On the Usefulness of Satellite Infrared Measurements in the Determination of Cloud Top Heights and Areal Coverage

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ABSTRACT

The assumptions inherent in the determination of cloud top heights and areal coverage of clouds from infrared measurements made by satellites are discussed. The problems of interpretation caused by radiometer spatial resolution being of the same order of size as individual cloud elements are studied through mathematical simulation of the viewing process. An analysis of the simulated measurements from simple, specified cloud conditions produces quantitative estimates of the errors of interpretation.

It is found that individual cloud elements of a diameter slightly less than the viewed spot can be very misleading and the height of cloud tops might be judged to be several thousand feet below their true height; tops of larger clouds can be determined more accurately. If the actual height of the tops can be determined, either by the infrared measurements from large cloud masses or by other means, the areal coverage can be estimated rather well.

1. Introduction

Two related possibilities for the use of meteorological satellites are the determination of cloud top heights and the amount of cloudiness from measurements of infrared radiation. Such uses have been discussed in some detail by many authors, including Blankenship (1962, 1963), Wood (1963), Fritz and Winston (1962), and Maykut (1964). The primary assumptions involved for these determinations are that the cloud top radiates very nearly as a black body, that atmospheric absorption is negligible above that level in the frequency band being monitored, that the clouds are opaque to infrared radiation, and that reflected solar radiation does not contribute significantly to the response received. Then if the vertical temperature structure of the atmosphere is a monotonically decreasing function of height from the surface of the earth to the maximum possible cloud height and is known for a particular geographical location, the cloud height can be inferred directly from the measured return from that location. In actual practice there are several problems with this approach. These are enumerated below:

1) The clouds may not absorb and radiate as black bodies. If the clouds are thick and composed of liquid water drops this effect is probably much less than other inaccuracies in the procedure. However, thin clouds, and especially cirrus, will not absorb all radiation coming from below and reradiate at their own temperature, but the radiation measured from above will be a combination of that coming from below the thin clouds and from the clouds themselves.

2) Atmospheric absorption above the radiating surface may not be negligible. This, of course, depends on the wavelength band being monitored and the height of the radiating surface. Hanel and Wark (1961) have shown for a cloudless condition that 25 per cent of the radiation received by the TIROS channel 2 ($\approx 8-12\,\mu$) may originate in the lower atmosphere rather than at the ground. Also, Rasool (1964) has shown that the difference between the indicated equivalent black-body temperature and the ground temperature can be as large as 11.5C or as low as 3.5C for a hot, humid and a cold, dry atmosphere, respectively. Nordberg *et al.* (1962) have shown by analysis of actual data that the equivalent black-body temperatures indicated by TIROS III channel 2 can be as much as 20C lower than the expected sea surface temperatures. However, much less absorption will occur above cloud tops a few thousand feet high. NIMBUS I measured in the 3.6–4.2 μ band and Nordberg and Press (1964) state that equivalent black-body temperatures were correct to $\pm$1C.

3) The temperature profile may contain isothermal regions or inversions which might cause ambiguities in cloud height determination. Also, the temperature profile is not well known over the very areas where cloud observations are most needed.

4) The exact position on the earth from which the radiation emanated may not be known. This was true of TIROS II data studied by Fritz and Winston (1962). Darling (1964) states, "Errors . . . are expected to cause a maximum overall error of 50 n mi in the geographic referencing of NIMBUS A cloud pictures

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[1] This research was performed while the author, employed by the U. S. Weather Bureau, was on duty with the U. S. Air Force.

[2] The views expressed herein are those of the author and do not necessarily reflect the views of the U. S. Air Force or the Department of Defense.

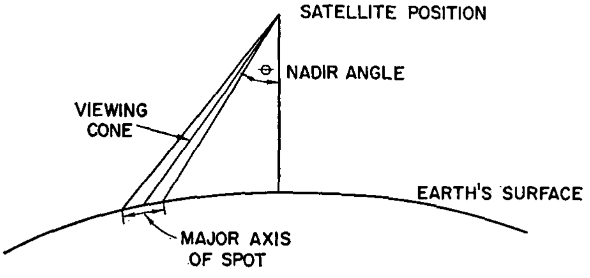

FIG. 1. The relationship between viewing cone, spot, and nadir angle.

. . . . For future NIMBUS vehicles it is anticipated that this error can be reduced to less than 20 n mi."

5) Instrumental calibration may be in error. Deterioration was noted in the response of the TIROS II and TIROS III radiometers (Nordberg, 1963).

6) Sensor response is not instantaneous. This produces a smearing from spot to spot in a swath.

7) The spatial resolution of the radiometer may not be high enough to distinguish small cloud masses. Also, the response may not be flat over the viewed region.

8) The radiation received when the radiometer is not pointing straight down (nadir angle $\neq 0$) can be due to a combination of cloud tops, cloud sides, and ground (or a lower cloud deck). This limb darkening effect is listed as a separate problem although it is related to the spatial resolution mentioned above. (Limb darkening due to absorption may also occur but can be considered as part of the absorption problem.)

It seems likely that the inaccuracy of inferred cloud top heights due to some of the above problems will become negligible in the future as better instrumentation becomes available. However, some practical limitations may exist for quite some time. For example, the spatial resolution of the TIROS III channel 2 radiometer was about 38 statute miles at zero nadir angle. [This is the half power point; actually some radiation was received from a spot with a diameter of approximately 130 miles (Fujita, 1963).] The NIMBUS I resolution was 4 or 5 miles. The early phases of TOS (TIROS Operational System) will not include a scanning radiometer.

In order to make adequate use of infrared measurements for the determination of cloud top heights and areal coverage, quantitative estimates of the effect of non-vertical viewing and of the smearing effect due to spatial resolutions of the order of a few miles are needed. For this purpose the following experiment was performed.

2. Numerical simulation of the measurement process

A numerical model was designed to simulate the measurement of infrared radiation received at a satellite from the ground and prescribed cloud conditions. The cloud locations were specified by x and y coordinates on a 110 by 80 mi grid. The viewing process was modeled similar to that used by the earth oriented NIMBUS I satellite. The simulated satellite track was parallel to the y-axis and could be located such that the nadir angle θ would have any reasonable and desired value relative to the line $x=60$. The radiometer scanned a swath perpendicular to the satellite track, the scan time being such that adjacent swaths were conterminous when θ was equal to zero; an overlap occurred when θ was greater than zero. The first swath was centered over the line $y=12.5$ and the final swath was centered

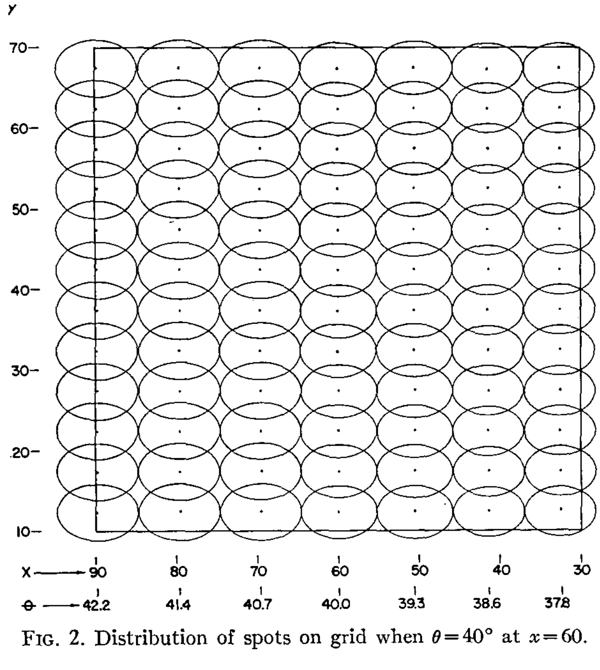

FIG. 2. Distribution of spots on grid when $\theta=40°$ at $x=60$.

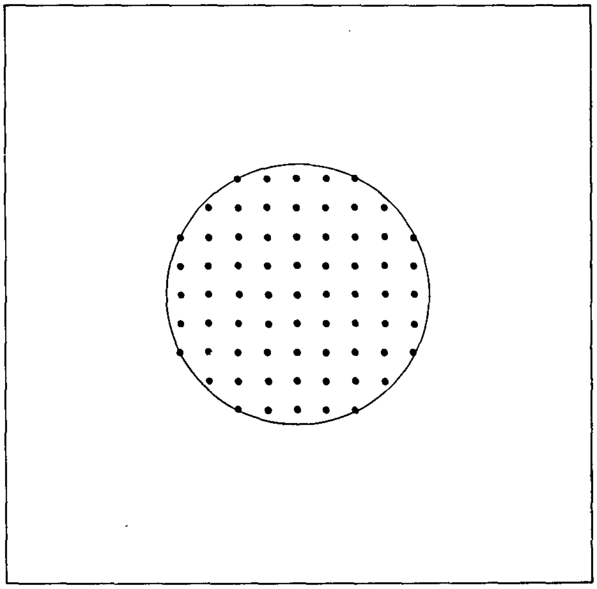

FIG. 3. A cross section of the viewing cone showing the 69 points used in the numerical integration.

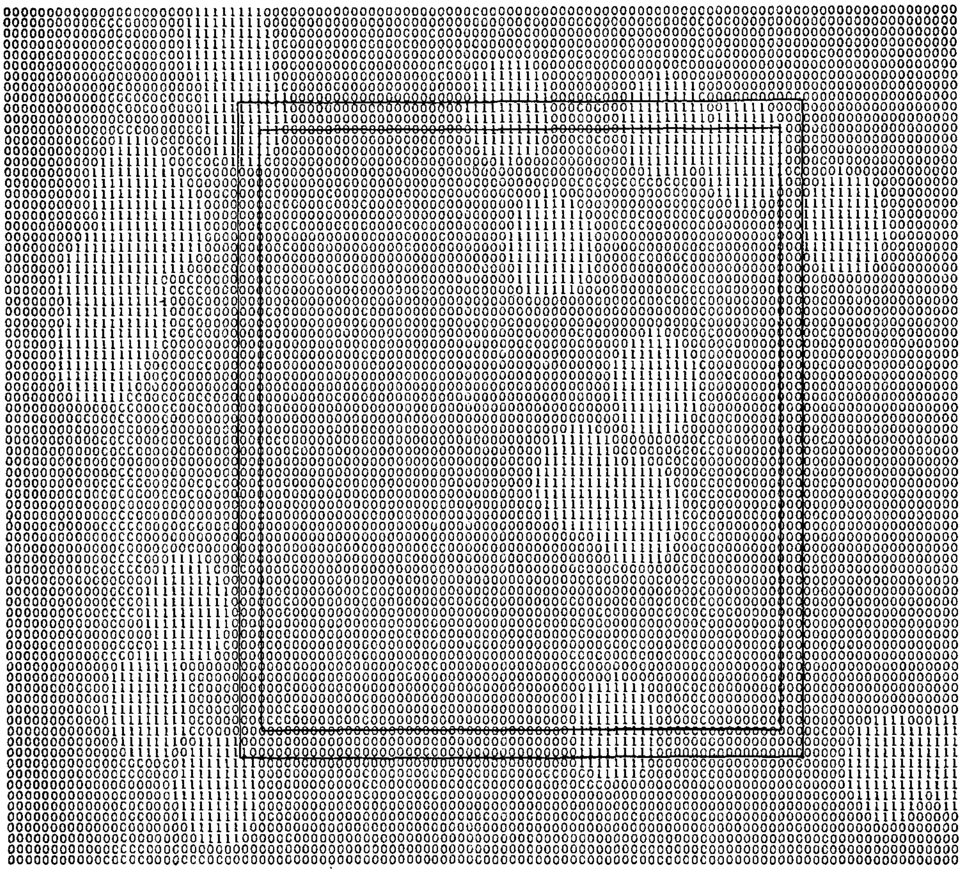

FIG. 4. The cloud distribution used for run 5; the 1's indicate the portion covered by clouds. The actual per cent coverage was computed numerically over the area within the larger box. For a spot to be considered in the analysis its center had to fall within the smaller box.

over the line $y=67.5$. (Actually the swaths should have been at a slight angle to the x-axis but this approximation is of little concern for the purpose at hand.) Each swath was composed of a number of spots or areas from which measurements were available. These spots were defined by the intersection of the viewing cone (see Fig. 1) with the ground or clouds. Spots in each swath were considered if the center of the viewing cone intersected the ground in the range $30 \leqslant x \leqslant 90$. In this manner all spots (at ground level) were centered in a 60 by 60 statute mile area which is approximately the area used for some operational mapping codes.

The geometry used to find the location, size, and shape of the viewed spot as a function of nadir angle is shown in Fig. 1. When the nadir angle was not zero the viewed spot was considered to be an ellipse whose center was at the point where the center of the viewing cone intersected the earth's surface. This approximation had a negligible effect on the results but somewhat simplified the computations.

The size of the viewed spot is affected by θ in two ways. First, the larger slope of the earth's surface for larger θ results in an elongation of the spot in the direction of the swath. Also, the greater distance between the satellite and the viewed spot for greater θ results in a porportionate increase in both dimensions of the spot. Digitization of the simulated analogue radiometer return was accomplished by sampling once as θ changed by an amount equal to the radiometer aperture (diameter of the viewing cone). Therefore, the spots never overlap anywhere along the swath. Fig. 2 shows the distribution of spots on the grid when $\theta=40°$ at $x=60$. The 60 by 60 area into which the centers of all spots must have fallen to have been considered in the analysis is indicated. It can be seen from this diagram that nadir angles of approximately $40 \pm 2.2°$ yield spots within the area when $\theta=40°$ at $x=60$.

The simulated return from each spot was found by considering each viewing cone to be composed of 69 individual, equally spaced rays (see Fig. 3). Each ray was traced from the satellite to the level at which it first intersected a cloud or the ground; the temperature at that level (the U. S. Standard Atmosphere temperature profile was specified) was noted as T. The integrated return was then computed by the formula

$$IR=\left(\frac{1}{69}\sum_{i=1}^{69} T_i^4\right)^{\frac{1}{4}}.$$

The satellite was considered to be at an altitude of 400 statute miles and the aperture of the radiometer such that the spot diameter was 5 mi at zero nadir angle. The viewing cone was approximated by a cylinder in the region where clouds might occur in order to simplify the calculations, the effect of this approximation being negligible since the diameter of a spot is only about 2 per cent less at 8 mi altitude than at the ground.

Since the rays were not in general parallel to the vertically oriented cloud sides, a cloud whose base was nearer to the subsatellite point than $x=30$ might have intercepted a ray and thereby furnished a portion of the integrated return; this same problem would occur with a real measuring system.

For each simulation run or a group of runs a pseudorandom cloud distribution (the term "cloud distribution" will be used to denote only cloud positions and not other information about them) was specified on the 110 by 80 grid. Each cloud had the shape of a cylinder and all clouds had the same base height, top height, and radius. The clouds could overlap and form larger cloud masses. The areal coverage of one specified cloud pattern is shown in Fig. 4. The per cent areal coverage of clouds in the 65 by 61 area (larger area in Fig. 4) was determined numerically for each specified cloud condition. This area is roughly that covered by the spots at nadir angles near zero.

3. The measurements

It may be argued that a random cloud distribution is not a good one to use since clouds are not randomly spaced in nature. There is an infinite number of cloud distributions which might occur and probably there is no exact repeat of any one distribution that does occur. It is feasible to study only a small portion of such possible distributions so an attempt should be made to use ones which are somewhat representative of a class of distributions. The return from some patterns, such as bands of clouds, would depend on their orientation on the grid and considerable care would be necessary to insure that the viewing process was not "in phase" or

TABLE 1. Parameters describing the cloud conditions for the 19 computer runs. The radius is given in miles and the height of the tops and bases are given in feet.

Run no.	Distribution no.	No. of clouds	Height of tops	Height of bases	Radius	Per cent coverage
1	1	150	30,000	10,000	2	17
2	2	150	30,000	10,000	2	19
3	3	150	30,000	10,000	2	20
4	4	150	30,000	10,000	2	20
5	1	21	30,000	1,0000	5	15
6	2	14	30,000	10,000	5	17
7	3	24	30,000	10,000	5	18
8	4	24	30,000	10,000	5	18
9	1	7	30,000	10,000	10	13
10	2	3	30,000	10,000	10	16
11	3	5	30,000	10,000	10	17
12	4	6	30,000	10,000	10	13
13	1	150	30,000	28,000	2	17
14	1	881	14,000	12,000	2	70
15	1	165	14,000	12,000	5	70
16	1	39	14,000	12,000	10	69
17	1	372	6000	2000	2	40
18	1	71	6000	2000	5	39
19	1	17	6000	2000	10	39

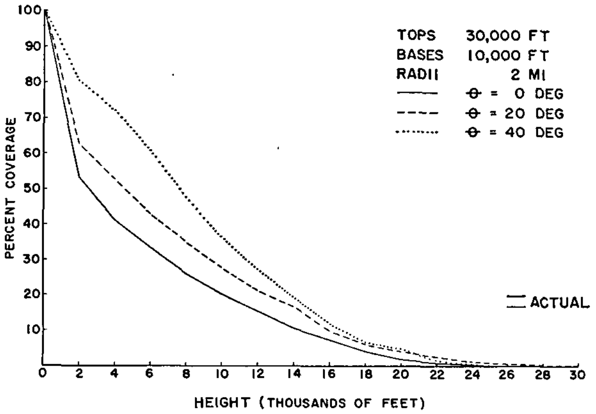

FIG. 5. The percentage of cloud tops indicated at and above the specified heights. The values are averages from runs 1–4.

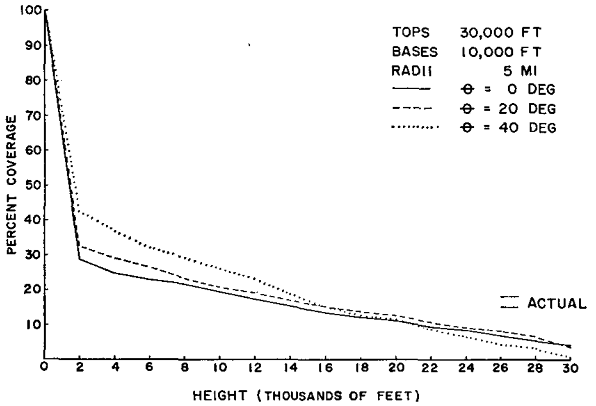

FIG. 6. The percentage of cloud tops indicated at and above the specified heights. The values are averages from runs 5–8.

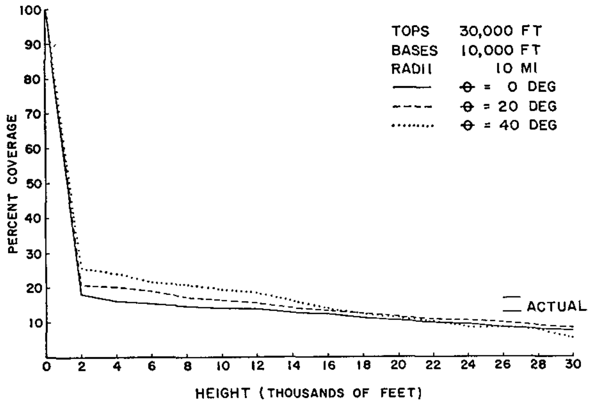

FIG. 7. The percentage of cloud tops indicated at and above the specified heights. The values are averages from runs 9–12.

"out of phase" to such an extent that the results would not be representative of the class of which this pattern was a member. Many cloud distributions over an area 60 mi on a side do look somewhat random and for the top-base-radius combinations used in this study a random distribution is not unreasonable. A random distribution as used here does not necessarily give an "evenly spaced" pattern. In fact, the clouds shown in Fig. 4 appear to line up parallel to the y-axis so that one band is within the area over which the per cent coverage is computed.

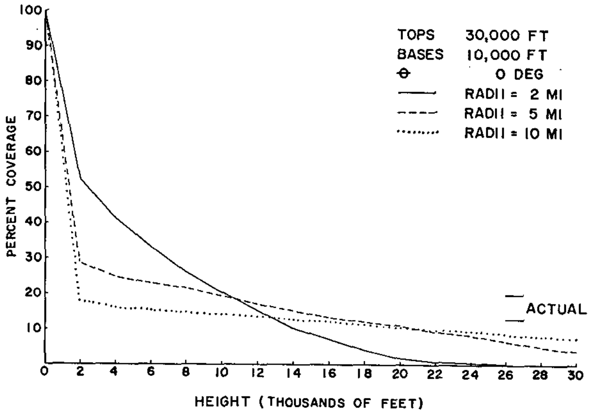

Fig. 8. The percentage of cloud tops indicated at and above the specified heights. The values are averages from runs 1–12.

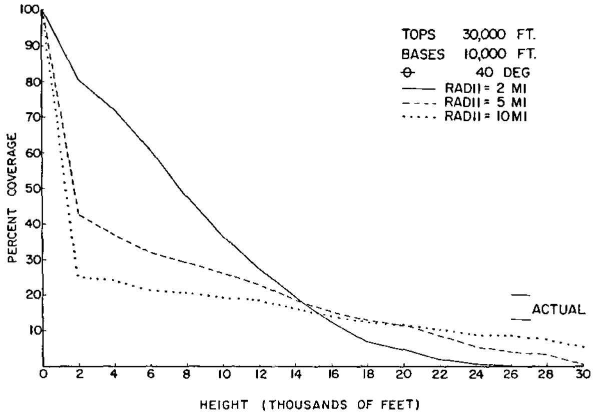

Fig. 9. The percentage of cloud tops indicated at and above the specified heights. The values are averages from runs 1–12.

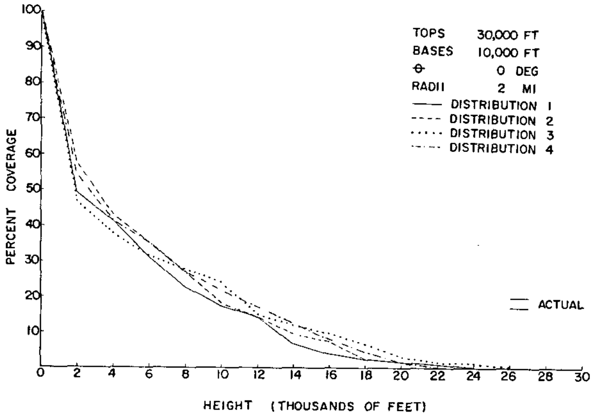

Fig. 10. The percentage of cloud tops indicated at and above the specified heights, runs 1–4.

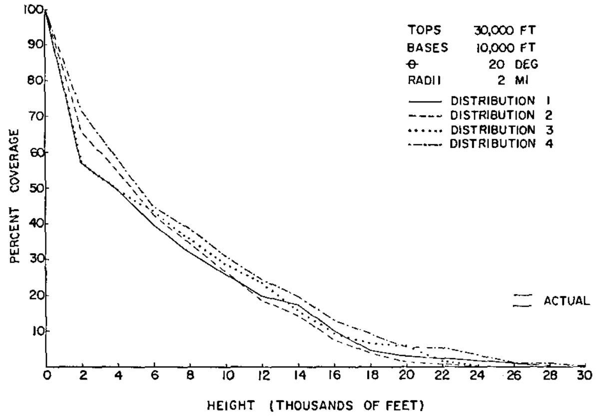

Fig. 11. The percentage of cloud tops indicated at and above the specified heights, runs 1–4.

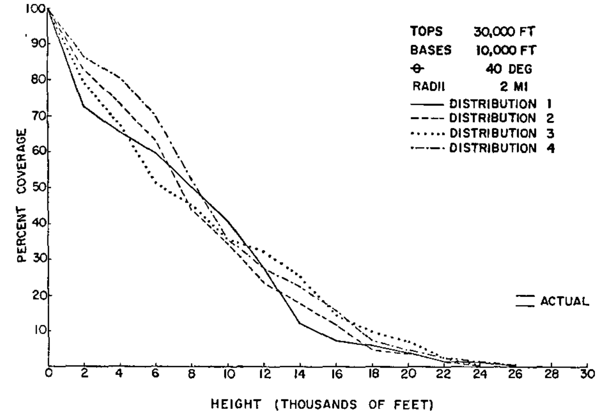

Fig. 12. The percentage of cloud tops indicated at and above the specified heights, runs 1–4.

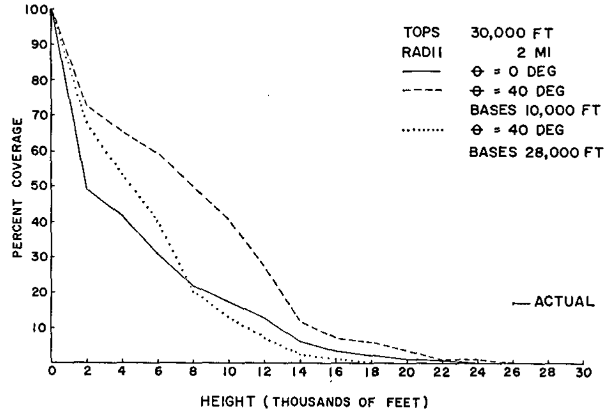

Fig. 13. The percentage of cloud tops indicated at and above the specified heights. The $\theta=0$ values are averages from runs 1 and 13; the dashed line was taken from run 1 and the dotted line from run 13.

Nineteen different computer runs were made; parameters describing the runs are shown in Table 1.

In each run the viewing angles were centered around three nadir angles—0°, 20° and 40° (see Fig. 2). The pseudo-random number generator requires a starting integer. Therefore, if the same starting integer is used in two or more runs, the same distribution of clouds is generated. Since only four different starting integers were used, only four different distributions, numbered 1 through 4 in Table 1, were generated. The first 21 clouds in run 1 were in the same locations as the 21 clouds in run 5.

For each of the runs and viewing angles the percentage of clouds at or above a specified level as judged by the percentage of simulated infrared returns at or below the corresponding temperature was tabulated at increments of 2000 ft. Graphs of these data are shown in Figs. 5–18 and are discussed below.

Clouds with radii of 2, 5 and 10 mi, tops 30,000 ft, and bases 10,000 ft, were used in all four distributions (runs 1–12). This combination of bases, tops, and total coverage of about 19 per cent might represent air mass thunderstorms although bases of such clouds are usually lower than 10,000 ft. The mean indicated cloud heights are shown in Figs. 5–9. Although the average cloud coverage was 19 per cent at 30,000 ft, in no case was a 19 per cent coverage indicated above 14,000 ft. Large cloud radii (Fig. 7) are conducive to clouds being indicated at 30,000 ft and for lower percentages being indicated at low levels than are indicated for small radii. For small radii, large coverages are indicated at low heights, especially at large viewing angles (Fig. 5). Viewing at large angles causes larger indicated coverages at low heights than does viewing at small angles; the viewing angle effect is reversed and not so marked for indicated coverages at high elevations (Figs. 5–7).

The distribution of infrared measurements varies with the (random) cloud distribution even though all other parameters are the same. This variability is exhibited in Figs. 10–12 for cloud radii of 2 mi. The range of indicated coverage at any altitude seldom exceeded 6 and 7 per cent for viewing angles of 0° and 20°, respectively; the variability was somewhat greater for the 40° viewing angle, the range being 10 to 15 per cent. However, a comparison of Figs. 10–12 reveals that the difference between the curves in Fig. 5 is due mostly to viewing angle and not to extremely large dependence on the particular random distribution of clouds.

The vertical extent of the cloud elements has a considerable effect on the indicated coverages at large viewing angles. The comparison of the results of runs 1 and 13, graphed in Fig. 13, reveals this effect. At a 40° viewing angle, clouds only 2000 ft thick gave returns indicating 20 per cent coverage at and above 8000 ft, while clouds 20,000 ft in vertical extent gave returns indicating 50 per cent coverage at and above that level.

Runs 14–16 were made with cloud conditions that

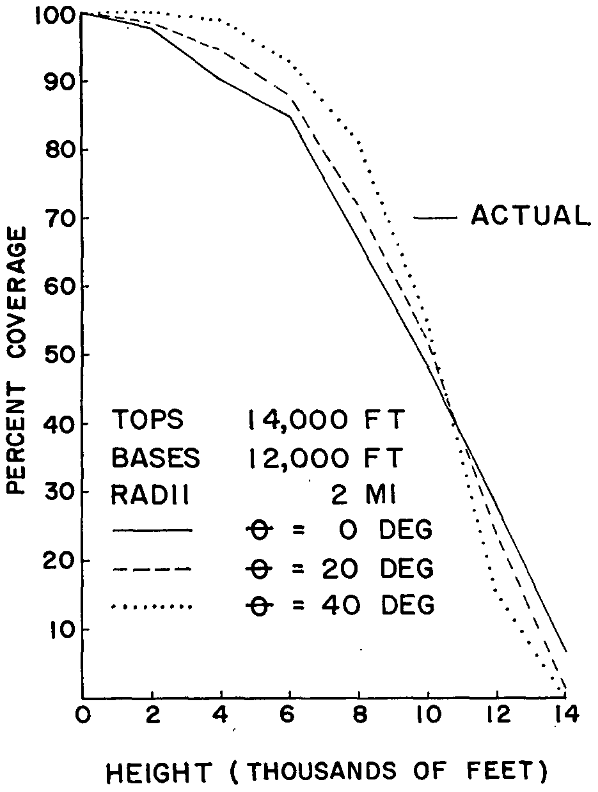

FIG. 14. The percentage of cloud tops indicated at and above the specified heights, run 14.

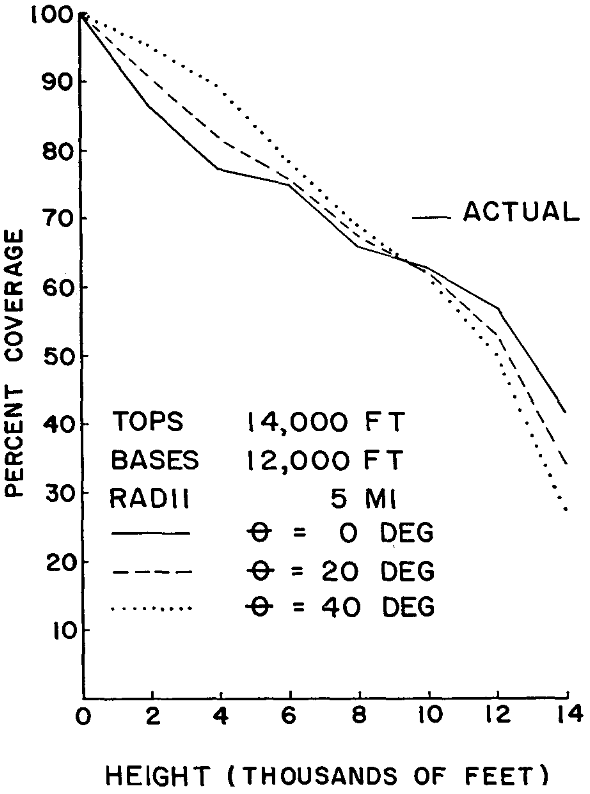

FIG. 15. The percentage of cloud tops indicated at and above the specified heights, run 15.

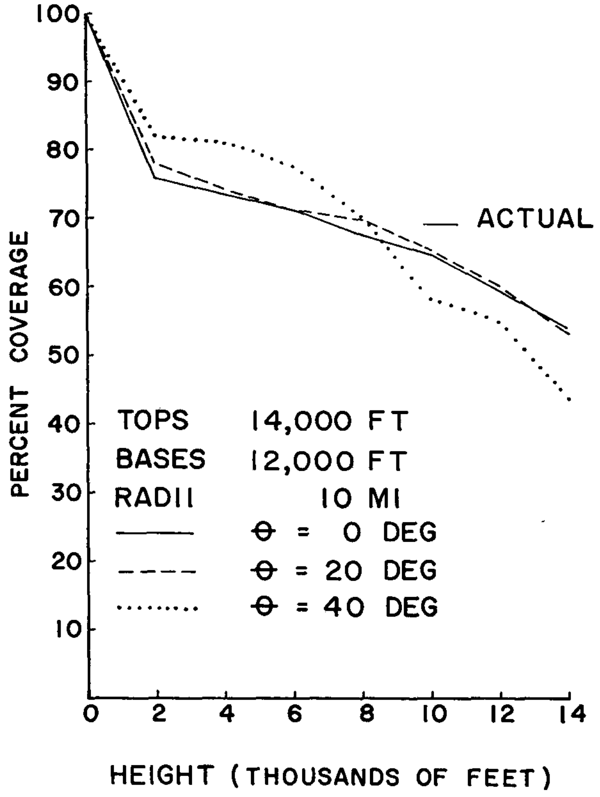

FIG. 16. The percentage of cloud tops indicated at and above the specified heights, run 16.

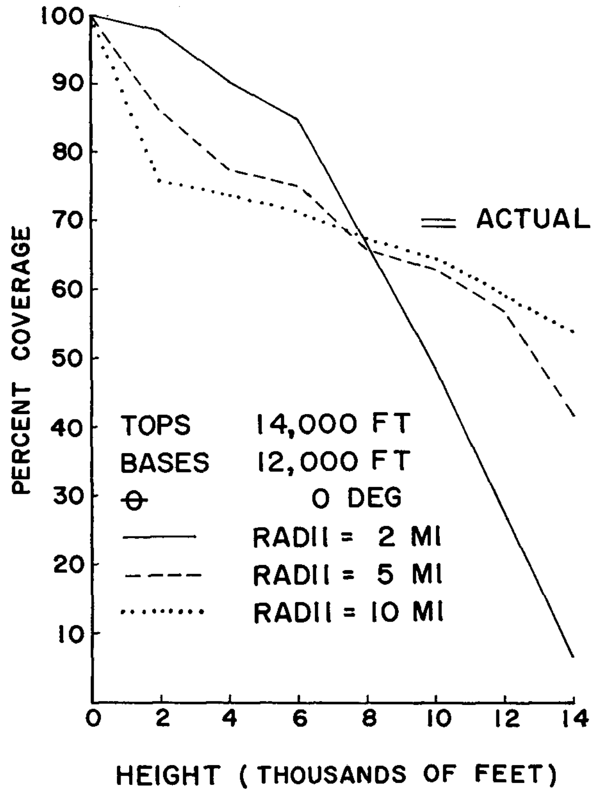

FIG. 17. The percentage of cloud tops indicated at and above the specified heights, runs 14–16.

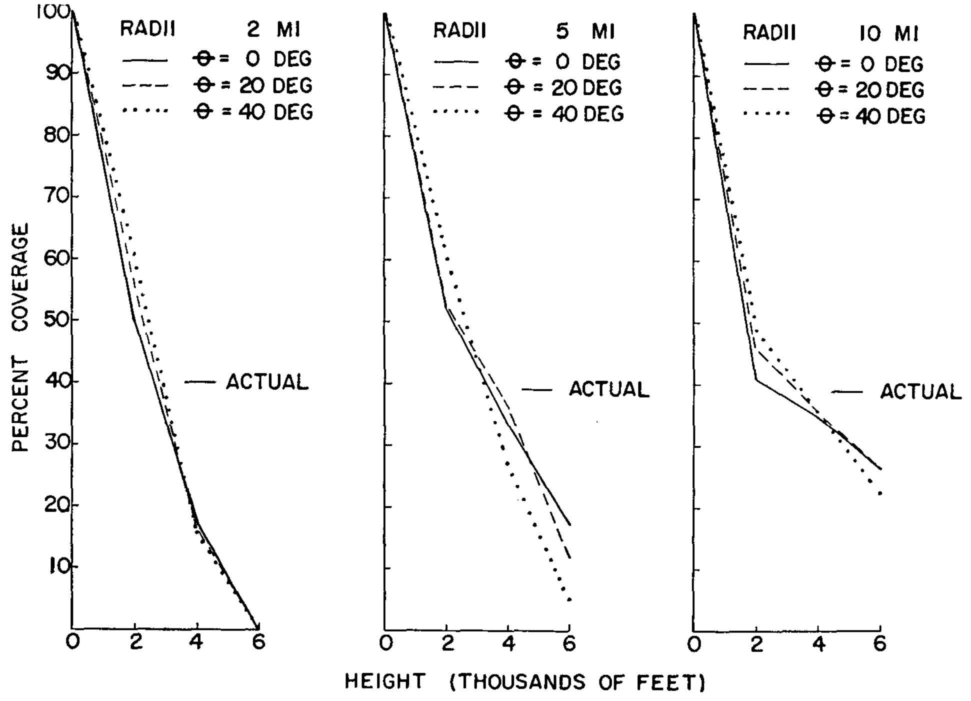

FIG. 18. The percentage of cloud tops indicated at and above the specified heights, runs 17–19. The cloud tops were 6000 ft and bases were 2000 ft.

might be typical of an altocumulus layer; tops 14,000 ft, bases 12,000 ft, and 70 per cent total coverage were specified. The results are shown in Figs. 14–17. Since the clouds were only 2000 ft thick there was not a great deal of viewing angle dependence. Small cloud elements were very deceptive; greater than 90 per cent coverage was indicated at and above 4000 ft while only about 20 per cent was indicated at and above 12,000 ft. Larger elements gave more realistic returns but perhaps small elements are more typical of a broken middle cloud deck than large elements except at the edge of large cloud shields. Middle cloud elements only a few hundred feet in diameter are many times observed. The return from 70 per cent coverage of such small elements at a nadir angle of 0° would indicate nearly 100 per cent coverage at 10,000 ft and none at 12,000 ft and above; the coverage would be incorrect by 30 per cent and the tops by 4000 ft.

The cloud conditions specified for runs 17–19 were somewhat like what might be observed in the subtropics over the oceans—bases 2000 ft, tops 6000 ft, and 40 per cent total coverage. The vertical temperature distribution was the same as for all other runs. The results are shown in Fig. 18. Again the viewing angle effect was not large which was due in part to the relatively small vertical extent of the clouds and in part to their close proximity to the ground. The dependence on cloud element size is still marked. Only 16 per cent coverage at and above 4000 ft was indicated for elements of 2-mi radius, while 35 per cent was indicated at and above that height for elements of 10-mi radius.

4. Conclusions and possibilities for operational use

The effects the size of cloud elements and the viewing angle have on the distribution of measurement values and, hence, cloud top height and per cent coverage inferences have been demonstrated for some hypothetical, but perhaps typical, cloud conditions. It has also been shown how these effects can vary with vertical cloud extent.

When the individual elements were slightly smaller than the spot at zero nadir angle few if any returns indicated the true cloud top height even though clustering of individual elements could give cloud masses larger than the spot. When the individual elements had areas of four and sixteen times the size of the zero angle spot, the inferred per cent coverage at the actual cloud top height was between about 15 and 50 per cent and 35 and 70 per cent, respectively, of the actual coverage. These values tended to be larger for smaller viewing angles and for larger actual coverages.

The heights at which the actual amount of coverage was indicated were about 20 to 55 per cent of the actual cloud height. This indicated height tended to be slightly higher for larger viewing angles and actual coverage. However, if the tops could have been inferred from the few returns indicating that correct height or by other means, the actual coverage at that level could have been determined to within 7 per cent for most cases from the coverage indicated at one-half of the actual height. Conversely, though, if the per cent coverage were known, possibly from satellite pictures, the height could not have been determined to within several thousand feet by using the 50 per cent or any other single factor.

In nature cloud conditions are usually much more complicated than those studied here. Clouds may have distinct non-random patterns over the area being considered and large cloud masses and large clear spaces will give a more realistic distribution of returns than small cloud elements more or less randomly spaced. A cloud shield may cover all or a portion of an area and the tops slope upward in some direction. While the measurements from this shield may be misinterpreted to some extent, the general character of the cloudiness could probably be specified correctly when surrounding areas are considered.

The most troublesome conditions would be the existence of clouds at more than one level or more than one type of cloud with different top heights. But even then some information could be gained from the infrared measurements, particularly if they were used in conjunction with other information such as conventional cloud observations, satellite cloud pictures, or continuity in space and time.

In any case, the meteorologist must be aware of the problems of interpretation of radiometric observations and deal with them as best he can. Automatic processing and intermediate, if not final, interpretation is almost mandatory when such vast quantities of data are available and the computer programs should be sufficiently sophisticated to give the kinds of information the meteorologist needs. This sophistication necessitates analysis concerning and, possibly, adjustment for the effects studied in this paper, namely those connected with imperfect spatial resolution and the limb darkening due to clouds. Such analysis or adjustment could be approached through the study of simulated measurements of many hypothetical cloud conditions as was done for a few in this study.

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