# Reply

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The comments of Twomey are helpful in understanding the complexities associated with interpretation of remotely sensed radiation data to infer cloud microphysical parameters. We are in general agreement with several of the points raised by Twomey. However, we feel it necessary to give some clarification to the discussion of the remote sensing procedure presented in Curran and Wu (1982, hereafter CW82) and to mention the significance of Figs. 10 and 11.

First we will address Twomey's comments concerning our conclusions. In CW82, several complications were considered which might cause misinterpretation of the observations. One complication considered was the effect of the ice particle density on the particle absorption coefficient. Twomey comments that the single scattering albedo of inhomogeneous bubble filled ice is different from the single scattering albedo of homogeneous ice particles due to modified internal scattering and absorption. Following Twomey's arguments it appears that ice particles with internal scattering mean free paths only slightly smaller than the particle dimensions will have a single scattering albedo less than that of a homogeneous particle. Such decreased single scattering albedos would produce cloud reflection functions smaller than those of homogeneous ice particles. This does not agree with the large reflection functions observed. Particles with very short internal scattering mean free paths (requiring large bubble number densities and/or large bubble cross sections) would increase the single scattering albedo above the homogeneous ice value in better agreement with the observations. However, such an explanation should also be accompanied by some evidence supporting the existence of bubble filled ice at these cold temperatures. Diagrams of ice crystal habitat versus temperature, as reviewed by Pruppacher (1981), indicate the solid column habitat is commonly found at temperatures lower than −22°C. Unless there is sufficient justification, we consider the inhomogeneous ice hypothesis interesting in terms of its radiation transfer, but not applicable to the situation presented in CW82.

Second, we will address Twomey's comments on the disparity between the theoretical calculations and observations. Before giving a general discussion of this matter we feel that some discussion of our Figs. 10 and 11 is needed. Fig. 10 of CW82 displays curves generated from a doubling radiation transfer procedure simulating the 1.61 $\mu$m reflection function. The particular geometry used in the radiation calculations is identified in the figure. Two curves are shown for each phase with two different particle size distributions. The same pair of particle size distributions were used in each phase merely to illustrate the effect particle size distribution has on the reflection functions at the two wavelengths. The two curves shown for each phase are representative of a family of curves which are dependent upon the particle size distribution. As mentioned in CW82, for most cases, interpretation of the observations at 1.61 $\mu$m and 0.83 $\mu$m in terms of a single phase and particle size is ambiguous. That is, the observed reflection function pair could be explained either by a cloud composed of very small homogeneous ice spheres or by somewhat larger water droplets. This ambiguity may be alleviated by observations at an additional wavelength (2.125 $\mu$m) which may be considered independent.

Fig. 11 of CW82 is similar to Fig. 10 with the exception that the ordinate is now the reflection function at 2.125 $\mu$m. Observations of a portion of a cloud at two different wavelengths can be used to remove the ambiguity by a technique which seeks the best agreement in interpretation of particle size and phase between the two wavelengths.

The circles placed on Figs. 10 and 11 are observations of cloud reflection functions for the positions identified in CW82. Each circle in Fig. 10 has a corresponding observation in Fig. 11. The precise values for these observations are listed in Table 2 of CW82. The analysis upon which the conclusions were based was applied only to those picture elements in the scene which appear to contain optically thick clouds. This was done to minimize the uncertainties caused by variable ground reflection and to make use of the asymptotic behavior of optically thick clouds. The reflection function for clouds at wavelengths in which the single scattering albedo is less than unity, becomes relatively independent of optical thickness at moderate values of optical thickness. By choosing those cloud obscured picture elements which have large optical thickness, the analysis performed at the near-infrared wavelengths will not be affected by errors made in determining optical thickness. Since each observation is for a different cloud, there is no reason to believe *a priori* that the phases or particle sizes are identical. From these considerations, there is no evidence indicating a disparity between the theoretical calculations and observations larger than the error bars indicated.

We are not in a position to explain the reasons for the disagreement between the radiometric observations of Twomey and Cocks (1982, hereafter TC82) and their predicted radiances. Since a detailed estimate of the uncertainties expected in either the radiometric observations or the predicted radiances was not given in TC82, it is difficult to assess the magnitude of the disagreement relative to the uncertainties. In our opinion geometric effects and radiometric calibration errors could be a major contributor to the anomalous comparison found in TC82.

The radiance measurements presented in CW82 and TC82 were provided by instrumentation which observes at relatively high spatial resolution (70 m resolution in CW82, and somewhat higher resolution for TC82). Two effects related to cloud geometry can be noticed in high resolution data: a sloping surface effect and finite cloud effects. For a sloping cloud top surface the normal to the cloud surface within the instantaneous field of view (ifov) of the instrument may not be parallel to the local zenith. In general, the reflection function for a sloping cloud surface will not compare well with the reflection function calculated for a horizontal cloud layer. To illustrate the effect consider an isotropically reflecting layer. In order to compare reflection function values obtained from theoretical calculations with "observations" of such a layer, it would be necessary to use the actual geometry in correctly calculating the incident solar flux density. For arbitrarily chosen ifov's, it is difficult to know the precise angular position of the normal to the cloud surface. The observed reflection function of the hypothetical isotropically reflecting cloud, based on a surface whose normal is assumed to be aligned with the local zenith, could be corrected for by multiplying by the ratio of the cosine of the solar zenith angle to the cosine of the angle between the sun's direction and the true surface normal. For reasonable geometries, this correction factor is a positive number which can deviate quite substantially from unity.

Although naturally occurring clouds are *anisotropic* reflectors of solar radiation, the effect of increased solar flux density on surfaces inclined toward the sun is easily identifiable in high resolution scanner data. The cloud identified by D in CW82, when the scanner image is expanded, shows a noticeable brightening in the azimuth of the sun (relative to the geometrical center of the cloud) and a noticeable darkening 180° from the sun's azimuth. In addition to slope effects, cloud elements of finite horizontal extent have modified reflection characteristics. Theoretical calculations indicate that the reflection function is larger near the side exposed to direct solar illumination and smaller near the opposite side. These geometry dependent effects contribute to the deviations found in comparing high resolution observations of cloud tops to calculations.

It has been our experience that accurate radiometric calibration of narrow band radiometers for either aircraft or spacecraft applications is quite difficult (see Curran *et al.,* 1981). Laboratory radiometric sources presently available for calibration have an expected spectro-radiometric uncertainty of no less than ±3%. This uncertainty is compounded by the non-laboratory environment in which the radiometers are placed. The effects of temperature dependent detector electronics, condensation on optical surfaces and unknown additional sources of error make determination of instrument accuracy very difficult. In addition, tables of the spectrally dependent solar flux density have an absolute accuracy of ±2% in the spectral region of interest (see Labs and Neckel, 1968). These various sources of uncertainty contribute to the seemingly large values mentioned in CW82. It should be mentioned in support of the data presented in CW82 that the Skylab radiometer contained an internal source which was useful in relating the in-flight radiometric performance to the pre-flight calibration of the instrument. Although the calibration procedure used in TC82 is apparently different than that outlined above (use of a reflectance target illuminated by solar irradiance), the absolute accuracy is not expected to be any greater than CW82. Since the comparisons presented in TC82 are between absolute quantities which can be effected by systematic biases, and since the degree of agreement or disagreement is important, an explicit and accurate accounting of all errors should be given. In view of the accumulated uncertainty caused by geometry and calibration errors and the expected uncertainty in the *in situ* observations due to spatial inhomogeneities of cloud parameters from which optical thickness and particle size were derived, the magnitude of the disparity in TC82 is difficult to assess.

The geometry involved in the observations presented by Rozenberg *et al.* (1974) is somewhat different from the geometry of CW82 and TC82. The instrument aboard the Kosmos 320 satellite had a spatial resolution at the cloud top of approximately 15 km. For most cloud forms observed from satellite, including stratiform clouds, cloud features are smaller than 15 km. Thus the ifov of the Kosmos 320 instrument measures a mean value of the geometry dependent cloud reflection function. In addition, due to the lack of information, it is difficult to compare calibration procedures and solar constant values used by Rozenberg *et al.* (1974) with those used in CW82. It is doubtful that either cloud geometry or calibration will totally account for the small values of reflection function found. The lack of suitable agreement between theory and observations in both TC82 and Rozenberg *et al.* (1974) certainly indicates the need for continued study.

Finally, we agree that a logical development of the remote sensing procedures described in CW82 would include validation of the techniques by comparison of the results of analysis of remote determinations with *in situ* determinations of the same parameter. However, this procedure was not available to us at the time of the Skylab observations. Furthermore, the data appeared to be of sufficient scientific potential that detailed analysis was performed prior to either remote sensing technique development or validation. We appreciate the comments of Twomey. The discussion of the strengths and weaknesses of comparing cloud radiance observations with radiation transfer calculations is useful because of their importance in understanding cloud/radiation processes.

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