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Surface temperature sensitivities from cloud cover variations in the Hummel-Kuhn radiative–convective model with three different cloud approximations

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ABSTRACT

In modeling the thermal structure of the atmosphere, the role of clouds is critically important. Clouds modify the solar flux distribution throughout the atmosphere, radiate significantly in the infrared, and provide large thermal reservoirs because of the large latent heat of water.

In the best current radiative convective one-dimensional models the global atmosphere is modeled as the sum of clear and cloudy sky parts weighted by a fractional cloud cover. In considering the cloudy sky part, previous models have treated the clouds as input and characterized them simply in terms of their altitudes, thicknesses, and optical properties.

This report compares the surface temperature sensitivities to variations in cloud cover for three cloud approximations: (1) a single effective fixed cloud with a mean water vapor profile, (2) a floating clouds approximation in which cloud altitudes and thicknesses are calculated and a mean water vapor profile is used and (3) a fully interactive formulation in which cloud altitudes and thicknesses are calculated and separate clear and cloudy water vapor profiles are used. In all three approximations the cloud cover amount, A_c, is an input. The fully interactive approximation is shown to reduce the sensitivity of surface temperature to cloud cover variations from -4.7×10^{-2} K/(1% A_c) for the single effective approximation to -3.6×10^{-2} K/(1% A_c). This reveals that when the model allows the clouds and water vapor to interact, calculated surface temperature changes caused by changing the amount of clouds are less than previous studies indicate.

1. Introduction

Both cloud amount and height are known to affect surface temperature. In globally averaged models, as the amount of clouds increases, the planetary albedo increases and the surface temperature decreases (e.g. Schneider, 1972). The surface temperature also responds to changes in cloud height, the nature of the response (i.e. whether the surface temperature increases or decreases) depending on the cloud and its original height (e.g. Manabe and Wetherald, 1967). In globally averaged models cloud cover amount is held fixed during the course of the calculations. Typically, a globally averaged cloud cover amount of around 50% is used and may be due to a single effective cloud (e.g. Ramanathan, 1976) or the effective cloud cover amount from multiple cloud layers (e.g. Manabe and Wetherald, 1967).

In terms of the altitudes where clouds are found in radiative-convective models, two approximations are currently used. The first approach assigns to the tops and bottoms of clouds fixed pressure or height levels. This is known as the fixed cloud pressure (or height) approximation, fcp. In their single effective cloud models, Schneider (1972) and Ramanathan (1976) use the fixed cloud heights of 5.5 km and 6.25 km respectively. The altitudes were determined by assuming a specific outgoing infrared flux at the top of the atmosphere for a specified surface temperature and then determining what cloud altitude would give that infrared flux. The Manabe and Wetherald model, in use here at the General Motors Research

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Laboratories (GMR), uses fixed cloud pressure levels based on the data of Telegadas and London (1954).

The second cloud approximation involves fixing a temperature to the top of the cloud. Based on the suggestion of Cess (1974), the assigned cloud top temperature is found by determining what cloud top temperature will give a model atmosphere an assumed outgoing infrared flux at the top of the atmosphere for an assumed surface temperature. This approximation is known as the fixed cloud top temperature approximation, fctt. Reck (1979) has recently compared the fcp and fctt approximations in the GMR Manabe and Wetherald radiative-convective model and demonstrated that temperature sensitivities are from 1.43 to 1.56 times larger with the fctt than the fcp approximation. With either of these approximations, cloud conditions become imposed and decoupled from the temperature profile.

In radiative-convective models examining mean global or latitudinal conditions, separate clear and cloudy sky flux calculations are typically made and the mean atmosphere modeled by weighting the clear and cloudy sky calculations by the assumed cloud cover fractions. In the present generation of radiative-convective models (including the GMR model) a single water vapor distribution is used for both the clear and cloudy atmospheres. The water vapor profile used is typically determined by assuming that the vertical distribution of relative humidity, $h(P)$, where P is pressure, is constant (Manabe and Wetherald, 1967). The distribution suggested by Manabe and Wetherald (1967) is

$$h(P) = 77\,\frac{P/P_0 - 0.02}{1.0 - 0.02} \qquad (1)$$

where P_0 is the surface pressure and the 77 refers to the surface value of the relative humidity in percent. As can be seen from the distribution, $h(P)$ decreases with altitude. In the real world, however, when clouds exist the relative humidity should increase with altitude up to 100% at the cloud base and be 100% throughout the cloud. As a result, the relative humidity distribution given by (1) will not model the expected distribution in an atmosphere containing clouds. The distribution (1) also does not reproduce observed mean conditions and results in the amount of atmospheric water vapor being about 30–35% less than observed (Sellers, 1965; Starr et al., 1969).

In the real atmosphere, clouds float up and down, changing their density, vertical thicknesses, temperatures, and horizontal extents as the temperature and moisture fields change. Obviously, a one-dimensional, globally averaged model cannot describe the complex dynamical and thermodynamical process responsible for actual cloud formation. However, the large scale response of averaged clouds to temperature changes can be simply simulated. Results of surface temperature changes to changes in fractional cloud cover will now be presented using the interactive radiative-convective model developed at the University of Michigan to predict cloud properties. The model includes the vertical transport of water vapor and predicts at what altitude clouds should form in the model atmosphere. The surface temperature sensitivity predicted by the model due to changes in fractional cloud cover will be presented and compared to predictions from the model using two other cloud treatment approximations.

2. The Hummel-Kuhn radiative–convective model with interactive clouds

The Hummel-Kuhn radiative–convective model with interactive clouds (HK) predicts cloud altitudes and thicknesses with a vertical water vapor transport model. The transport calculations include transport by large scale vertical winds and vertical eddy diffusion. Both transport contributions are coupled to temperature. The vertical extent of the "convection" is limited to 450 mb. The transport calculations are conceptually similar to models of Weare and Snell (1974) and Hess (1976). The features of the model are summarized in Table 1 and compared with the standard Manabe and Wetherald model. The model, at present, does not predict total fractional cloud cover. This value is imposed. If multiple cloud layers are formed, the clouds (up to 3), are assumed to be randomly overlapped (e.g. Kuhn, 1978) and give a total fractional cloud cover equal to the input value. The liquid (or solid) water content within the cloud is also computed, thereby, allowing cloud optical properties to be evaluated if desired. The "clouds" generated are not meant to be characteristic of specific cloud types (i.e. cumulus, stratus, etc.) but only representative of average cloud features.

Separate clear and cloudy sky water vapor profiles are computed and used to compute water vapor transmission functions. The clear sky profile is determined by using (1). The cloudy sky profile is calculated with the transport model used to predict cloud altitudes. Separate clear and cloudy sky infrared radiative fluxes are then computed and weighted by the cloud cover amount to give an average atmospheric radiative flux. Specific details of the model are given in Hummel (1978) and Hummel and Kuhn (1981b).

Table 1. *Model properties and comparison with the Manabe–Wetherald (MW) model*

Surface albedo	$\omega_s = 14\%$			
Planetary albedo	$\omega_p = 30\%$			
Surface relative humidity	$h_0 = 77\%$			
Carbon dioxide	456 ppmm			
Vertical extent of convection	450 mg*			
	MW			HK
Number of pressure levels	9			12
Cloud layers	3†			up to 3
Aerosols included	Yes			No
Clear and cloudy H_2O profiles	No			Yes
Cloud locations	Assigned by either fcp or fctt			Calculated
Cloud reflectivity	High	Middle	Low	
(%)	21	48	63	32‡
Cloud absorptivity	0.5	2.0	3.5	Not included§

* See Hummel (1978) or Hummel and Kuhn (1981b).

† The MW can handle any number of layers but three are typically included.

‡ This is the reflectivity of the total cloud cover. Individual cloud reflectivities are not needed. An accurate empirical relationship is used in the solar flux calculations that requires only the clear sky fluxes (Budyko, 1964).

§ The individual cloud absorptivities are not needed. See above.

In the original study, Hummel (1978) and Hummel and Kuhn (1981b) examined the surface temperature sensitivities in the fully interactive model to changes in carbon dioxide content and surface relative humidity. They then compared the results to sensitivity estimates made by (1) assuming a single cloud with fixed cloud pressures and a mean water vapor profile based on a constant distribution of relative humidity and (2) predicting the cloud altitudes but using a mean water vapor profile based on the constant distribution of relative humidity. The differences between the sensitivities were found to be large with the relative errors (relative to the estimates from the fully interactive model) exceeding, at times, a factor of 2.

Results will now be presented for surface temperature sensitivities for changes in total effective cloud cover. As with the original study by Hummel (1978) and Hummel and Kuhn (1981b), the results from the fully interactive model will be compared against (1) those obtained by only predicting cloud altitudes and (2) by assuming a single effective fixed cloud. In both of these cases a mean atmospheric water vapor profile will be assumed using a constant distribution of relative humidity based on (1). The conceptual differences between the cloud approximations are shown in Table 2. Convective adjustment is accounted for by

Table 2. *Cloud approximations used in this study*

Property	Fully interactive	Floating clouds only	Single effective cloud	Manabe–Wetherald
Number of cloud layers	Predicted (up to 3) and varies with $T(P)$	Predicted (up to 3) and varies with $T(P)$	1 and constant	3 and constant
Cloud altitudes	Predicted and varies with $T(P)$	Predicted and varies with $T(P)$	Fixed at constant pressure	Fixed at constant pressure
Cloud amounts	Fixed	Fixed	Fixed	Fixed
Water vapor profile	Separate clear and cloudy sky profiles. —Clear based on constant $h(P)$ —Cloudy based on vertical transport of water vapor	One profile based on constant $h(P)$	One profile based on constant $h(P)$	One profile based on constant $h(P)$

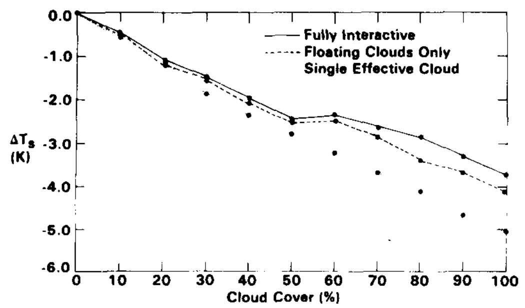

Fig. 1. Change in surface temperature with cloud cover for the three cloud assumptions described in the text.

limiting the tropospheric lapse rate to a maximum of 6.5 K/km in a particular atmospheric layer. As noted by Hummel and Kuhn (1981a) an alternate lapse rate formulation is now available that can be used in a greater variety of sensitivity studies than the lapse rate formulation based on a maximum tropospheric lapse rate of 6.5 K/km. However, to allow comparisons with previous studies the critical lapse rate of 6.5 K/km is adopted.

For cloud covers ranging from 0% (completely clear) to 100% (completely overcast) steady-state temperature profiles were calculated with the Hummel-Kuhn radiative–convective model for the three different cloud treatments just described. The differences in surface temperature, ΔT_s, for the model atmosphere with no clouds and a cloud cover A_c was computed for each cloud treatment and then averaged to give a $\Delta T_s/1\%\ A_c$. The results are plotted in Fig. 1.

3. Discussion of results

In Fig. 1, the curve labeled "Fully Interactive" refers to the results from the Hummel-Kuhn model with the cloud altitudes and separate clear and cloudy sky water vapor profiles computed. The curve labeled "Floating Clouds Only" refers to the results obtained by predicting the cloud altitudes but using a single water vapor profile based on a constant distribution of relative humidity. The curve labeled "Single Effective Cloud" refers to predictions made by including a single thin cloud with a fixed pressure level, 500 mb, and a single water vapor profile based on the constant distribution of relative humidity given by (1). For each non-zero fractional cloud cover, both the fully interactive and floating clouds only versions predicted a final, single clound with a base at 650 mb and top at 500 mb in their steady-state atmospheres.

3.1 *Single effective cloud*

Consider first the single effective cloud curve. As the cloud cover increased the surface temperature decreased at a nearly linear rate of -4.7×10^{-2} K per 1% increase in fractional cloud coverage. The decrease in surface temperature is a result of the decrease in net solar radiation. The surface temperature sensitivity to cloud cover changes is considerably different from that when three fixed clouds are included (e.g. Manabe and Wetherald, 1967) because of the impact of cloud height on surface temperature. If three fixed clouds were used, employing the cloud properties of Manabe and Wetherald (1967), the surface temperature change per 1% increase in low cloud amount is -0.6 K. The fact that the three cloud and single cloud results differ so much further stresses the impact of cloud approximations.

3.2. *Floating clouds only*

For the curve labeled "Floating Clouds Only" the differences between clear sky and cloudy sky water vapor profiles were ignored. In all cases, the steady-state atmosphere predicted a final single cloud with a base at 650 mb and top at 500 mb.

The sensitivity for the "Floating Clouds Only" assumption is -3.9×10^{-2} K/(1% A_c) as compared with -4.7×10^{-2} K/(1% A_c) for the single effective cloud assumption. The reduced sensitivity results from the thicker cloud and the cloud locations changing during the course of the calculations. With the lower cloud base the amount of downward infrared radiation from the cloud base is greater than in the single effective cloud case because the cloud base temperature is higher; therefore, the surface temperature is higher. The change in slope around 50 to 60% cloud cover arises from the fact that the cloud locations changed during the course of the calculations. The model cloud thickened, for all values of A_c, to 400–650 mb before reaching the steady-state value of 500–650 mb. The higher cloud top leads to a higher surface temperature because the cloud top temperature is less. However, the impact of the cloud location on the radiative flux depends on A_c because the average atmospheric radiative flux is the weighted average of the clear and cloudy sky fluxes. Around 50 to 60% cloud cover the contributions from the changing cloud locations in the cloudy part of the sky become significant enough to change the slope of the curve.

3.3. *Fully interactive*

Finally, consider the curve labeled "Fully Interactive." These results are from the Hummel-Kuhn model with the cloud altitudes and thicknesses predicted and separate cloudy and clear sky water vapor profiles included. As with the floating clouds assumption, all of the steady-state clouds had a top at 500 mb and base at 650 mb. The reduced cooling from the lower cloud base is again evident as well as a further reduction in the cooling brought about by the cloudy sky water vapor profile.

As with the floating clouds only results, the change in the slope around 50 to 60% cloud cover results from the changing cloud locations during the calculations. The cloud locations varied in the same way as the floating clouds only results, first thickening to 400–650 mb and then converging on the steady-state 500–650 mb thickness.

The cloudy sky water vapor profile contains more water vapor than that found in a clear sky. The additional infrared absorption by the water vapor below the cloud leads to an enhanced "greenhouse effect." The final result being that the surface temperatures predicted for a particular cloud cover fraction are larger than those predicted with the floating clouds and single effective cloud assumptions by about a degree. Also, the sensitivity to cloud cover changes is the smallest, -3.6×10^{-2} K/(1% A_c).

4. Conclusions

Comparing the different sensitivities it is seen that the surface temperature sensitivity to changes in cloud cover depends on three components: (1) the change in planetary albedo as cloud cover amount changes, (2) the coupling of cloud locations to temperature, and (3) a greenhouse effect from the larger water vapor profiles found in cloudy skies. Previous studies (e.g. Schneider, 1972; Cess, 1974; Ramanathan, 1976) have only included the first component. Relative to the single effective cloud results, coupling the cloud locations to temperature alone reduces $\Delta T_s/\Delta A_c$ about 17%. Coupling the cloud locations to temperature and including separate clear and cloudy water vapor profiles reduces $\Delta T_s/\Delta A_c$ about 23%. It can be concluded, then, that when water transport is included to allow separate clear and cloudy sky water vapor profiles and cloud locations to be computed the surface temperature sensitivity to changes in cloud cover amount is less than has been suggested by previous studies (e.g. Schneider, 1972, Cess, 1974; and Ramanathan, 1976). The implications for global climatology need to be examined by coupling the cloud cover amount as well as cloud numbers and locations to the temperature profile.

Cloud formation results from the horizontal and vertical transport of water vapor. The Hummel-Kuhn interactive model includes the role of vertical transport processes while the Manabe and Wetherald radiative-convective model with its treatment of fixed multiple clouds approximates the role of horizontal circulation in defining clouds. Seeing that the numerical values of the surface temperatures and the surface temperature differences are significantly different for both processes it is clear that an improved version of a radiative-convective model should include both the effect of horizontal and vertical transport.

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ЧУВСТВИТЕЛЬНОСТИ ТЕМПЕРАТУРЫ ПОВЕРХНОСТИ К ВАРИАЦИЯМ ОБЛАЧНОГО ПОКРОВА В РАДИАЦИОННО-КОНВЕКТИВНОЙ МОДЕЛИ ХАММЕЛА-КУНА С ТРЕМЯ РАЗЛИЧНЫМИ АППРОКСИМАЦИЯМИ ОБЛАЧНОСТИ

В моделировании термической структуры атмосферы роль облаков чрезвычайно важна. Облака модифицируют распределение солнечного потока в атмосфере, излучают существенно в инфракрасном диапазоне длин волн и обеспечивают большие тепловые резервуары из-за большого скрытого тепла воды.

В лучших современных одномерных радиационно-конвективных моделях глобальная атмосфера моделируется как сумма безоблачной и облачной частей, взвешенных с учетом доли облачного покрова. В рассмотрении облачной части атмосферы в предыдущих моделях облака рассматривались заданными и характеризовались только в терминах высот облаков, толщин и оптических свойств.

В данной работе сравниваются чувствительности температуры поверхности с вариациями облачного покрова для трех облачных приближений: (1) одного эффективного фиксированного облака со средним профилем водяного пара, (2) приближения плавающих облаков, в котором высоты облаков и толщины рассчитываются и используется средний профиль водяного пара и (3) формулировки с полным взаимодействием, в которой высоты облаков и толщины рассчитываются и используются отдельные профили водяного пара для облачной и безоблачной атмосферы. Во всех приближениях количество облаков, A_c, является заданным. Показано, что чувствительность температуры поверхности при вариациях облачного покрова уменьшается в приближении с полным взаимодействием до $-3,6 \cdot 10^{-2}$ K/(1% A_c) по сравнению с чувствительностью $-4,7 \cdot 10^{-2}$ K/(1% A_c) для приближения одного эффективного облака. Тем самым показано, что когда облака и водяной пар взаимодействуют в модели, рассчитанные изменения поверхностной температуры при изменении количества облаков меньше, чем указывалось в предыдущих исследованиях.