NOTES AND CORRESPONDENCE

Cloud Decoupling of the Surface and Planetary Radiative Budgets

GRAEME L. STEPHENS AND PETER J. WEBSTER[1]

CSIRO, Division of Atmospheric Physics, Mordialloc, Victoria, Australia, 3195

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ABSTRACT

We employ a one-dimensional radiative–convective equilibrium model with multiple cloud layers to demonstrate that the surface equilibrium temperature is highly sensitive to the vertical distribution of effective cloud base heights. It is also demonstrated that the reflected solar flux from an ensemble of cloud layers is independent of the vertical distribution of these cloud layers and is a function only of the total water path integrated in the vertical, a property which also determines the solar radiation reaching the surface. The downward longwave radiation, on the other hand, depends strongly on the effective cloud base height as well as the background water vapor distribution.

It is argued that the longwave radiative transfer processes of cloud tend to decouple the radiative budgets at the top of the atmosphere and the surface. Thus, for a given total atmospheric optical thickness, it is possible to obtain different values of surface temperature under conditions of radiative equilibrium at the top of the atmosphere.

1. Introduction

It is an established tenet that clouds are a critical factor involved in the global climate system. Their importance stems from the fact that of all climate constituents, they possess the potential for producing the maximum changes in the radiative budget overall and in the individual shortwave and longwave components. An increase of cloud, for example, will impart on the radiative budget at the top of the atmosphere (i.e., the *planetary* budget) an increased reflected solar energy but (usually) a substantially reduced longwave emission to space. At the surface, clouds produce the *reverse* effect with an increase in amount, reducing the incident solar radiation together with an enhanced downward longwave flux.

Although the influences of cloud on the individual short- and longwave components of the planetary and surface radiation budgets are reversed, the net effect is the result of the compensation between changes in these fluxes. At the surface, clouds change the ratio of longwave and shortwave radiation, in addition to the production of a possible change in intensity of the total radiant energy.

The extent to which the compensating solar and thermal effects cancel to produce a smaller (or nonexistent) impact on the net radiation budgets is a controversial subject (e.g., Schneider, 1972; Cess, 1976; Ohring and Clapp, 1980; Hartmann and Short, 1980; Cess *et al.*, 1982; among others). A related, but neglected aspect, is whether or not the surface and planetary budgets are effected equally by a given change of cloudiness. While it may be possible to infer certain of the surface radiative fluxes from satellites (e.g., Gautier *et al.*, 1980), the extent to which the planetary and surface budgets are correlated has not been established. The whole issue of whether or not satellite monitoring of changes in the net radiation balance at the top of the atmosphere is indicative of changes in (surface) climate hinges on this correlation.

In order to study the influence of clouds on the radiation budgets separately and on the correlation between the two under conditions of radiative and convective equilibrium, a one-dimensional radiative equilibrium model with convective adjustment is employed. An important factor in establishing whether or not such correlations exist lies in whether or not the vertically integrated emission of longwave radiation from the atmosphere plus surface to space is related in some way to the integrated atmospheric emission of longwave radiation to the surface. In this note we study the effects of cloud height on the radiation balances at the boundaries of the atmosphere and specifically describe the effects of cloud height on the respective integrated atmospheric emissions. We employ different vertically overlapping cloud distributions and examine their effect on both surface temperature and planetary temperature. By employing different vertical distributions of cloud, we decouple the effective emission from cloud top to that from cloud base and thus demonstrate that cloud base height is a more crucial height parameter in the determination of surface tem-

[1] Current affiliation: Department of Meteorology, Pennsylvania State University, State College, PA.

perature. This approach contrasts with those of existing studies which consider the effects of cloud top height (or alternatively, cloud top temperature) on surface temperature by considering a single layer cloud located at specific preassigned levels, thus ensuring a correlation between cloud top and base heights.

2. Model and cloud parameterization

a. *The radiative transfer model*

The radiative transfer model is identical to that described by Stephens and Webster (1981). Briefly, the model includes molecular absorption by ozone and water vapor in the short- to near-infrared spectral regions, and absorption by water vapor, carbon dioxide and ozone in the infrared region as well as the so called "*e*-type" absorption by the proposed water dimer. Shortwave radiative transfer was calculated via a two-flow model (e.g. Stephens and Webster, 1979) which is a simplification of the more complex *n*-flow models usually associated with detailed multiple scattering models.

The radiative (optical) properties of clouds were determined from the parameterizations of Stephens (1978) for water clouds and by the techniques of ice clouds discussed by Stephens and Webster (1981). These parameterizations provide a unique estimate of cloud albedo and emittance given the cloud liquid (or ice) water content and solar zenith angle.

b. *Overlapping clouds*

Multiple cloud layers were treated in the manner discussed by Manabe and Strickler (1964). Clouds were overlapped in nine model layers (from 300 to 913 mb). The mean cloud amount of the entire atmospheric column covered by *n* cloud layers is

$$\bar{A}_c = 1 - \prod_{i=1,n} (1 - A_{ci}),$$

where A_{ci} is the cloud amount of the *i*th layer.

The cloud cover is fixed for all calculations and chosen to be 0.3 for all layers in order to provide an almost totally overcast (96%) cloud cover. The vertical distribution of cloud optical properties can in fact be considered as a convolution of the vertical distributions of cloud amount and of cloud liquid water. A constant value of A_{ci} at all levels therefore allows us to define the vertical distribution of the relevant cloud properties in terms of a single distribution function. The distribution functions chosen in this study are presented in Fig. 1.

As an example, the high cloud distribution (profile 1) is composed of nine juxtaposed cloud layers; the optical depths vary for each layer according to the distribution function. These distributions are taken to represent globally averaged distribution of cloud liquid (or ice) water path in the vertical and, therefore, from the relationships of Stephens (1978), of cloud optical depth. The normalizing factors are chosen such that the vertically integrated optical thickness $\Sigma\delta$ is normalized to specific preset values. The choice of a different value of A_{ci} then amounts to the choice of a different normalization factor for the integrated optical thickness while the choice of a different distribution of A_{ci} corresponds to a distribution of optical thickness different from those shown in Fig. 1. While different distributions could have been employed, those selected for this study (especially profiles 1 and 2) are considered to portray the two extreme limits in cloud distribution.

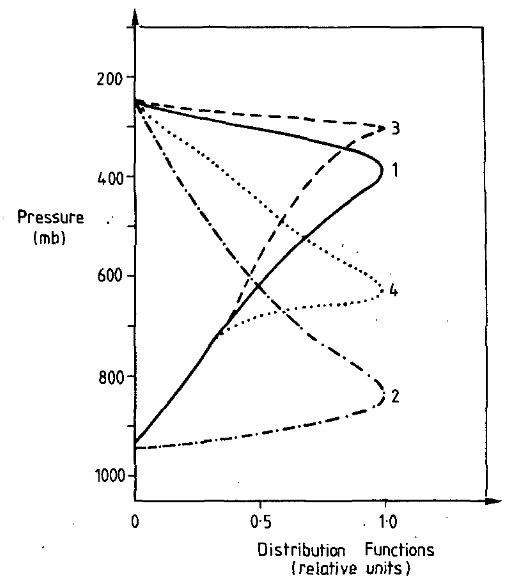

FIG. 1. Four distribution functions assumed for the vertical distribution of cloud liquid water (and hence optical depth).

c. *Convective adjustment model*

The one dimensional radiative equilibrium model with a convective adjustments scheme (ID–RC) has been discussed by Stephens and Webster (1981). The convective adjustment part resembled most other models of this type (e.g., Manabe and Strickler, 1964). Model equilibrium is achieved by forward time marching until energy balance occurs at all levels. The distribution of relative humidity assumes a constant functional form in the vertical following Manabe and Wetherald (1967) allowing feedbacks between absolute humidity and temperature. The radiative transfer calculations are performed at each model layer, the vertical positioning of which is identical to the distribution of Manabe and Möller (1961). "Convective" heating is determined via the convective adjustment scheme of Manabe and Strickler (1964) for which the constant empirical lapse rate of 6.5 K km^{-1} is assumed. A discussion of the appropriate choice of a lapse rate is given by Hummel and Kuhn (1981) where it is suggested that a moist adiabatic lapse rate should be assumed throughout the troposphere. We believe that choice leads to problems in the lower troposphere, where the lapse rate is observed to be closer to dry than moist. For example, in the boundary layer, the moist adiabatic lapse rate is order 4 K km^{-1} compared to an observed 8 K km^{-1}. In the lower troposphere, the moist adiabatic lapse rate increases to ~5.5 K km^{-1} compared to the observed 6 K km^{-1}. As a consequence, we follow the reasoning that unless a hydrology cycle is incorporated into the model (which is probably inappropriate for the simple questions we are raising in this study), a lapse rate should be chosen which is closer to the tropospheric average. In any event, the choice of lapse rate is not likely to alter the results described below, since these results involve comparison between experiments which employ the same lapse rate but different cloud distributions.

3. Results

The ID–RC model was applied to investigate the role of overlapping multiple cloud layers on the thermal structure of the atmosphere. The cloud liquid water path (and thus optical depth) of each of the nine model layers was determined from the distribution functions shown in Fig. 1 and normalized to provide a prescribed value of vertically integrated cloud optical depth of the atmospheric column ($\Sigma\delta$).

For our purposes, we define the equilibrium surface temperature (T_g) as that temperature arrived at by the ID–RC model for a given cloudiness and moisture distribution. The equilibrium planetary temperature (T_p) is the corresponding effective emitting temperature at the top of the atmosphere for the same cloudiness and moisture distribution; ΔT_g and ΔT_p refer to the differences between T_g and T_p for cloudy and clear skies and are shown in Figs. 2a and b as a function of $\Sigma\delta$ for the two cloud liquid water distributions 1 and 2 of Fig. 1.

Figures 2a and 2b indicate the effect of different vertical cloud structures with some vertically integrated optical depth on the surface and planetary temperatures. Profiles 1 and 2 were chosen because they represent high tropospheric and low tropospheric cloud ensembles respectively.

The general feature of the ΔT_g distributions in Fig. 2a is the cooling trend for nearly all values of $\Sigma\delta$ for each distribution. The general cooling effect is also apparent in T_p shown in Fig. 2b. A warming of T_g is only evident for the small vertically integrated total water content clouds ($\Sigma\delta < 5$) of the high cloud distribution. From Fig. 6 of Stephens and Webster (1981) we can see that such values of $\Sigma\delta$ with vertical structures like profile 1 are representative of thin cirrus.

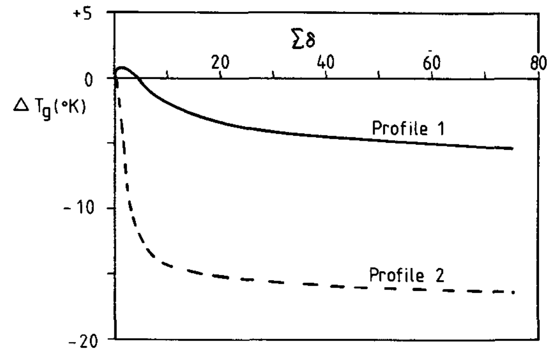

FIG. 2a. ΔT_g as a function of the vertically integrated optical thickness $\Sigma\delta$ for the two vertical profiles of Fig. 1. The solar insolation of 340 W m^{-2}, surface albedo of 0.1, and the mean solar zenith angle of Manabe and Möller (1961) for April were employed in the calculations.

Examination of the T_p curves of Fig. 2b reveals an entirely different character compared to the T_g curves. Instead of the acute sensitivity to the vertical cloud structure, the planetary temperature appears *nearly insensitive to the way in which the optical depth is distributed in the vertical.* This sensitivity is further highlighted in Fig. 3 where, for each of the four distributions of cloud shown in Fig. 1, the surface convective equilibrium temperature is shown as a function of planetary temperature for both $\Sigma\delta = 8$ and $\Sigma\delta = 4$.

4. Discussion

In order to understand the character of the ΔT_g and ΔT_p curves, a number of points regarding cloud optical properties and radiative balances should be stated:

(i) In equilibrium, the net flux at the top of the atmosphere, on the planetary scale, must be zero.

(ii) The relevant cloud optical properties (i.e., cloud albedo and emittance) are functions of *only* liquid water path (and hence optical thickness) and solar zenith angle.

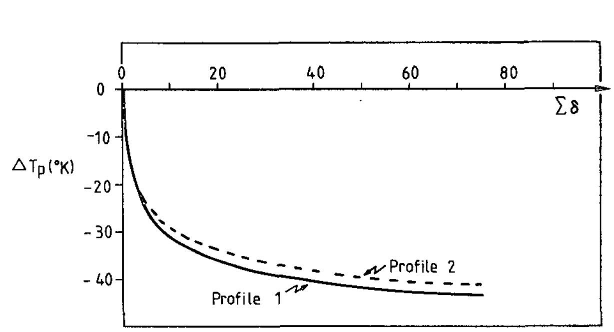

FIG. 2b. As in Fig. 2a, but for ΔT_p. Planetary temperature is defined for a system in equilibrium as $(R_s/\sigma)^{1/4}$, where R_s is the net solar radiation input to the top of the atmosphere.

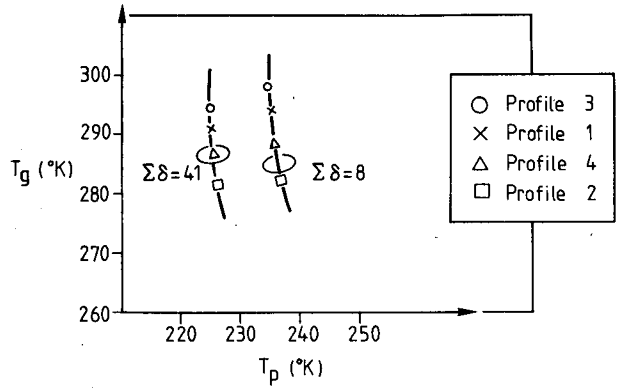

FIG. 3. Surface equilibrium temperature T_g is a function of planetary temperature. Calculations were carried out for the two total optical thickness values shown, but for the vertical distributions shown in Fig. 1. All other conditions are the same as in Fig. 2a.

(iii) As the optical depth of a cloud increases, the cloud adopts the characteristics of a blackbody radiator. As is the case for surface temperature, the critical parameter is the level or temperature from which cloud effectively radiates when viewed from below.

(iv) The cloud albedo asymptotes to some maximum values although at a slower rate with δ (or $\Sigma\delta$) than does ϵ [see Stephens and Webster (1981)].

With (i) and (ii) in mind, it is easy to reconcile the behavior of ΔT_p and its relative insensitivity to $\Sigma\delta$ (when $\Sigma\delta > 20$) and to $\delta(z)$. Simply, for a given solar zenith angle and optical depth δ, the net solar input at the top of the atmosphere is fixed. Thus, at equilibrium, the net outward emission by the atmosphere (σT_p^4) must balance the net inward solar flux so that *planetary temperature is a direct consequence of planetary albedo.* The results shown in Fig. 2b therefore suggest that the reflection of solar radiation to space by cloud is basically independent of the vertical distribution of optical depth (and thus, more or less, of cloud) and depends *only on* $\Sigma\delta$*!* Since cloud albedo asymptotes for large $\Sigma\delta$ (Stephens and Webster, 1981) then so must the planetary temperature T_p.

It is not surprising that ΔT_g appears sensitive to both $\Sigma\delta$ and $\delta(z)$. The surface radiation budget is a function of both the incoming solar and longwave fluxes at the surface. As discussed above, the surface solar flux depends only upon $\Sigma\delta$. The surface longwave flux, on the other hand, depends upon both $\Sigma\delta$ and $\delta(z)$ and at least seemingly, in a paradoxical manner!

One of the critical factors in determining the behaviors of surface longwave flux is the approach of the cloud emissivity to unity. From (iv), above, we have noted that the cloud albedo and emissivity approach their asymptotic values as different functions of $\Sigma\delta$. These different functional forms cause immediate differences in the longwave and shortwave flux relationships with total cloudiness. Considering only the infrared effect (of clouds which are effectively black), one would expect that the equilibrium surface temperature would be colder for higher cloud distributions than for lower cloud distributions simply because the higher clouds radiate at lower temperatures to the surface than lower clouds. In fact, Fig. 3 illustrates the opposite effect. The compensating factor which produces the reversal (the seeming paradox) relates to the increase of atmospheric emissivity with cloud compared to the background clear sky emissivity due to the background water vapor distribution. For example, a cloud residing at low levels within a very moist water vapor distribution will cause little change to the surface temperature (ΔT_g small) because the layer was already relatively black when viewed from below.

The compensating factors are illustrated in the curves of Fig. 4 which were produced by considering various 100 mb thick cloud slabs successively at different levels in the tropical model atmosphere of McClatchley *et al.* (1972). For each layer, the difference between the preset cloud emittance and the background water vapor emissivity [calculated using the appropriate water vapor amount for the layer and the emissivity parameterizations of Rodgers (1967)] was determined. Fig. 4 shows the ratio of this emissivity difference $\Delta\epsilon$ to the water vapor emittance for three different values of cloud emittance. The values are plotted as functions of pressure height. Fig. 4 also shows the ratio of the fourth power of the mean layer temperature under consideration to the fourth power of the surface temperature.

We may summarize Fig. 4 as follows: a cloud increases the clear sky emittance marginally in the lower troposphere but substantially (by more than a factor of 10) in the upper troposphere. This pronounced increase of $\Delta\epsilon$ with height is partially offset by the decreasing cloud temperature. However, according to Fig. 4, the effect of decreasing cloud temperature on the emitted radiation can only be, at the most, a factor of 4. Thus, in relation to Figs. 2 and 3, the effect of increasing cloud base height is an increase in the longwave radiation to the surface thus producing a surface warming effect relative to an atmosphere with lower cloud.

5. Conclusions

Calculations using a simple radiative–convective equilibrium model were performed using multiple overlapping cloud layers. While the results presented cannot be considered full-fledged climatic simulations, since these are strictly possible with only multi-dimensional GCMs, the results do provide new insights into the cloud climate problem. The relevant conclusions deduced from the present study are:

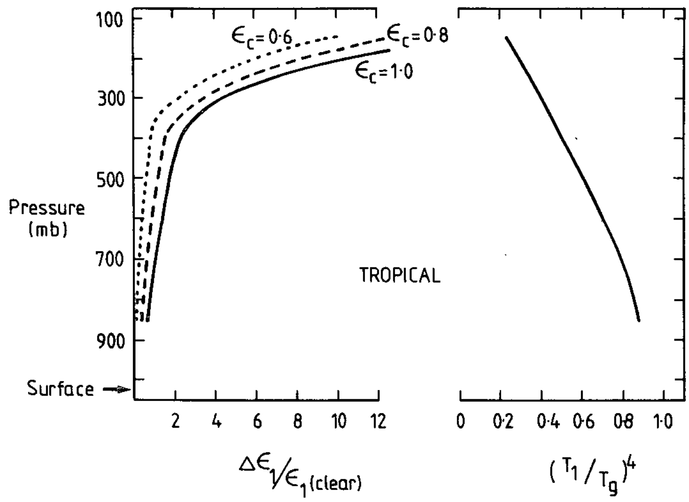

FIG. 4. The relative increase in layer emissivity from clear to overcast sky for the three given cloud emissivities as a function of the mid-pressure of the cloud situated in a 100 mb slab. Also shown (right) is the relative change in the blackbody longwave flux as a function of pressure arising from changing cloud temperature. Curves were deduced for a model tropical atmosphere.

1) A number of studies have already indicated that the cloud base temperature is an important property of the atmosphere in determining the surface energy budget. We have shown in Fig. 2a however, that a more critical quantity is the *effective cloud base temperature* which depends on the *vertical distribution of cloud* [i.e., on $\delta(z)$].

2) The results of Fig. 2b suggest that the net solar flux into the atmosphere is generally insensitive to $\delta(z)$ and therefore, more or less, to the vertical cloud structure. Thus, a sufficiently accurate calculation of solar radiative transfer for simple low vertical resolution models may be possible by specifying only vertically integrated quantities like liquid water path.

3) For a given total optical thickness of the atmosphere, assuming an equilibrium exists at the top of the atmosphere, it is possible, in principle, to obtain different values of equilibrium surface temperature for the same vertically integrated cloud optical thickness (i.e., $\Sigma\delta$) and the same net solar radiation input into the top of the model atmosphere. That is, a whole family of T_{g_i} may exist for distributions $\delta_i(z)$ even if $\Sigma\delta_i$ is constant; T_g is controlled by both the incident solar radiation at the surface (a function of $\Sigma\delta$) and the downward longwave radiation [a function of $\delta(z)$]; T_p is set by $\Sigma\delta$ alone. This conclusion is independent of the inherent assumptions contained in the present study (such as the cloud overlap treatment, choice of lapse rate, etc.) and is based on the physical effects of longwave radiative transfer processes in cloud which act to decouple the radiation budgets at the boundaries of the atmosphere.

A number of corollaries and inferences may be made relative to the conclusions listed above.

- Coupled ocean–atmosphere models which require rather precise surface radiation budget calculations will require the added complexity of determining both $\delta(z)$ and $\Sigma\delta$ in addition to the background water vapor distribution.
- An implication of the decoupling of the surface and planetary radiation budgets is that surface temperature responses from changed in-cloud conditions cannot be inferred directly from the planetary radiation budget without explicit assumptions about the correlations of effective cloud base and cloud top temperature.
- Given that the correlations mentioned above do exist for certain cloud systems (*and this is a questionable assumption*), then it may be possible, in principle, to categorize those cloud systems that have the greatest potential influence in the cloud-climate feedback problem by using radiation measurements obtained remotely from satellite.

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