Comments on "The Parameterization of Radiation for Numerical Weather Prediction and Climate Models"

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In a recent review article, Stephens (1984) discusses the various aspects of radiation parameterization, primarily for the benefit of those dynamically oriented researchers in the global modeling community who are not very familiar with the intricacies of radiative transfer. We commend him on this effort, but we are concerned that, despite a caveat in the last paragraph of his paper, he inadvertently gives the impression that an estimate of the vertical liquid water path (LWP) in a cloudy layer can be used to obtain the shortwave and longwave optical properties of the layer, based on some reasonable assumptions regarding the drop size distribution. This would imply that if (if!) general circulation models (GCM) can, in principle, compute the mean LWP from the water balance equations, then there is a consistent and "correct" method available to determine the optical properties of a cloudy grid box. Unfortunately, subgrid-scale irregularities in the LWP prevent this hope from being realized.

Our concern is with the use of model-generated LWP to compute optical properties representative of a GCM grid box that extends a few hundred kilometers horizontally, and a kilometer or so in the vertical. Any satellite picture shows that cloud cover is not homogeneous on this scale: only a fraction of the area is covered by clouds, and even the cloudy areas appear as varying shades of gray. In fact, cloud cover is not homogeneous even at considerably smaller scales, as can be seen from LANDSAT pictures of areas that appear to be completely overcast in a GOES image. For this reason, the grid-box average LWP is usually much less than the local LWP that would be measured by an aircraft flying in the box. Using NIMBUS 7 SMMR data, Prabhakara *et al.* (1983) inferred maximum grid-box-scale LWPs on the order of a few hundred g m^{-2}, while aircraft measurements commonly show local values more than ten times larger (e.g., Stephens, 1978). A successful method for predicting LWP in a GCM should give grid-box average values comparable to those reported by Prabhakara *et al.*

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A simple exercise can show that vastly different optical properties can be obtained by distributing a given amount of liquid water over a grid box in different ways. Consider the three possibilities shown in Fig. 1. In Case A, the entire cloudy layer has a uniform plane-parallel LWP of $\bar{W}$ g m^{-2}; in Case B, 20% of the area has a uniform plane-parallel LWP of $4\bar{W}$ g m^{-2}, while 80% of the area has a uniform plane-parallel LWP of $0.25\bar{W}$ g m^{-2}; and in Case C, 20% of the area has a uniform plane-parallel LWP of $5\bar{W}$ g m^{-2}, while 80% of the area has no liquid water. In all three cases, the LWP averaged over the grid box is $\bar{W}$. Obviously the LWP in real cloud fields has an enormously more complicated structure than any of those considered here, but our three idealized examples serve to illustrate some of the effects of inhomogeneities in the cloud. We have computed the albedo (diffuse reflectance) and longwave emissivity of the entire layer as a function of $\bar{W}$, neglecting molecular scattering and cloud absorption in the visible and gaseous emission in the longwave. The optical thickness of the cloud in the visible is obtained from Eq. (10a) of Stephens (1978), and the albedo is then simply calculated using the two-stream approximation for an asymmetry parameter of 0.85. The emissivity of the cloud is again based on the methods of Stephens (1978). The computed area-averaged albedo and emissivity, appropriate for a GCM grid box, are shown in Figs. 2 and 3, respectively. The nonuniqueness of the LWP parameterization is apparent. Moreover, as can be seen for the case of $\bar{W}$ = 100 g m^{-2}, the albedo in Case A considerably exceeds the planetary average cloud albedo of roughly 0.50, even though the LWP is really quite moderate in comparison with typical local values as is evident from the range given by Stephens (1978). Inclusion of the absorbing region in the solar infrared would reduce the computed cloudy sky albedo somewhat, but not enough to yield a realistic planetary albedo.

Reasonable values of both the albedo and the emissivity can be obtained for Case A with $\bar{W} \approx 30$ g m^{-2}. However, the retrieved mean LWPs reported by Prabhakara *et al.* (1983) are much greater than 30 g m^{-2} over most of the cloudy regions of the global oceans, and are ten times higher in the Intertropical Convergence Zone. For $\bar{W} \approx 100$ g m^{-2}, Case B gives realistic

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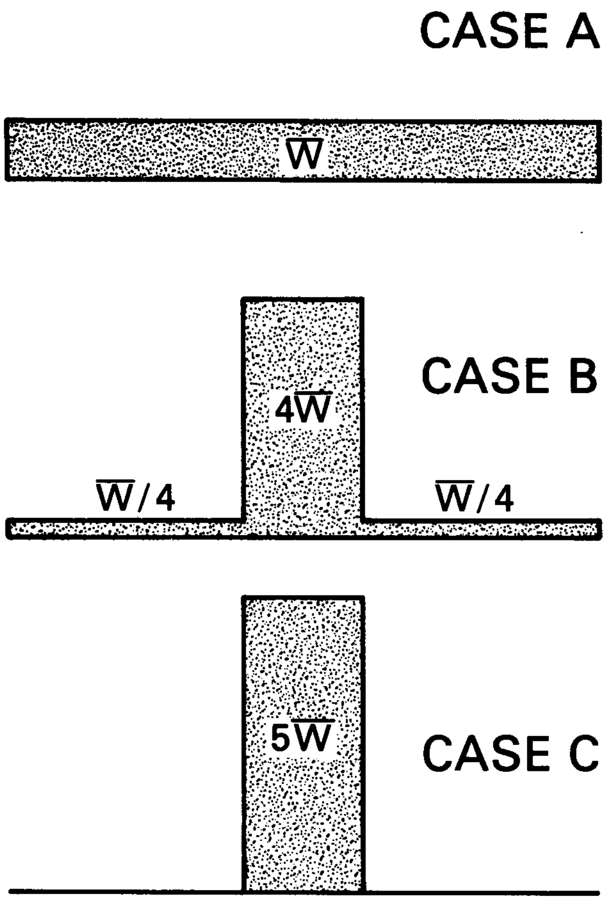

FIG. 1. Schematic illustration of three LWP distributions considered as examples.

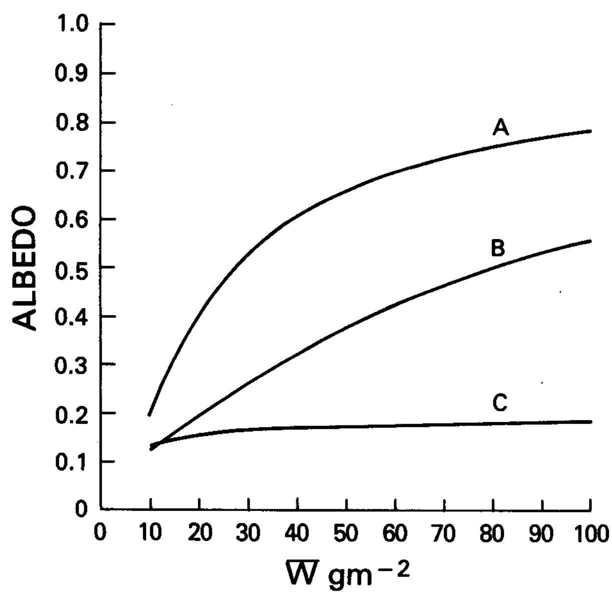

FIG. 2. Albedo as a function of LWP, for each of the three cases illustrated in Fig. 1.

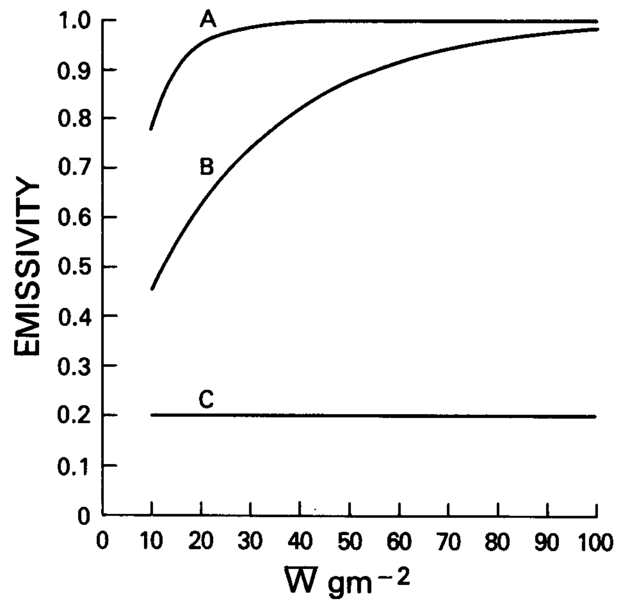

FIG. 3. As in Fig. 2, but for emissivity.

values for the albedo and emissivity. The results of Figs. 2 and 3 may help to explain the "optical depth paradox" mentioned by Wiscombe *et al.* (1984).

In summary, we conclude that a realistic predicted LWP obtained from the water budget of a GCM cannot yield realistic radiative properties without a correction to take into account the spatial inhomogeneity of liquid water. It may be true that the use of cloud liquid water as a predictor of cloud optical properties is essential for GCM studies of cloud feedbacks on climate change (Somerville and Remer, 1984), but the *distribution* of cloud liquid water in the grid box will also be needed to obtain the average optical properties of the layer. Thus, as Stephens (1984) concludes, "it (is) important to parameterize the effects of subgrid-scale radiative transfer on the grid-scale radiation budget. This problem remains as one of the major challenges for cloud-radiation parameterizations."

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