diameter an increase of 22% over maximum separation occurs. Figure 10 shows the five cloud, two layer array, along with the fitted curve. This shows almost a 40% increase over maximum separation and a 5% increase at 1.75 separation diameter.

Figure 11 shows the three layer, five cloud array with the fitted curve plotted and the equation in the upper right. The three layer shows a maximum increase at one separation diameter of almost 42%. This is a much smaller change than observed going from the one layer to the two layer model. A 5% increase is observed at a separation of 1.95 diameters. The four layer model is shown in Figure 12, with the best fit equation in the right hand corner. The square term has almost insignificant size. The maximum increase is 43% at one separation diameter, with the 5% increase occurring at two diameters. In the five layer model, which appears in Figure 13, the maximum increase is 42.5% and 5% increase occurs at 1.9 separation diameter, which is a decrease from the four cloud.

The reason for the large differences between the one layer and the two layer model is that it does increase the distance which the

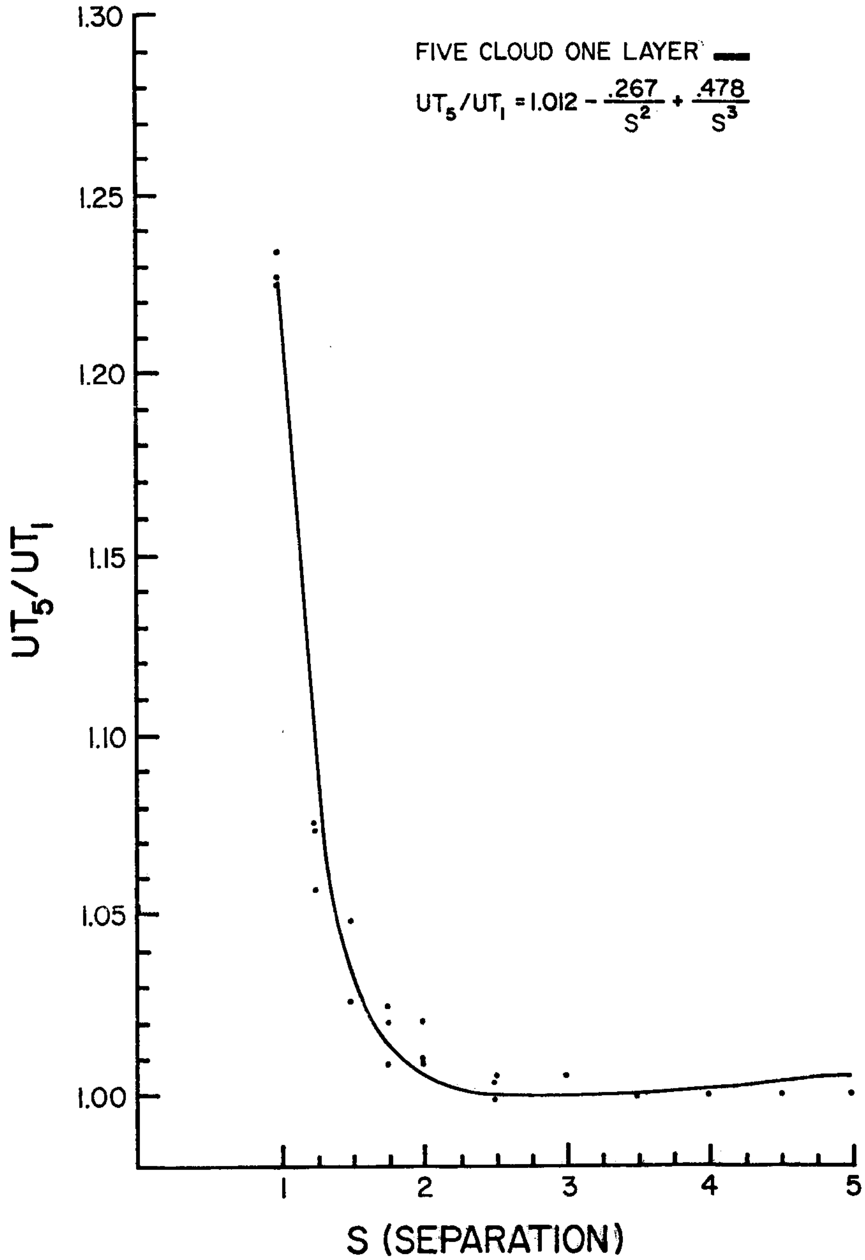

Figure 9. Five cloud one layer graph.

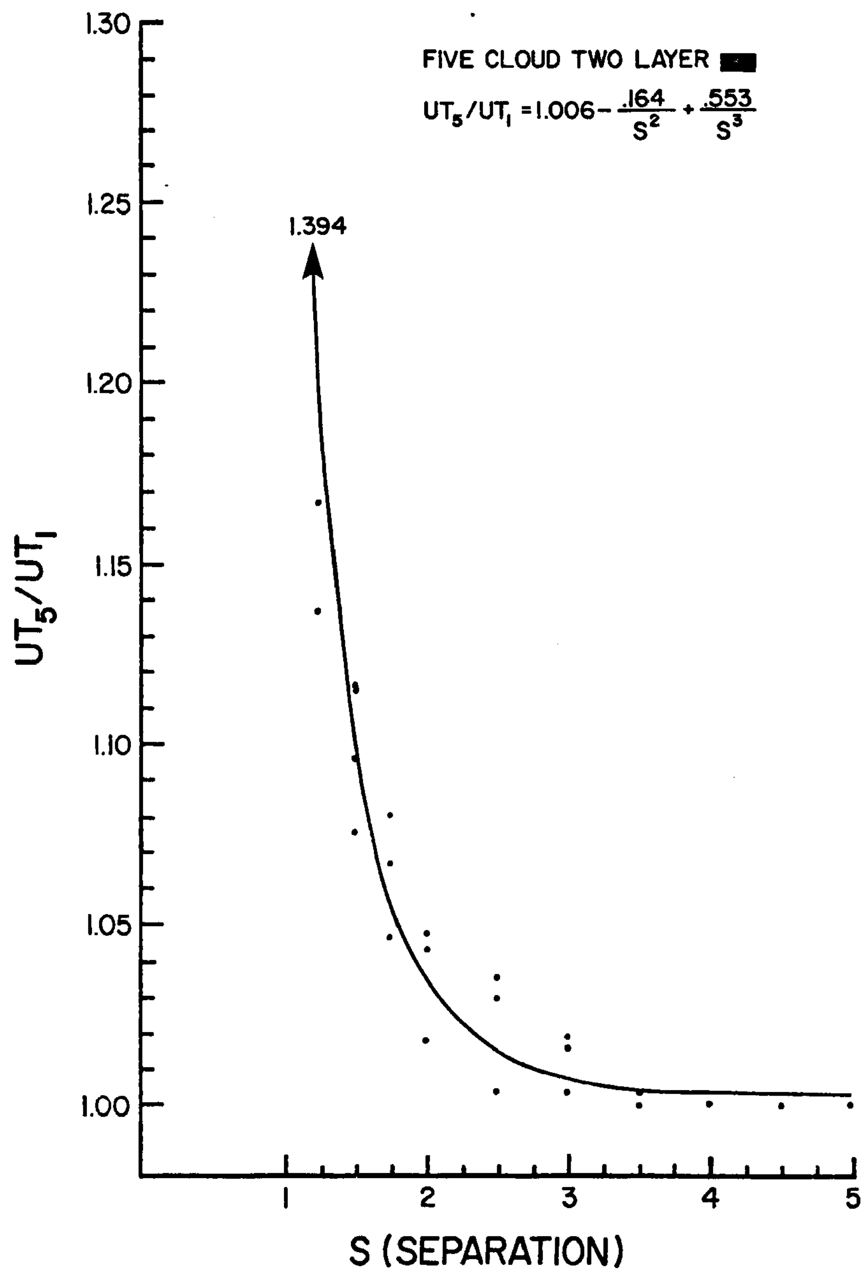

Figure 10. Five cloud two layer graph.

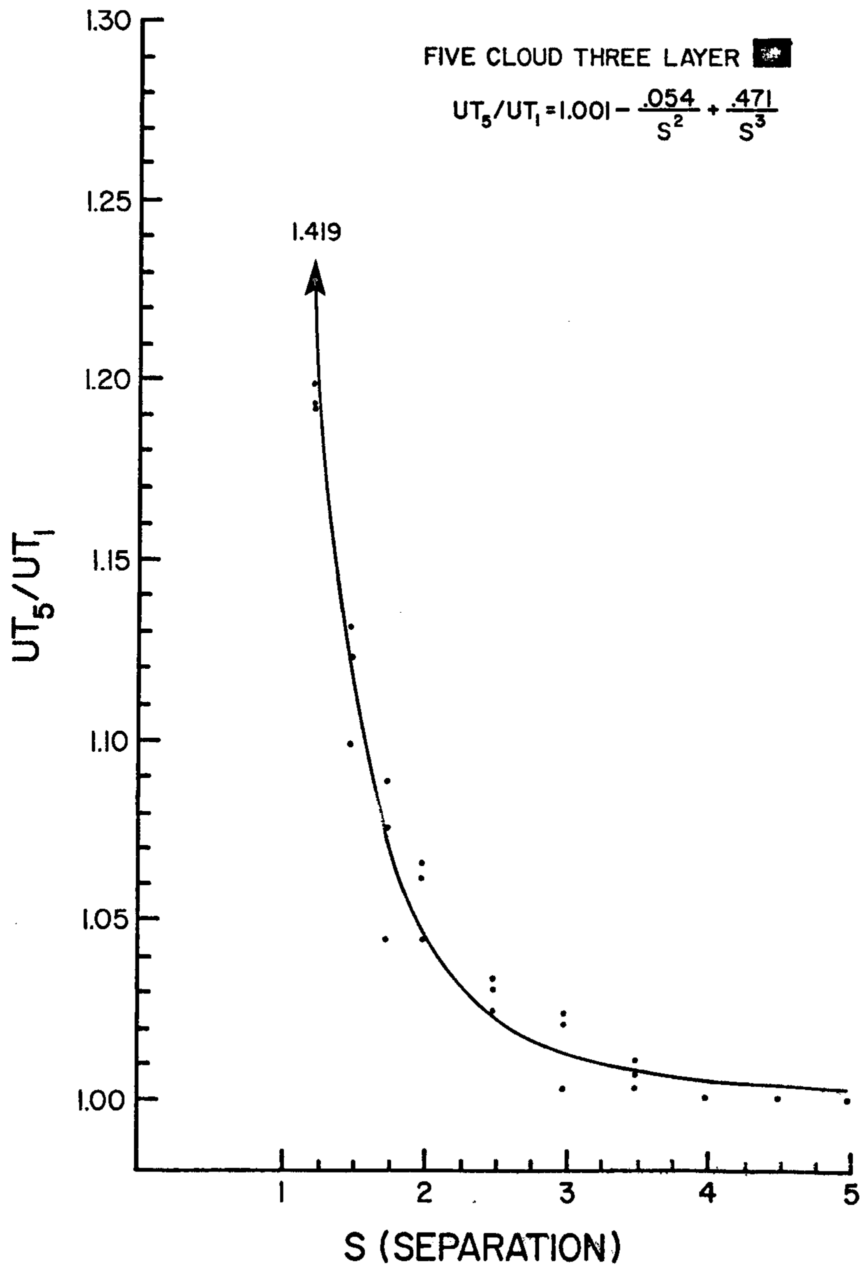

Figure 11. Five cloud three layer graph.

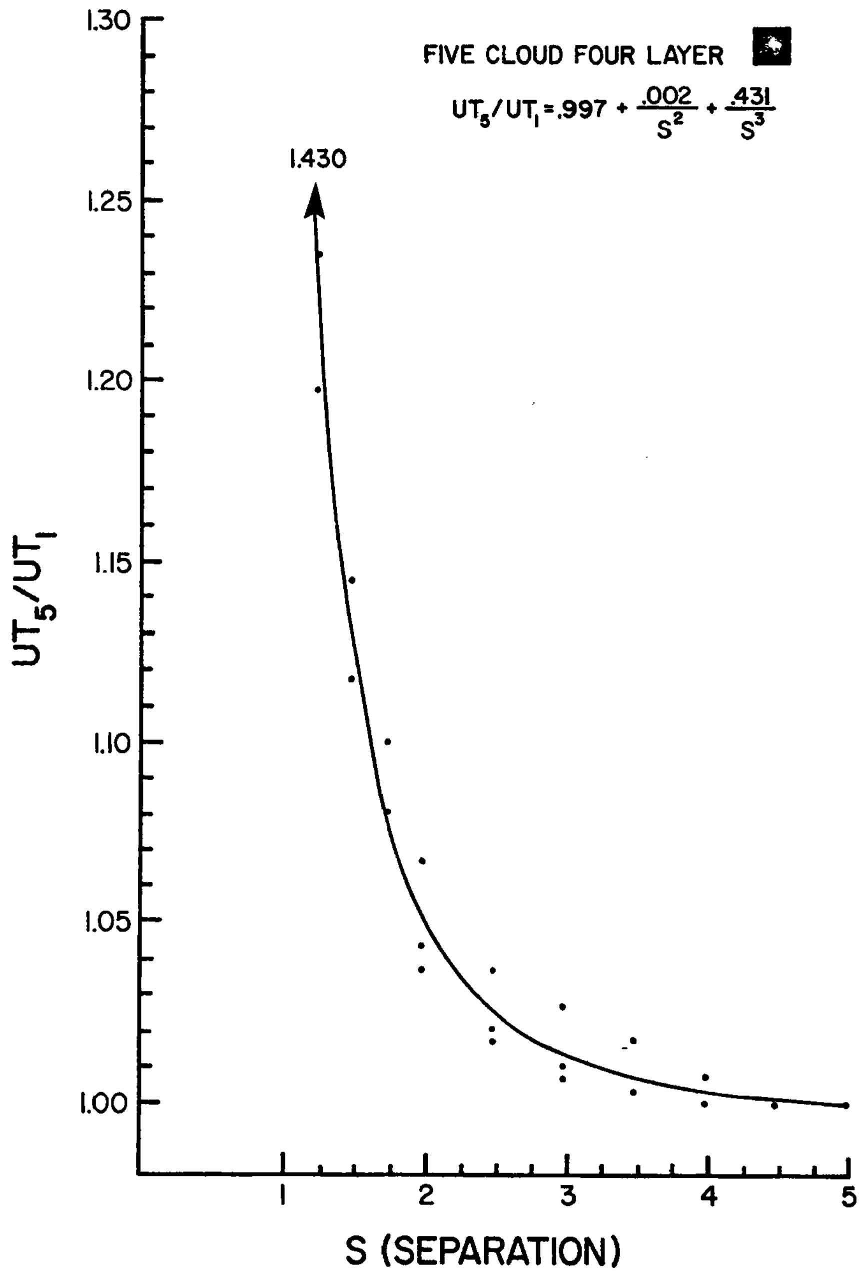

Figure 12. Five cloud four layer graph.

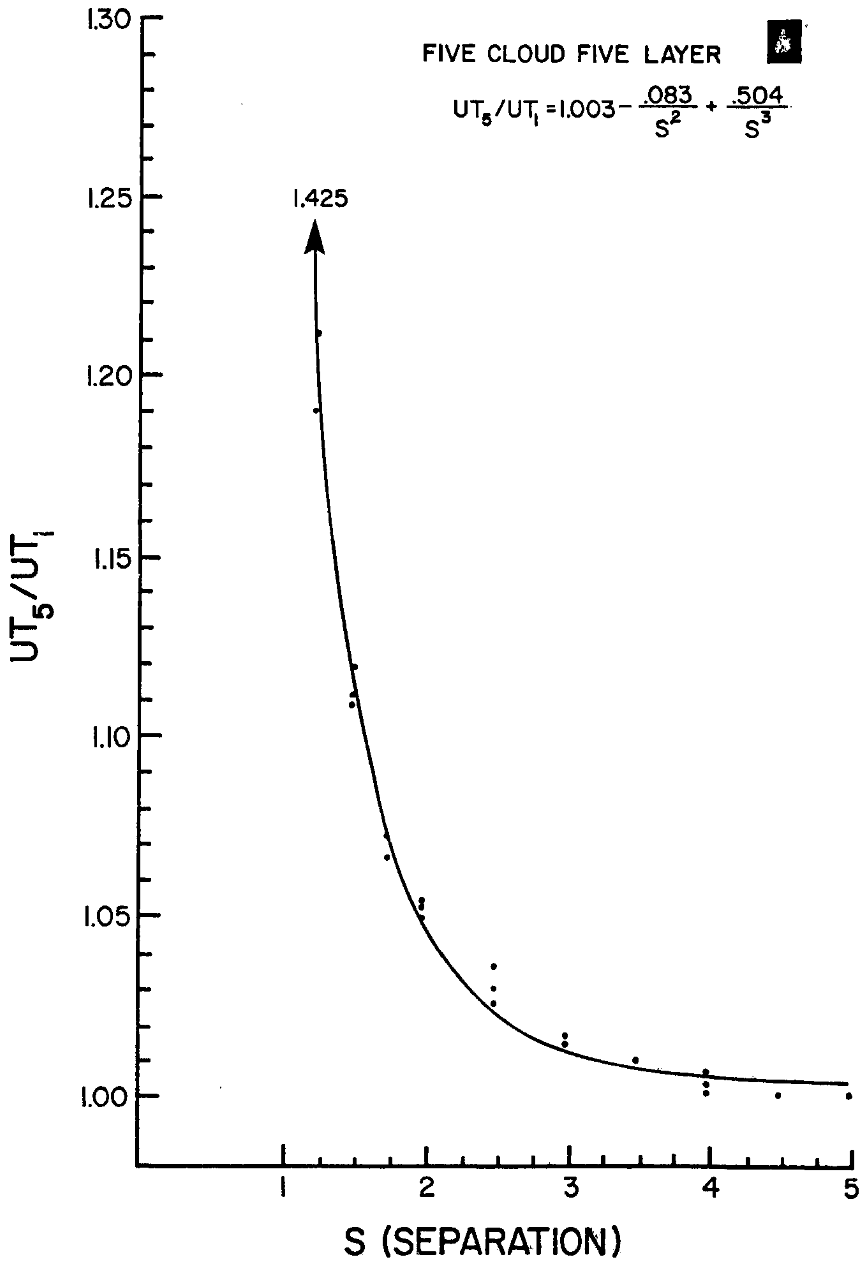

Figure 13. Five cloud five layer graph.

clouds interact by giving more distance for the light to scatter through the optical thickness. But as one increases the optical thickness even more, the interaction distance does not change much, because the interaction takes place mainly in the upper part of the cloud. In the lower parts of the cloud, the optical thickness is so large, the transmittance so small, that little of the light penetrates far into the cloud.

In an experiment to try to measure the optical depth of the styrofoam, it appears that a 2.5 centimeter thickness has an optical depth of approximately 50. This was deduced by measuring the reflected light as the depth of the foam was increased. This curve was then compared to a curve given by McKee and Cox (1976) which gave the increase in albedo as a function of the optical thickness of a cubic cloud (see Figure 14). So increasing the height of the clouds would not make a significant increase in the interaction distance, since most of the interaction takes place in the upper part of the clouds.

Consider some of the implications involved with the measurements given here. Below are the percent changes for the models presented so far. The percent changes are for how much the ratio decreased when going from a separation of one diameter to a separation of two diameters for each different model.

If one considers the magnitude of these percentage changes, it appears in most cases, except possibly the nine cloud cotton ball model, that if the clouds in the atmosphere are separated by more than two diameters, they could be treated as if they were finite non-interacting clouds, because any separation of larger than two diameters

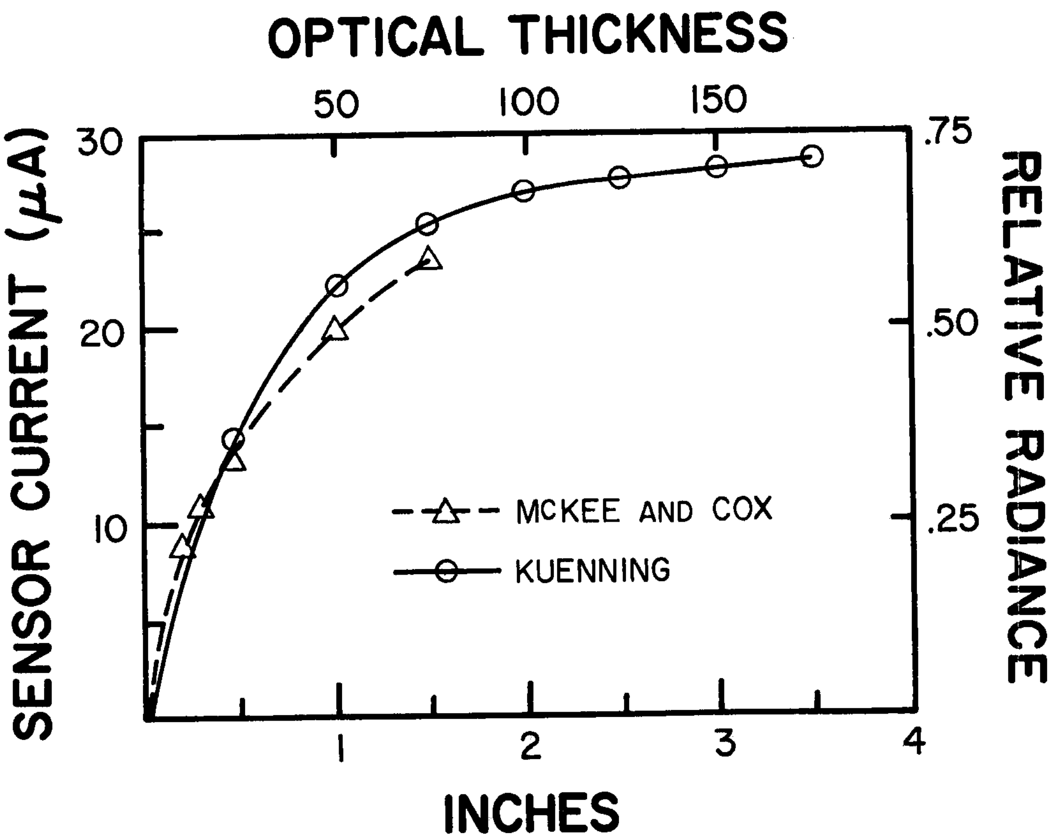

Figure 14. Graph shows the approximate optical depth of styrofoam plotted against a Monte Carlo generated graph from McKee and Cox (1976).

Table 2. Percent changes for models.

Model	Percentage
5 cloud cotton	76%
9 cloud cotton	68%
5 cloud styrofoam 1 layer	97%
5 cloud styrofoam 2 layer	91%
5 cloud styrofoam 3 layer	89%
5 cloud styrofoam 4 layer	88%
5 cloud styrofoam 5 layer	90%

does not significantly increase the upward-going radiance fields. At small separations, there is a very large change which could have a large impact on what one observes in the atmosphere.

Consider a semi-infinite cloud whose optical depth is around seventy. There are models available to calculate the albedo for this type of cloud. The Monte Carlo technique predicts an albedo of 91.7%. But measurements in our atmosphere seem to indicate that clouds seldom have albedos higher than 80%. So there arise some significant differences between theoretical calculations and observational data. Consider the following example as an explanation of the differences.

Suppose that a semi-infinite cloud is not horizontally homogeneous and is made up of 4 kilometer cubes with optical depths of 70. The cubes have a separation of 1.1 diameters or the edges are separated by 0.4 kilometers. This separation is below the resolution of most satellites used in the late 1960's and therefore would be difficult to discern whether it was one cloud or a bunch of small clouds close together. Using the results of the five-cloud, four-layer model (Figure 12), the value of UT_5/UT_1 at a separation of 1.00 is 1.43, while at a separation of 1.1 the ratio is 1.32. This means that in going from a maximum separation to a 1.1 separation, one would detect only 74% of the change in albedo from the maximum to minimum separation. A cubic cloud of optical depth 70 and sun vertical has an albedo of 70% while semi-infinite has an albedo of 91.7%. Therefore, the albedo of the semi-infinite composed of finite cubes would have an albedo of 86%. Larger separations than 1.1 would decrease the albedo.

While the previous argument does not explain all the differences between theoretical and observational results, it does explain a significant portion of the discrepancy. More generally, a semi-infinite cloud will lose its semi-infinite characteristics quickly when broken up into separate components, because of the rapid drop of the quantity UT_5/UT_1 as the separation is increased.

IV. Implications

IV.1. Discussion

Consider a single isolated cubic cloud and one wishes to study how the albedo of that cloud changes due to its interaction with the surrounding clouds. The nine cloud model, whose graph appears in Figure 6, is an example of what happens to a single cloud when eight other clouds are brought into the area. It shows an increase of about 30% at minimum separation. At first glance, this might be termed as a 30% increase in the albedo of the center cloud. But albedo is defined as ratio of all energy at all wave lengths leaving the system in the upper hemisphere to that which is incident on the system at all wave lengths and all angles. Normally in our atmosphere, there is one primary source of energy confined to a relatively small solid angle. However, when considering the interaction of clouds, energy enters the cloud from the adjacent clouds through the scattering process.

It seems plausible that most of the apparent increase in albedo is only due to the increase in energy incident on the sides of the cloud. Directional reflectance is defined as the ratio of all energy at all wave lengths leaving the system going upward to that energy which is incident at all wave lengths and just one angle. If one considers directional reflectance as a variable measuring the cloud radiance fields, the directional reflectance does change value as the clouds are moved in closer together. Normally in our atmosphere, albedo and directional reflectance are considered to be equal. This is not true when dealing with multi-directional energy incident upon the cloud. In this case if one uses directional reflectance it does change, since the light coming from the adjacent clouds adds to the energy leaving in the upper hemisphere. This reasoning does not apply when one considers the entire field as a unit, since the energy incident on the field is constant.

If one envisions an instrument capable of measuring the albedo of a cloud field instantaneously, one would expect an actual increase in the cloud field albedo as the cloud separation becomes smaller. The amount of incident energy does not change with decreasing separation, but the total upward-going radiances do change, due to the interaction. The interaction among the clouds permits energy that would have exited going downward from the clouds to interact further with the adjacent clouds and possibly exit going in the upward direction, adding to the albedo of the cloud field.

The separation among the clouds may be decreased by simply moving the clouds closer together or by adding more clouds to a given size of area, increasing the sky cover. When increasing the sky cover, the albedo will increase according to the formula $A_s = a_s SC$ where a_c is cloud albedo and SC is sky cover, but it will also increase because of the smaller separation distances. In the nine cloud model, the amount that the directional reflectance increased was found for various separations. These correction factors can be applied to the cloud field if the separation among the clouds is known.

IV.2. Comparison of Finite to Infinite

If one defines an area that will be considered as the entire sky cover, calculations can be done using the Monte Carlo program and data from the nine cloud model to calculate the albedo of the entire system as a function of sky cover for various cases. The area which represented 100% sky cover was 20 x 20 kilometers.

The first case is what will be called the "Basic Cube". The Monte Carlo program was used to calculate the albedo of a single cubic cloud 1.5 x 1.5 x 1.5 kilometers for the sun vertical and an optical thickness of 73.5. The scattering is conservative with the C1 (Deirmendjian) cloud droplet distribution. The albedo calculated was .700. By using the formula $A_s = a_c SC$, where A_s is the system albedo, a_c is the cloud albedo, and SC is the sky cover, one can generate the system albedo for sky covers from 0% to 100%. This relationship is linear and appears in Figure 15 labeled as "Basic Cubic". Physically what is happening is that more and more cubic clouds are being placed inside the area, but they are not permitted to interact. Their placement in the cloud field and with respect to each other is not critical, since only the area covered by them increases the system albedo.

The second is the opposite of the first and will be called the "Slab". In this case, we place the cubic clouds so that they are touching and therefore may be treated as one large cloud. The Monte Carlo program may be made to expand the cubic cloud out to a slab maintaining the same vertical optical depth. This was done for slabs of the following horizontal dimensions: 1.5 x 1.5, 3 x 3, 4.5 x 4.5, 6 x 6, 9 x 9, 15 x 15, and 18 x 18 kilometers. For each slab cloud, an albedo was calculated by the program and then multiplied by the sky cover they represent in the area. The slab runs are graphed in Figure 15 and labeled "Slab". This slab run represents the maximum

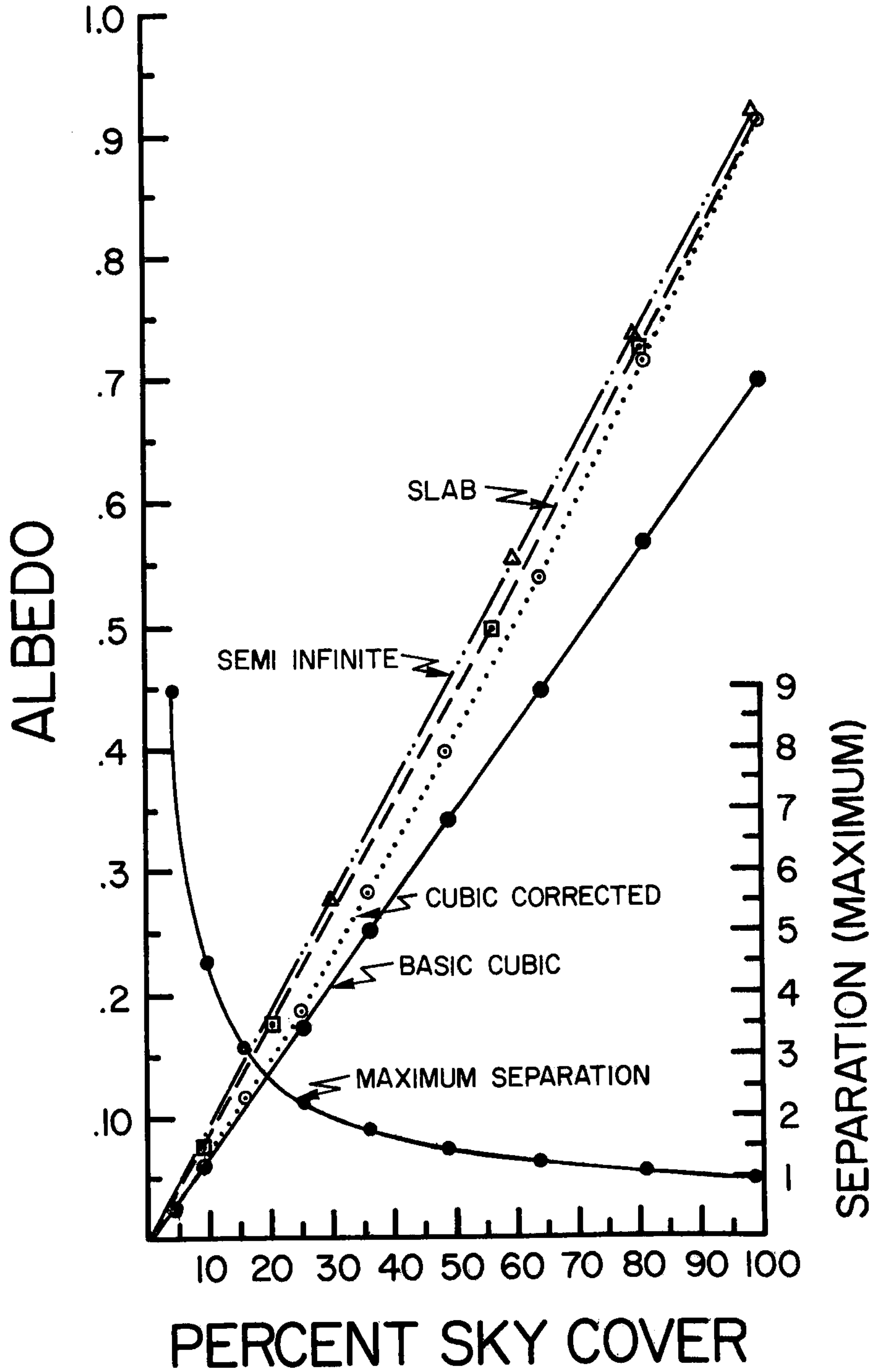

Figure 15. Graph showing the different cloud field albedoes for non-interacting cubic, semi-infinite, slab, and interacting cubic clouds for sky covers from 0% to 100% for optical thickness of 73.5.

possible albedo for finite clouds. Another case that can be studied is how the infinite cloud fits in with the other two cases.

The third case will be called the "Semi-infinite" case. This consists of calculating the albedo of an infinite cloud, using the Monte Carlo program, and multiplying the albedo by the sky cover. This is similar to the "Basic Cubic" case, only a different cloud albedo, namely the infinite cloud, is used in the formula. The graphic results of this case appear in Figure 15 and are labeled "Semi-infinite".

The fourth case deals with allowing the finite cubic clouds to interact to a lesser extent than the slab. This case is called the "Cubic Corrected." Recall that the "Basic Cubic" case is just finite clouds which are not permitted to interact. Now as the sky cover increases, the finite clouds get closer and closer together. Therefore, the constraint that the clouds not interact is unreasonable. But the case entitled "Slab" confines the finite clouds to be touching, which is only realistic at 100% sky cover. So the fourth case is the opposite of the "Slab" case in that it minimizes the interaction, but still allows the clouds to interact.

To compute the minimum interaction, one must first calculate the maximum separation the clouds could have for a given sky cover. If one uses only the symmetric cloud array, a formula can be developed to calculate the maximum separation. The formula is $S_{max} = \frac{\Delta x - D}{D(\sqrt{N}-1)}$ where ΔX is the width of the area, D is diameter of the clouds and N is the number of clouds in the area. The maximum separation was calculated for various sky covers and appears in Figure 15 labeled "Maximum Separation".

Recall that Figure 6 which is the nine cloud model gives the increase in the direction reflectance of the top of the cloud. With this data and the maximum separation, the "Basic Cube" case can be corrected for the interaction. At each step of the sky cover, a maximum separation is calculated. With this maximum separation, a correction factor may be obtained from the nine cloud model. This correction factor is multiplied by the respective albedo from the "Basic Cube" to obtain the corrected albedo. The results are shown in Figure 15 and labeled "Cubic Corrected".

The results of Figure 15 have some rather interesting implications about how one should treat the cloud fields when trying to model their radiative characteristics. Classically, in the past, large global climate models or energy budget computations, in attempting to model the radiative transfer in cloud fields, have used the infinite cloud assumption for calculating the transfer. This method takes the calculated albedo and reduces it for the sky cover. McKee and Cox (1974) disputed this almost universal application of this semi-infinite approximation, saying that radiatively the finite clouds are much different from the infinite clouds. Since the finite clouds had much lower albedos than the infinite clouds, it was assumed that the infinite cloud approximation could lead to erroneous results. However, finite clouds lead to the complication of interaction and how the interaction could be treated.

Many studies have dealt with this problem. Aida (1976) used Monte Carlo techniques and some of his results have been presented. Barkstrom (1976) used a diffusion model equation to study its effect.

The author's results and the aforementioned papers all seem to indicate that this interaction is very significant when the clouds are within 2.5 separation diameters.

In Figure 15 the curve marked "Cubic Corrected" is a curve showing the minimum albedo that a field of cubic clouds would have. This is because the clouds are as far apart as possible for the particular sky cover. The curve marked "Semi-Infinite" would be the albedo for the infinite cloud approximation. As can be seen, the semi-infinite does not differ much from the corrected cubic.

One point to make is that where the "Cubic Corrected" albedo exceeds the "Slab" albedo, the experimental results in this paper have overestimated the interaction, since the "Cubic Corrected" should only equal the "Slab" at 0% and 100% sky cover and in between those two points, it should always be less.

The most important thing about the "Cubic Corrected" and the "Slab" is that any cloud field composed of single sized cubic clouds with the same optical depth must have an albedo that is greater than or equation to the "Cubic Corrected", but less than or equal to that of the "Slab". Any cloud field, no matter if the placement is random or symmetric, must fall between these two limits for all sky covers. As can be seen from Figure 15 the infinite is in fairly close agreement to the slab case. Hence, the infinite approximation has a maximum known amount of error from the "Cubic Corrected".

Figure 16 shows the same type results for an optical depth of twenty. Analyzing the results for a smaller optical depth will give an indication as to whether these results change drastically for

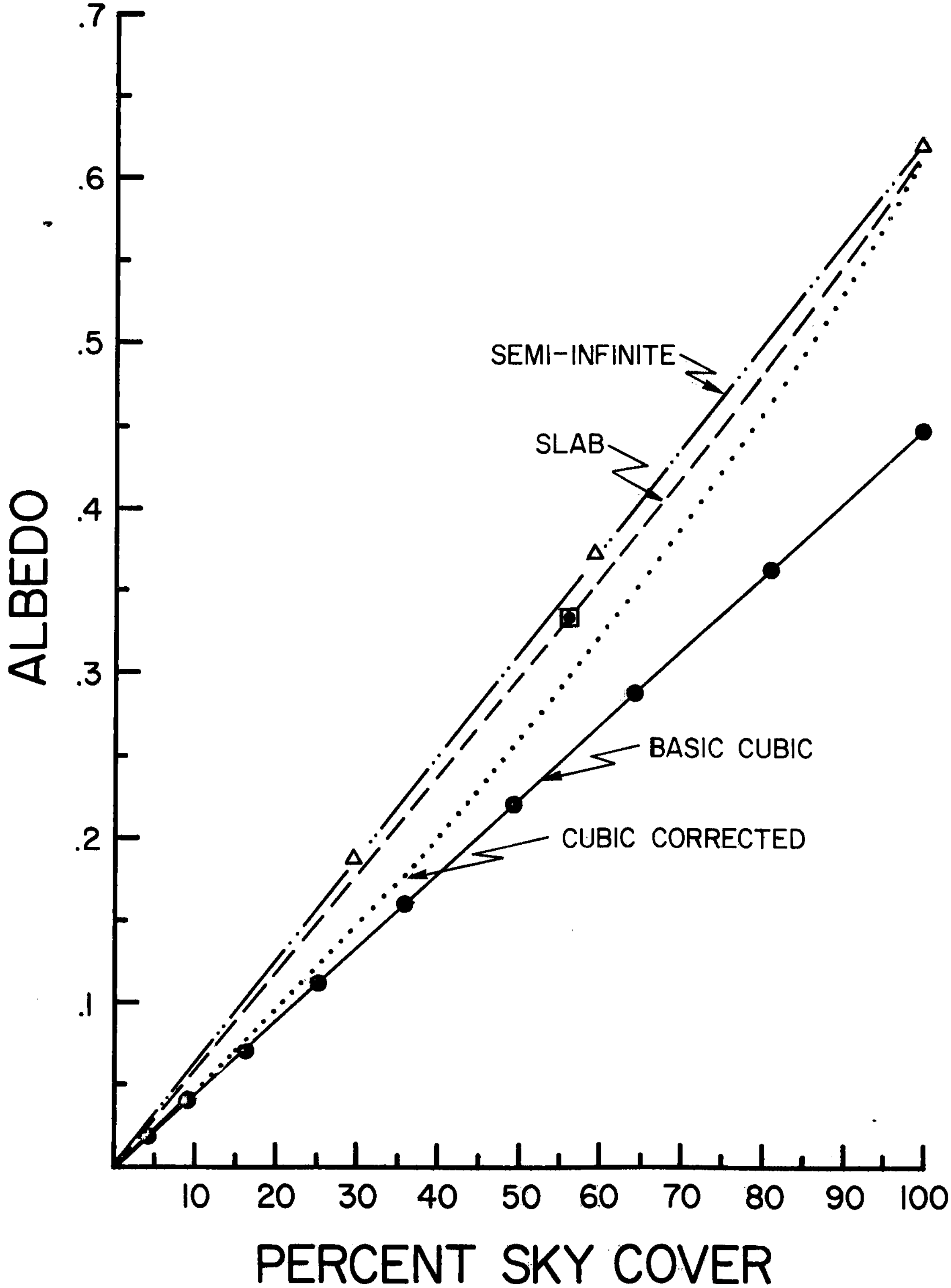

Figure 16. Same as Figure 15 except the optical thickness is 20.

different optical depth. One thing quite different about this graph for optical depth of twenty is that while the "Basic Cubic", "Semi-infinite", and "Slab" cases are all generated from Monte Carlo programs, the "Cubic Corrected" is placed in by simply knowing the two end points and basically following the same shape as the bigger optical depth case. The only reason the "Cubic Corrected" could be in large error is that if the interaction distance changed for the optical depth to be much smaller, the "Cubic Corrected" might not diverge from the "Basic Cubic" until a sky cover of, for instance, 30%, where maximum separation is two diameters. Again this shows the infinite cloud approximation to be in error at most of 5% in albedo. This is deceptive in nature because this occurs in small albedos.

A better analysis of how much the infinite cloud could vary from the "Cubic Corrected" was done. A percent error was defined to evaluate the difference between the infinite and "Cubic Corrected". It was defined as

$$\text{Percent Error (SC)} = \frac{\text{INF(SC)} - \text{CC(SC)} \times 100}{\text{CC(SC)}}$$

where INF is the infinite cloud albedo at some sky cover and CC is the Cubic Corrected albedo at the same sky cover. CC(SC) and INF(SC) only denote that these are functions of sky cover. This percent error represents the largest amount the infinite cloud approximation could overpredict the system albedo.

Figure 17 shows the results for both optical depths. The smaller the optical depth, the larger the possible error. Small sky covers lead to larger maximum errors. Recall that this error is the largest

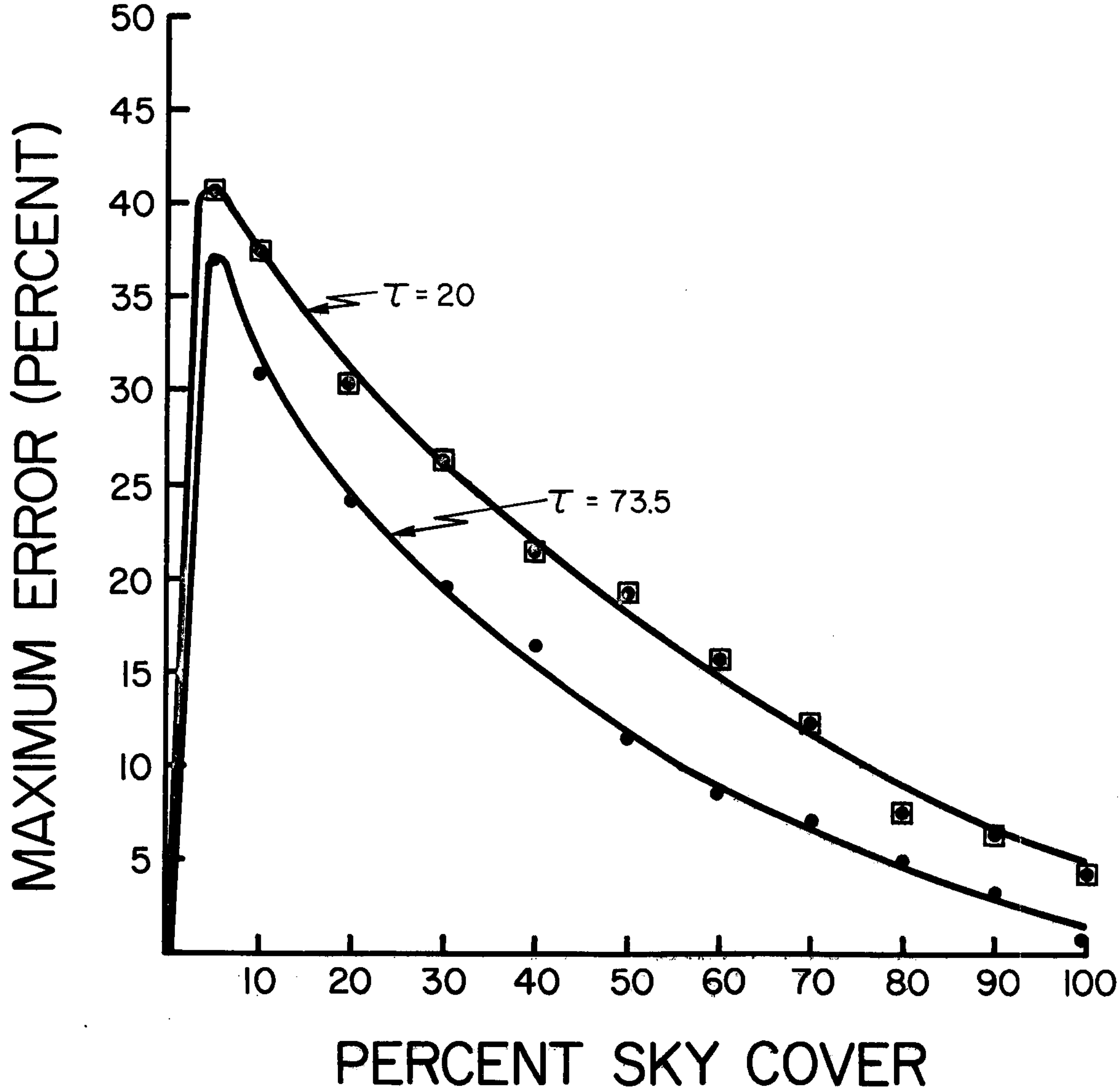

Figure 17. Maximum error versus sky cover for optical thickness of 20 and 70.

amount of error the infinite cloud model would overpredict a field of interacting cubic clouds. The relative error analysis is helpful in some applications but can be misleading. In the small sky cover regime, even though the percent errors are on the order or 40%, the absolute errors are only 0.8%. It would be instructive to look at the albedo differences between the "Infinite" and the "Corrected Cubic" as a function of sky cover.

Figure 18 shows the "Infinite" and "Corrected Cubic" albedo errors as a function of sky cover for an optical thickness of 73.5. It is interesting to note that the maximum error occurs at approximately 50% sky cover and is of apparent symmetric bell shaped curve. It is estimated that the average global cloud cover is on the order of 50% also. These two facts indicate that global energy budget calculations, using an infinite cloud approximation, are modeling cloudiness in a regime where the maximum albedo differences occur. What is not known is where the finite cloud regime ends and semi-infinite begins. If at 50% sky cover clouds are not finite clouds but more slab in nature one would expect a smaller difference between the interacting cubic and infinite cloud models. There is presently no detailed data available presenting average cloud diameter for sky covers from 5% to 95%.

All of the results in this paper are based on sun vertical and optically thick clouds. Figures 15 and 16 show the infinite cloud approximation overpredicting the directional reflectance. These results could change for large zenith angles where the infinite cloud model actually underpredicts the directional reflectance.

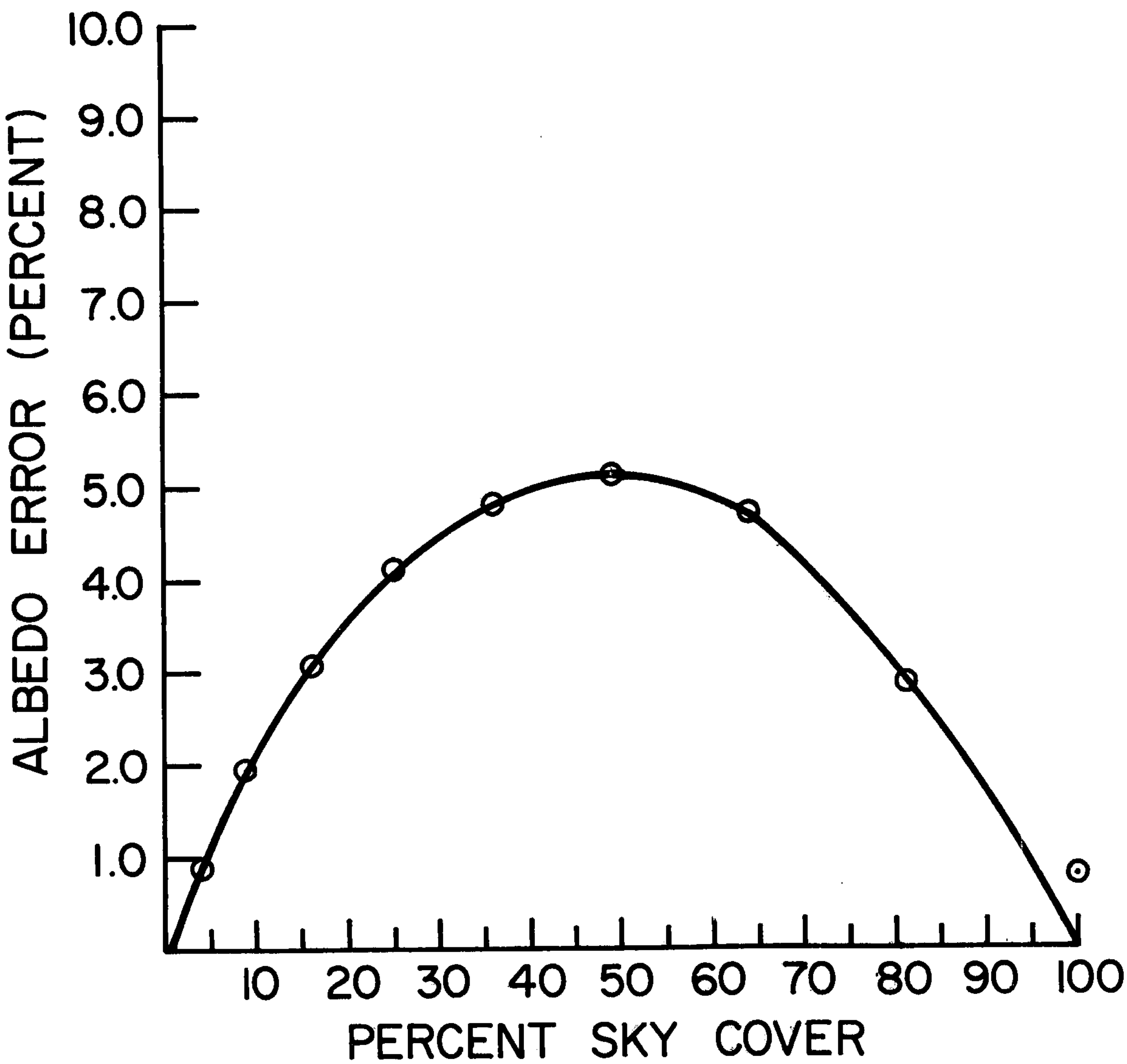

Figure 18. Absolute error between infinite and corrected cubic cloud field albedoes for an optical depth 73.5.

V. Suggestions for Future Research

During the experiment randomly placed cloud fields were investigated. The clouds were placed randomly into the coordinate system to simulate possible configurations of real cloud fields in the atmosphere. The sensors were placed high above the cloud fields in order to get a total view of the field. Unfortunately there were errors in this logic since the background signal was far too large compared to the signal received from the clouds. The problem was not discovered until too late, so no data of these experiments are included in this paper. However it is the opinion of the author that this would be a productive pursuit for further research and is included below. Several improvements in the experimental design are desirable and include the following:

1) To develop a better system of measuring the albedo;
2) To develop a method of calibration of the system against a known;
3) To develop a method of accurately controlling and measuring the optical depth;
4) To have a larger working area.

Future areas of research that would be most productive relating to the work done here are as follows:

1) To measure the entire albedo for cubic and spherical clouds undergoing interaction;
2) To measure the albedo of the random placement;
3) To extend the random cloud placement into larger cloud covers to complete the picture;

4) To study interaction distance and magnitudes of it as a function of optical depth;

5) To study the effect of using a size spectrum in the cloud fields according to know distributions of Planck;

6) To study the height versus interaction in greater detail using material whose geometric thickness is larger to its optical depth than the material used in this study;

7) To incorporate the random placement into the comparison of infinite to corrected cubic to better evaluate the possible error using the infinite cloud model.

VI. Concluding Remarks

The most important conclusion from this research is that useful data can be obtained from the physical modeling of clouds. Radiance patterns from complex cloud structures may be too difficult to calculate theoretically, whereas physical modeling may be the simplest means to approach the problem.

The center cloud in a 3 x 3 array of modeled clouds was found to have a 5% increase in the top directional reflectance over the isolated cloud case at a separation of 2.5 cloud diameters, and increased to 30% at a separation of one cloud diameter. The increase of the top directional reflectance as the separation increased behaved similar to $1/S^2$ where S is the cloud separation. The cloud interaction distance was found to rapidly increase as the height to diameter ratio increased, but then leveled off as the optical thickness of the clouds got larger than about 100 to 125. It was concluded that cubic clouds separated by more than 2.5 cloud diameters could be treated as non-interacting clouds.

A comparison of calculated directional reflectances for cloud fields was done using the infinite cloud approximation, non-interacting cubes, slab clouds, and interacting cubic clouds for sky covers of 0% to 100% sun vertical. An error analysis between the infinite cloud approximation and the interacting cubic clouds showed a maximum relative error of 40% at cloud covers under 5% but the absolute error maximum was 5% directional reflectance at sky covers around 50%.

REFERENCES

Aida, B., 1976: Transfer of solar radiation in an array of cumuli. Paper delivered at Symposium on Radiation in the Atmosphere, Garmisch-Partenkirchen, Germany, held 19-28 August, 1976.

Barkstron, B. R. and R. F. Arduini, 1976: The effect of finite horizontal size of clouds upon the visual albedo of the earth. Paper delivered at Symposium on Radiation in the Atmosphere, Garmisch-Partenkirchen, Germany, held 19-28 August, 1976.

Deirmendjian, D., 1969: Electromagnetic scattering on spherical polydispersions. Elsevier, 78 pp.

London, J., 1957: A study of the atmospheric heat balance. Final Rept. Contract AF19 (122)-165, College of Engineering, New York University, (ASTIA No. 117227), 98 pp.

London, J. and T. Sasamori, 1971: Radiative Energy Budget of the Atmosphere. Space Research XI, Akademic-Verlag, Berlin, 639-649.

McKee, T. B. and S. K. Cox, 1974: Scattering of visible radiation by finite clouds. J. Atmos. Sci., 31, 1885-1892.

McKee, T. B. and S. K. Cox, 1976: Simulated radiance patterns for finite cubic clouds. J. Atmos. Sci., 31, 2014-2020.

Plant, V. G., 1969: The size distribution of cumulus clouds in representative Florida populations. J. App. Met., 8, 46-67.

Rasche, E. and W. R. Bandeen, 1970: The radiation balance of the planet Earth from radiation measurements of the satellite Nimbus II. J. App. Met., 9, 215-238.

Snedecor, George W. and William G. Cochran, 1971: Statistical methods, sixth edition. Iowa State University Press, Ames, Iowa.

Vonder Haar, T. H. and K. J. Hanson, 1969: Absorption of solar radiation in the tropical regions. J. Atmos. Sci., 26, 652-655.

Wendling, P., 1977: Albedo and reflected radiance of horizontally inhomogeneous clouds. J. Atmos. Sci., 34, 642-650.

APPENDIX A.

The appendix contains the data for the figures presented in the text. The tables are arranged in the same order as the figures in the text.

Table A1. Data for nine cloud model.

S	Output (μAmp)	UT_9/UT_1	Output (μAmp)	UT_9/UT_1	Output (μAmp)	UT_9/UT_1	FITTED
5.0	32.2	1.000	32.2	1.000	32.1	1.000	1.004
4.5	32.2	1.000	32.3	1.003	32.2	1.003	1.009
4.0	32.3	1.003	32.6	1.012	32.4	1.009	1.015
3.5	32.9	1.022	33.0	1.025	32.9	1.025	1.024
3.0	34.0	1.056	33.8	1.050	33.9	1.056	1.037
2.5	34.4	1.068	34.0	1.056	34.3	1.069	1.057
2.25	34.6	1.075	34.5	1.071	34.7	1.081	1.072
2.0	35.0	1.087	35.0	1.087	35.2	1.097	1.093
1.75	35.9	1.115	36.0	1.118	36.1	1.125	1.120
1.5	37.0	1.149	36.8	1.143	36.9	1.150	1.159
1.25	39.1	1.214	39.5	1.227	39.2	1.221	1.216
1.0	41.6	1.292	41.8	1.298	41.9	1.305	1.298

Table A2. Data for five cloud layer models.

ONE LAYER

S	Output (μAmp)	UT_5/UT_1	Output (μAmp)	UT_5/UT_1	Output (μAmp)	UT_5/UT_1
5.0	20.4	1.000	22.8	1.000	20.3	1.000
4.5	20.4	1.000	22.8	1.000	20.3	1.000
4.0	20.4	1.000	22.8	1.000	20.3	1.000
3.5	20.4	1.000	22.8	1.000	20.3	1.000
3.0	20.5	1.005	22.8	1.000	20.4	1.005
2.5	20.5	1.005	22.9	1.004	20.4	1.005
2.0	20.6	1.010	23.0	1.009	20.7	1.020
1.75	20.8	1.020	23.0	1.009	20.8	1.025
1.5	21.1	1.034	23.4	1.026	21.3	1.049
1.25	21.9	1.074	24.1	1.057	21.8	1.074
1.0	25.9	1.225	28.2	1.257	24.9	1.227

TWO LAYER

S	Output (μAmp)	UT_5/UT_1	Output (μAmp)	UT_5/UT_1	Output (μAmp)	UT_5/UT_1
5.0	27.7	1.000	27.0	1.000	25.0	1.000
4.5	27.7	1.000	27.0	1.000	25.0	1.000
4.0	27.7	1.000	27.0	1.000	25.0	1.000
3.5	27.7	1.000	27.0	1.000	25.1	1.004
3.0	27.8	1.004	27.5	1.019	25.4	1.016
2.5	27.8	1.004	27.8	1.030	25.9	1.036
2.0	28.2	1.018	28.2	1.044	26.2	1.048
1.75	29.0	1.047	28.8	1.067	27.0	1.080
1.5	29.8	1.076	29.7	1.100	27.9	1.116
1.25	31.5	1.137	31.5	1.167	29.8	1.192
1.0	37.2	1.343	37.8	1.400	36.5	1.460

Table A2. Continued.

THREE LAYER

S	Output (μAmp)	UT_5/UT_1	Output (μAmp)	UT_5/UT_1	Output (μAmp)	UT_5/UT_1
5.0	29.2	1.000	29.0	1.000	29.2	1.000
4.5	29.2	1.000	29.0	1.000	29.2	1.000
4.0	29.2	1.000	29.0	1.000	29.2	1.000
3.5	29.4	1.007	29.1	1.003	29.5	1.010
3.0	29.9	1.024	29.1	1.003	29.8	1.021
2.5	30.2	1.034	29.9	1.031	30.1	1.031
2.0	30.5	1.045	30.9	1.066	31.0	1.062
1.75	30.5	1.045	31.2	1.076	31.8	1.089
1.5	32.1	1.099	32.8	1.131	32.8	1.123
1.25	34.8	1.192	34.6	1.193	35.0	1.199
1.0	41.5	1.421	41.0	1.414	42.0	1.438

FOUR LAYER

S	Output (μAmp)	UT_5/UT_1	Output (μAmp)	UT_5/UT_1	Output (μAmp)	UT_5/UT_1
5.0	29.9	1.000	30.0	1.000	29.9	1.000
4.5	29.9	1.000	30.0	1.000	29.9	1.000
4.0	29.9	1.000	30.2	1.007	29.9	1.000
3.5	30.0	1.003	30.5	1.017	30.0	1.003
3.0	30.1	1.007	30.8	1.027	30.2	1.010
2.5	30.4	1.017	31.1	1.037	30.5	1.020
2.0	31.2	1.043	22.0	1.067	31.0	1.037
1.75	32.3	1.080	33.0	1.100	32.2	1.077
1.5	33.4	1.117	33.8	1.127	34.2	1.144
1.25	35.8	1.197	35.9	1.197	36.9	1.234
1.0	42.9	1.435	42.8	1.427	43.0	1.438

Table A2. Continued.

FIVE LAYER						
S	Output (μAmp)	UT_5/UT_1	Output (μAmp)	UT_5/UT_1	Output (μAmp)	UT_5/UT_1
5.0	30.5	1.000	30.5	1.000	30.4	1.000
4.5	30.5	1.000	30.5	1.000	30.4	1.000
4.0	30.5	1.000	30.6	1.003	30.6	1.007
3.5	30.7	1.007	30.8	1.010	30.7	1.010
3.0	30.9	1.013	30.9	1.013	30.9	1.016
2.5	31.3	1.026	31.4	1.030	31.5	1.036
2.0	32.0	1.049	32.1	1.052	32.0	1.058
1.75	32.5	1.066	32.7	1.072	32.6	1.072
1.5	33.8	1.108	33.9	1.111	34.0	1.118
1.25	36.3	1.190	36.7	1.203	36.8	1.211
1.0	43.8	1.436	44.0	1.443	44.0	1.447

Table A3. Values predicted for layer models by regression equations.

ONE LAYER MODEL FITTED

$$UT_5/UT_1 = 1.012 - \frac{.2673}{S^2} + \frac{.4782}{S^3}$$

S	UT_5/UT_1	S	UT_5/UT_1	S	UT_5/UT_1
1.00	1.223	2.25	1.001	4.5	1.004
1.25	1.085	2.50	1.000	5.0	1.005
1.50	1.035	3.00	1.000		
1.75	1.014	3.50	1.001		
2.00	1.005	4.00	1.002		

TWO LAYER MODEL FITTED

$$UT_5/UT_1 = 1.006 - \frac{.1645}{S^2} + \frac{.5533}{S^3}$$

S	UT_5/UT_1	S	UT_5/UT_1	S	UT_5/UT_1
1.00	1.394	2.00	1.034	3.5	1.005
1.25	1.184	2.25	1.022	4.0	1.004
1.50	1.096	2.50	1.015	4.5	1.004
1.75	1.055	3.00	1.008	5.0	1.003

Table A3. Continued.

THREE LAYER MODEL FITTED

$$UT_5/UT_1 = 1.001 - \frac{.0538}{S^2} + \frac{.4711}{S^3}$$

S	UT_5/UT_1	S	UT_5/UT_1	S	UT_5/UT_1
1.00	1.419	2.00	1.047	3.5	1.008
1.25	1.208	2.25	1.032	4.0	1.005
1.50	1.117	2.50	1.023	4.5	1.004
1.75	1.072	3.00	1.013	5.0	1.003

FOUR LAYER MODEL FITTED

$$UT_5/UT_1 = .9969 - \frac{.0025}{S^2} + \frac{.4311}{S^3}$$

S	UT_5/UT_1	S	UT_5/UT_1	S	UT_5/UT_1
1.00	1.430	2.00	1.051	3.5	1.007
1.25	1.219	2.25	1.035	4.0	1.004
1.50	1.126	2.50	1.025	4.5	1.002
1.75	1.078	3.00	1.013	5.0	1.000

Table A3. Continued.

FIVE LAYER MODEL FITTED

$$UT_5/UT_1 = 1.003 - \frac{.0829}{S^2} + \frac{.5045}{S^3}$$

S	UT_5/UT_1	S	UT_5/UT_1	S	UT_5/UT_1
1.00	1.425	2.00	1.045	3.5	1.008
1.25	1.208	2.25	1.031	4.0	1.006
1.50	1.116	2.50	1.022	4.5	1.004
1.75	1.070	3.00	1.012	5.0	1.004

Table A4. Data used in Figure 15 for optical depth of 70.

BASIC CUBIC					
N	Sky Cover	S_{max}	A_s a_c=.700	Correction Coefficient	Corrected Cubic
4	.04	9.0	.028	1.000	.028
9	.09	4.5	.063	1.008	.063
16	.16	3.0	.112	1.037	.116
25	.25	2.25	.175	1.072	.188
36	.36	1.8	.252	1.120	.282
49	.49	1.5	.343	1.159	.398
64	.64	1.29	.448	1.204	.539
81	.81	1.125	.567	1.260	.714
100	1.00	1.000	.700	1.298	.909

SLAB				
Size	A_c	Sky Cover	Slab Albedo A_s	Infinite
1.5 x 1.5	.700	.0056	.004	.0051
3 x 3	.792	.0225	.018	.0206
4.5 x 4.5	.824	.051	.042	.0467
6 x 6	.856	.09	.077	.0825
9 x 9	.865	.202	.175	.185
15 x 15	.888	.563	.499	.516
18 x 18	.889	.81	.720	.743

Table A5. Data used in Figure 16 for optical depth of 20.

BASIC CUBIC				
N	Sky Cover	S_{max}	A_s A_c=.449	Corrected Cubic
4	.04	9.0	.018	.018
9	.09	4.5	.040	.040
16	.16	3.0	.072	.076
25	.25	2.25	.112	.123
36	.36	1.8	.162	.180
49	.49	1.5	.220	.255
64	.64	1.29	.289	.350
81	.81	1.125	.364	.465
100	1.00	1.000	.449	.595

SLAB				
Size	A_c	Sky Cover	Slab Abledo A_s	Infinite
1.5 x 1.5	.449	.0056	.0025	.0035
3 x 3	.523	.0225	.0118	.0140
5 x 5	.552	.062	.0345	.0385
15 x 15	.593	.563	.333	.349

BIBLIOGRAPHIC DATA SHEET	1. Report No. ATS Paper No. 286	2.	3. Recipient's Accession No.

4. Title and Subtitle

A Laboratory Investigation of Radiative Transfer in Cloud Fields

5. Report Date: April 1978

6.

7. Author(s): James A. Kuenning and Thomas B. McKee

8. Performing Organization Rept. No.

9. Performing Organization Name and Address

Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado 80523

10. Project/Task/Work Unit No.

11. Contract/Grant No.
OCD-74-21678
ATM-77-15369

12. Sponsoring Organization Name and Address

National Science Foundation

13. Type of Report & Period Covered

14.

15. Supplementary Notes

16. Abstracts

Finite clouds were simulated with laboratory models in an investigation of cloud interaction distances, variation of the cloud interaction distances as a function of cloud height, and radiative properties of cloud fields. Comparisons were made between laboratory data and Monte Carlo calculations.

The center cloud in a 3 x 3 array of modeled clouds was found to have a 5% increase in the top directional reflectance over the isolated cloud case at a separation of 2.5 cloud diameters, and increased to 30% at a separation of one cloud diameter. The increase of the top directional reflectance as the separation increased behaved similar to $1/S^2$ where S is the cloud separation. The cloud interaction distance was found to rapidly increase as the height to diameter ratio increased, but then leveled off as the optical thickness of the clouds got larger than about 100 to 125. It was concluded that cubic clouds separated by more than 2.5 cloud diameters could be treated as non-interacting clouds.

17. Key Words and Document Analysis. 17a. Descriptors

Clouds
Solar radiation
Albedo

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group

18. Availability Statement

19. Security Class (This Report) UNCLASSIFIED

20. Security Class (This Page) UNCLASSIFIED

21. No. of Pages 55

22. Price