Computer Simulation of Irradiance Measurements from Aircraft

MICHAEL R. POELLOT[1] AND STEPHEN K. COX

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

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ABSTRACT

A computer simulation has been developed to optimize the use of the aircraft platform for the measurement of shortwave irradiances. This model simulates the measurement of radiative fluxes in order to determine the approximate sample sizes required under various conditions of cloudiness.

The simulated required sampling length or averaging distance was found to be inversely proportional to the height of the sensor above or below the cloud field. The magnitude of the averaging distance and the rate of its decrease with height are the result of signal variations on two scales. Near the cloud surface the data have a high variance due to small-scale, large-amplitude variations in the irradiance. These fluctuations are rapidly smoothed as the aircraft-cloud separation increases. The longer period oscillations are not as easily smoothed. When the aircraft is farther from the cloud, large-scale effects become the primary control on the averaging distance.

1. Introduction

A computer simulation of irradiance measurements from aircraft has been developed to optimize the use of the aircraft platform for the measurement of shortwave (0.3–3 μm) irradiances. Specifically this technique was developed for use in the radiation subprogram of the GARP Atlantic Tropical Experiment (GATE) conducted in the summer of 1974. As a part of this subprogram, radiative divergence profiles of the tropical atmosphere were to be derived from aircraft sampling of mean radiative fluxes. Optimal use of allocated aircraft time during GATE depended on the acquisition of sufficient data for calculating accurate mean values without oversampling or undersampling.

The radiation subprogram (Kraus *et al.*, 1973) has stated the desired accuracy of radiative cooling rates as $\pm 0.2°$C day^{-1} for a 6–12 h period over a 200 mb thick layer of the atmosphere. This implies that flux measurements at each level must have a relative accuracy of ± 2.4 W m^{-2} per 200 mb layer. This degree of accuracy may be achieved under heterogeneous conditions through bulk measurements and statistical techniques. The problem which remains is to determine how large a sampling volume is needed to obtain statistically significant mean irradiance values.

There are many factors which affect the relative accuracy of the mean values derived from aircraft data. The largest uncertainty and the factor being considered here is the natural signal variability in the presence of heterogeneous partly cloudly conditions. In this case the shortwave fluxes often vary by a factor of 4 or more. This computer model simulated the measurement of radiative fluxes in order to determine the approximate sample sizes required to meet the accuracy criterion noted above under various conditions of cloudiness.

2. Flux measurement model

The basis of this model is the sampling of finite areal elements through the application of fundamental radiation geometry. The hemispheric radiometers used in GATE have a flat plate sensor surface. Using the reflection of solar radiation from an isotropic plane surface as an example, the geometry of the radiant flux is shown in Fig. 1. The flat plate P is plane parallel to the reflecting surface R. An application of this geometry (Poellot and Cox, 1974) yields the expression

$$\Delta H_p = (\rho H_R dA \cos^2\theta)/(\pi d^2), \qquad (1)$$

where ΔH_p is the contribution to the irradiance at P from an areal element of the surface dA, ρ is the relative reflectivity of dA, H_R is the irradiance incident at the surface, θ is the nadir angle and d is the distance between dA and P. The total irradiance at P is the integral sum of ΔH_p for all dA for $\theta=0$ to $\theta=\pi/2$ over all azimuth angles $\phi=0$ to $\phi=2\pi$. This integral expression may be used to calculate the irradiance at any point as the sum of the contributions from a plane array of finite areal elements, such as a cloud field. For a point above cloud top, reflected shortwave radiance is considered and the elements are assigned

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[1] Current affiliation: Department of Aviation, University of North Dakota, Grand Forks 58202.

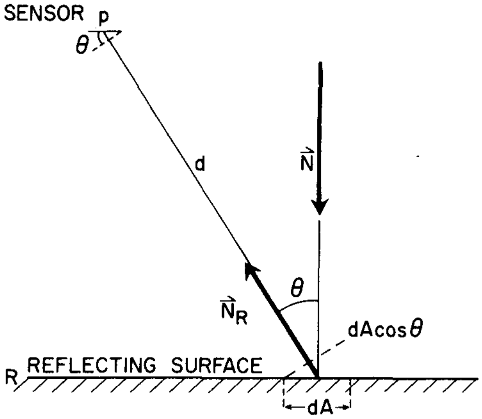

FIG. 1. Geometry of irradiance above an isotropic reflector.

relative values of reflectivity. Between-cloud elements are given a value corresponding to the reflectivity of the underlying surface and atmosphere. For the simulation of downward irradiance observed from below cloud level, transmitted radiances are assigned for the cloud and clear sky areas. The discussion in the remainder of this section will refer to the above-cloud case.

One of two assumptions made here is that all of the areal elements lie in the same plane. This is reasonable for the cloud types being studied, particularly when the sensor is considered to be on the order of 300 m or more from cloud top. It is also assumed that the anisotropic effects of the clouds are negligible, provided that the measurements are made at low solar zenith angles. Salomonson and Marlatt (1968) presented the anisotropy of stratus clouds in terms of relative anisotropy. This is a measure of the error in the albedo which would result if anisotropic effects are ignored. For a solar zenith angle of 17–18°, the relative anisotropy as a function of radiometer nadir angle θ and relative azimuth Ψ is shown in Fig. 2.

Recently, McKee and Cox (1976) calculated distributions of scattered shortwave radiance for simulated cumulus clouds of a cubic shape. For both small and large solar zenith angles, the angular distribution of radiance exiting the cloud top is similar for the cubic cloud and the layer-type stratus cloud. This allows the results of Salomonson to be applied in the following discussion.

As viewed from an aircraft flying over a uniform cloud deck, the anisotropy would appear as a bright spot off to one side. In this instance, the anisotropic effect would bias the mean value of the reflected radiation, but the convergence of the cumulative mean and hence the optimal sample size would remain virtually unaffected.

Over partly cloudy conditions, anisotropic effects would be greatest in two separate cases. One is if the maximum of anisotropy is centered over a cloud while the aircraft is also over a cloud. Ignoring the anisotropy here would cause an underestimate of the peak values of the sample time series to be made. The second case would find the aircraft centered over a clear area while the "bright spot" again covers a cloud. An assumption of isotropy here would lead to an underestimate of the time-series minima. If these two cases are equally likely to occur, the effect of the anisotropy again is to bias the mean, but leave the convergence time virtually unaffected. Thus, for small solar zenith angles, the assumption of isotropy for our purposes is valid.

These anisotropic effects could be included in the model if desired for a different application. Empirical observations like those of Salomonson and Marlatt may be developed into a table or matrix of anisotropic factors (Sikula and Vonder Haar, 1972). This matrix would then be applied to the simulated cloud field to adjust the reflectivity values for the anisotropy.

The projection of a hemispheric field of view on a plane surface is a circle with an infinite diameter. This diameter must be reduced to a usable size, which requires that the 2π steradian field of view be truncated at some nadir angle $<90°$. A cutoff angle of $\theta' = 83°10'$ was chosen as optimal. This allowed a substantial reduction of computer time while still retaining 98.6% of the incident radiant power.

In the simulation the cloud fields are stored in a two-dimensional array to maximize use of the core space within the computer and the areal elements are assigned relative reflectivities of integer values between 0 and 7. While some flexibility and resolution

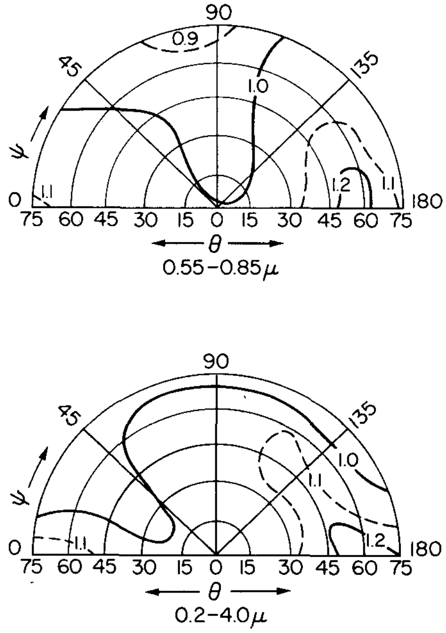

FIG. 2. Relative anisotropy of stratus clouds as a function of relative azimuth (ψ) and radiometer zenith angle (θ), for a solar elevation angle of 17–18° and spectral regions 0.55–0.85 μm and 0.2–4.0 μm (from Salomonson and Marlatt, 1968).

Table 1. Averaging distances for simulated randomly dispersed cloud elements and resulting cloud fields.

Cloud type	Box dimensions x, y	Element values	Array length	Cloud cover	Height z	Averaging distance (number of elements)
Scattered cumulus	1–3	Clear 1 Cloud 4	3000	0.10	3	2250
					6	1400
					10	650
				0.20	3	2250
					6	1400
					10	650
				0.40	3	2350
					6	1900
					10	1500
Broken deck	4–6	Clear 1 Cloud 4	3000	0.60	3	$\sim$3000
					6	2700
					9	2400
				0.80	3	2300
					6	2100
					9	1850
Uniform deck	10–14	37–43	1000	1.00	3	270
					6	105
					10	80
Stratocumulus	80–120	Clear 1 Cloud 4	3000	$\sim$0.80	3	$\sim$3000
					6	2800
					9	2600

is lost through the use of integer values, this is well compensated for by the increase in the possible size of the stored cloud field. The sampling of the cloud array is begun by centering the sensor over one of the areal elements at a simulated vertical distance z from the plane of the clouds. All elements whose center coordinates lie within the field of view are then included in the sample. The relative weight of each element is a function of its distance r from the center of the field of view. For a fixed z, these weights need only be calculated once and then stored in a one-dimensional weighting array $W(r)$. Subsequent samples are calculated by shifting the center point of the field of view and then applying $W(r)$ to a new set of elements. The propagation of the field of view simulates aircraft motion.

The framework has thus been set up for sampling a theoretical cloud field through the application of a geometric weighting array to an array of numbers representing reflected radiances from cloud elements. The simulated height of the sensor above the cloud field is changed by adjusting the size of the field of view and recalculating the weighting array.

Two methods of storing cloud fields were devised to simulate the cloud types being studied. The first utilized a direct input of the simulated cloud segment coordinates and their reflectance values. Cloud types processed for the GATE using this method included organized "street" cumulus and cloud bands. Since these types were assumed to be uniform and repetitive in nature, only a limited number of bands and streets had to be stored and sampled. The resultant data series was then iterated to produce a sample of any length.

The second method used an internal random routine for generating and storing the positions and reflectivity values of the segments. The essence of this technique was to allow three parameters to vary randomly within prespecified ranges: the dimensions of the simulated cloud or clear rectangles, the brightness value assigned to the rectangle and the ratio of cloud to clear areas. This random routine facilitated the rapid storage of very large arrays while eliminating any bias in the positioning of the clouds. Tropical cloud types simulated in this manner were organized trade cumulus, uniform cloud decks, broken decks and stratocumulus "closed cellular convection."

The result of sampling the simulated array is a time-series of relative irradiances x_i. This is the raw data set to be analyzed to determine the optimal averaging distance. The averaging distance is defined by the number of samples required to yield a mean irradiance value over a cloud field that is precise to within $\epsilon\%$ at an approximate 99% level of confidence. The $\epsilon\%$ precision is attained by observing the cumulative mean $\bar{x}_t$ of the time series relative to the true mean μ. Although $\bar{x}_t$ may oscillate about μ, in time it converges to μ. An error interval about μ is defined by $\mu+\epsilon$,

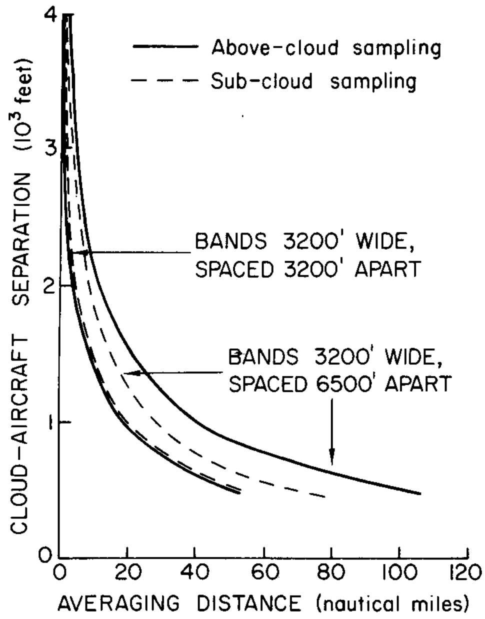

FIG. 3. Averaging distance for cloud bands as a function of cloud-aircraft separation.

where $\epsilon = e\mu$. The point in the time series at which the cumulative mean falls and stays within the error interval gives the required sample size.

The approximate 99% level of confidence is a constraint which is applied to the averaging distance to insure that the sample size will be sufficient for 99% of all the cases expected. For a given cloud field, different averaging distances may result if the cumulative mean is started at different points in the time series. This is due to the strong influence on the characteristics of $\bar{x}_t$ by the initial values of the sum. If $\bar{x}_t$ is calculated for 100 distinct starting points distributed throughout the time series, the approximate 99% level of confidence is represented by the second largest averaging distance. This value, however, may vary in the random cloud case for different arrays having the same characteristics. To maintain the high level of confidence, a number of similar cloud fields must be generated and sampled by changing the initial random number in the program. The approximate 99% level is held by selecting the largest averaging distance of these cases.

3. Results and conclusions

Optimal use of aircraft time allocated for radiative flux measurements depends on the acquisition of sufficient data for calculating accurate mean values without oversampling or undersampling. This model was used to simulate the measurement of radiant fluxes to determine the approximate sample sizes required under various conditions of cloudiness.

This sample size or averaging distance was found, in general, to be inversely proportional to the height of the sensor above or below the cloud field. This is due to a smoothing of the signal by the instrument as the diameter of the projection of its field of view increases with height. The magnitude of the averaging distance and the rate of its decrease with height is the result of signal variations on two spatial scales. Near the cloud surface, small-scale, large-amplitude changes in irradiance give the data a large sample variance. This must be reduced by increasing the sample size. As the height difference between the aircraft and the cloud surface increases, these high frequencies are rapidly filtered by the instrument. Further from the cloud, large-scale changes in the cloud properties become the dominant effect. These oscillations are not as easily smoothed and the averaging distance does not decrease as quickly with height. The large-scale effects are thus the overriding control on the averaging distance.

For GATE, specific cloud types were analyzed and averaging distances computed to obtain sampling times consistent with the radiation subprogram accuracy requirements. Table 1 lists the ranges used for the various input parameters according to cloud type. As a partial explanation of this table, consider an aircraft sampling the upward shortwave irradiance above a broken cloud deck. For the simulated randomly dispersed cloud deck a resolution of 100 m and x, y box dimensions of 4–6 are equivalent to cloud variations on the order of 0.5 km. The element values simulate a cloud reflectivity four times that of the underlying surface and atmosphere. This cloud field was stored in an array 3000 elements long. If 0.8 of the total area beneath the aircraft is covered by cloud and if the plane is 600 m above the cloud surface, this would require a sampling distance of 210 km for an accurate mean value. At an air speed of 100 m s^{-1}, this would be a sampling run of 35 min. Similar logic applies to other applications of the tabular values. These results were compiled into a series of graphs to permit a real-time decision on aircraft sampling altitudes and distances, and to assist in the subsequent analysis of the data (Poellot and Cox, 1974). A sample graph is shown in Fig. 3. The results of this irradiance measurement simulation could also be applied to the time series of surface observations using the motion of the clouds relative to the stationary sensor.

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