Comments on "Skylab Near-Infrared Observations of Clouds Indicating Supercooled Liquid Water Droplets"

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The recent findings of Curran and Wu (1982, hereafter CW82) merit further discussion.

Rozenberg *et al.* (1974) and Twomey and Cocks (1982) have already reported serious disparities between measurements and theory in the case of cloud reflectances in the near-infrared—discrepancies which must be resolved before the attractive possibilities of such measurements for remote sensing of cloud properties can be realized. In the case of Twomey and Cocks, detailed cloud microphysical measurements were made in conjunction with the optical measurements, and the measured reflectances simply did not agree with those computed from the microphysical data and optical constants (or, stated in the converse, drop sizes inferred from the optical measurements were substantially different from those found *in situ* by direct measurement; composition was assuredly liquid, so the composition was not an issue).

CW82 results provide another example where reflectance measurements did not agree with theory, at least when the expected composition (ice, the clouds being close to −50°C) was postulated. Up to this point, we take no issue with CW82, but we do question their next step: concluding that the clouds, even though extremely cold, contained *liquid* water droplets. To support such a contention, it would be necessary to show that measured reflectance values agreed, within plausible error limits, with computations for the postulated composition, liquid water. That, however, was not done: Figs. 10 and 11, which are the pivotal elements in CW82 reasoning, certainly show disagreements between the observational data (circles) and computations for ice (broken curves), but the data points do *not* all lie between the solid lines bounding the behavior pattern for liquid water—in fact, individually they range from close to the lower curve for ice to the upper curve for water. By permission, Figs. 10 and 11 of CW82 are reproduced here as Figs. 1 and 2. Furthermore, any reasonable line drawn through the data points would evidently have a slope considerably different from that exhibited by any of the ice or water reference curves.

In summary, it would appear that the disagreement between measured reflectances and those computed for a liquid composition is still substantial. The fact that it is less than that obtained when ice was assumed is hardly the point. A more objective conclusion would be: computations did not agree with measurements, irrespective of which possible composition was used.

At the time of writing, no satisfactory explanation is available for the discrepancies between theory and measurements for clouds *known to be liquid water* [as was the case in Twomey and Cocks (1982)]. If some kind of anomalous absorption is responsible [as Rozenberg *et al.*, 1974 (*loc. cit.*) suggested], there is no reason to suppose that it would not also take place in an ice cloud. Quite apart from that unproved suggestion, however, it is important to note that the uncertainties associated with ice are much greater than is the case with water: ice crystals are nonspherical, usually irregular, and the interior ice is almost never transparent because of irregularities, crystal boundaries, air bubbles, etc. It is well-known that the size-dependence of single-scattering albedo $\bar{\omega}_0$ is quite well described (for spherical drops or particles with radius $a \gg$ wavelength λ) by the simple geometric optics result (Bohren and Barkstrom, 1974)

$$(1 - \bar{\omega}_0) = 0.85\,ka,$$

k being the absorption coefficient of the bulk material. The origin of the above formula lies in the fact that, for a non-absorbing, uniform body of given geometry, the internal rays travel a variety of path lengths through the body before eventually emerging and that for a given shape this distribution scales with the dimensions of the body, *i.e.*, if p is the probability that an emerging photon has traveled a total path between x and $x + \Delta x$ within the body, then if the linear dimensions of the body are doubled, that same p will give the probability for paths lying between $2x$ and $2x + 2\Delta x$. The distribution is therefore invariant with size, if expressed in terms of x/a rather than x (a being any suitable length dimension, *e.g.*, radius, cube side

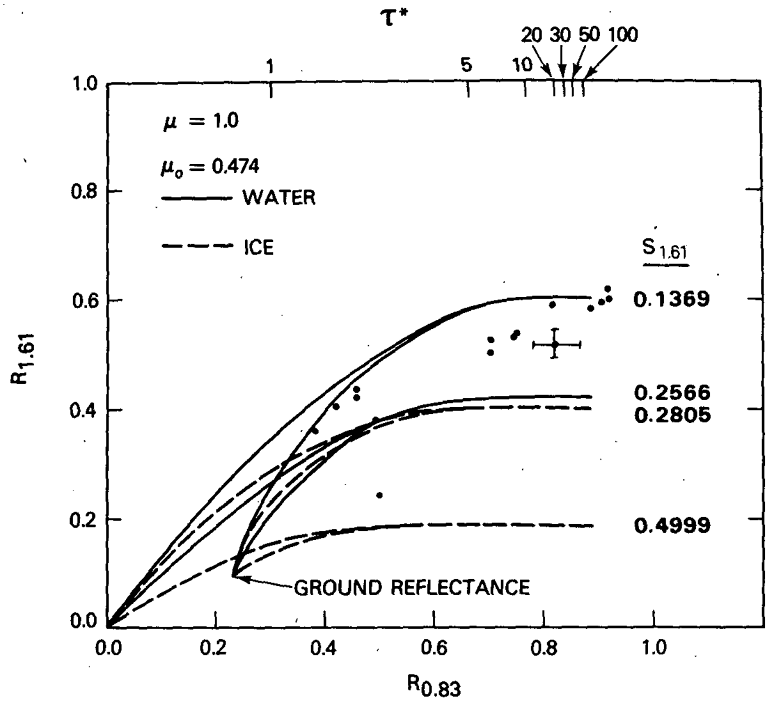

FIG. 1. Cloud reflection function at 0.83 μm vs 1.61 μm. The data points from Table 2 of CW82 are shown as black dots whose radii are approximately equal to the root mean square of the variance for the picture elements sampled. The absolute error is drawn on one sample point and is representative of each of the sample points. (Reproduction of Fig. 10, CW82, courtesy of Robert J. Curran and Man-Li C. Wu.)

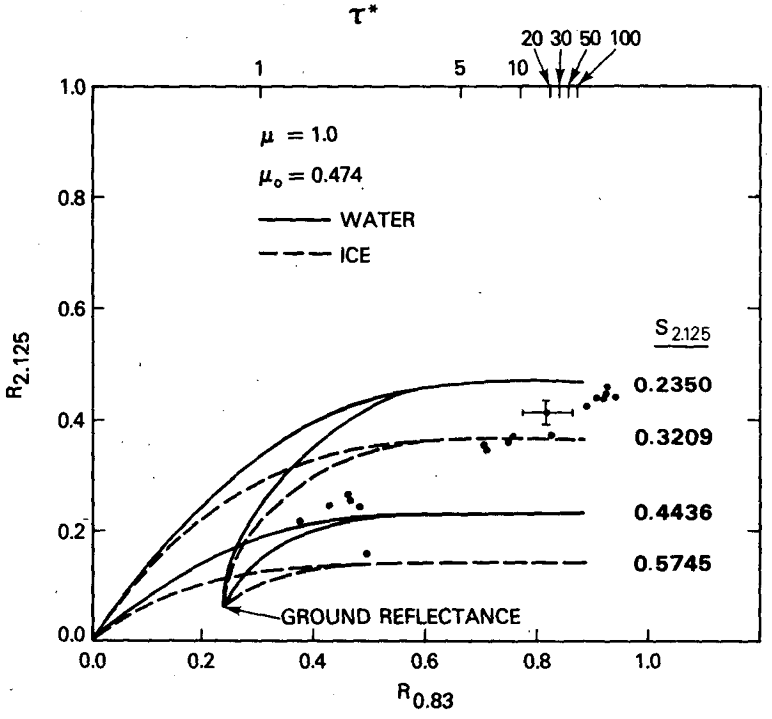

FIG. 2. As in Fig. 1, except for the reflection function of 0.83 μm vs 2.125 μm. (Reproduction of Fig. 11, CW82, courtesy of Robert J. Curran and Man-Li C. Wu.)

length, etc.). When absorption is present, an additional factor e^{-kx} appears, so the probability of eventual emergence, now <1, is

$$\int_0^\infty e^{-kx} p\left(\frac{x}{a}\right) d\left(\frac{x}{a}\right).$$

For $ka \ll 1$ (*i.e.*, weak absorption) the probability of absorption (*i.e.*, $1 - \bar{\omega}_0$) is given by

$$1 - \int_0^\infty e^{-kau} p(u) du \approx ka \int_0^\infty up(u) du,$$

establishing the approximate linear dependence of $1 - \bar{\omega}_0$ on particle dimension—*i.e.*, regardless of shape, we have the geometric optics result

$$1 - \bar{\omega}_0 \propto ka.$$

The role of a arises because the possible photon paths scale with a. Suppose now that inhomogeneities or inclusions are present in the material (previously assumed uniform), which by scattering can change the direction of propagation in a random manner, allowing some photons to travel shorter overall paths and others longer paths than before. If the fraction of photons traveling undeflected from surface to surface is small, *i.e.*, if the body is translucent rather than transparent, then the unique scaling role of the body's dimension a is no longer maintained. A further length scale comes into play, namely, the mean free path length between scatterings, and there is no longer any assurance that the linear proportionality between absorption and the product of particle dimension and bulk absorption coefficient will hold, even approximately. This is particularly true for weak absorption, and simple ray-tracing calculations in the spirit of Bohren and Barkstrom's (1974) geometric optics, treatments show that small absorptions can be grossly increased by internal scattering when the mean-free path is comparable to or less than the dimensions of the particle. When the mean-free path is very short, absorption decreases again, and in the mathematical limit of zero mean-free path, the absorption tends to zero (since the rays then fail to penetrate into the interior of the particle).

Since ice is manifestly nontransparent in most of its manifestations, it seems very possible that complications arising from internal scattering in ice particles gave rise to CW82 results, in which case their conclusion might better have been that the cloud particles were not composed of *homogeneous transparent* ice.

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