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Comparison of fixed cloud-top temperature and fixed cloud-top altitude approximations in the Manabe–Wetherald radiative-convective atmospheric model

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ABSTRACT

This work demonstrates the effect of fixing the cloud-top temperature during a numerical calculation of the atmospheric temperature profile using the GMR atmospheric model. In all earlier GMR calculations of the temperature response due to a parameter change the infinitely thin high and middle cloud layers and the thick lower cloud layer were held at fixed altitudes. Since recent cloud measurements have shown it may be more realistic to hold the cloud-top temperature fixed, we have compared the temperature response of the GMR model with fixed cloud altitudes and fixed cloud-top temperatures.

If our three cloud layers are maintained so as to hold the temperature of each cloud-top fixed (and the bottom of the lower cloud adjusted to maintain the same optical thickness) the calculated temperature differences due to parameter changes are 1.43 larger than when clouds are held at fixed altitudes in the model. If on the other hand the bottom of the lower cloud is maintained at a fixed altitude while the tops of the clouds are maintained at a fixed temperature the calculated temperature is 1.56 larger. These values compare with a value of 1.46 obtained by a radiative-convective model developed by Wang et al. (1976). Feedback mechanisms between the abundances of different clouds have not been included but could be important if sufficient detailed information were known about the interaction between different clouds.

1. Introduction

Early modeling studies by Schneider (1972) discussed cloudiness as a global climatic feedback mechanism. In his work he considered the effects on the radiation balance and the surface temperature of changes in cloud abundance and cloud altitude, pointing out that global-average results do not aply near the poles where the albedo of the cloudy area can be comparable to the albedo of the snow-covered area.

In more recent studies involving cloud parameterizations (Wang, 1976; Cess, 1975, Ramanathan, 1975), it has been suggested that atmospheric models should fix the cloud-top temperature (fctt) rather than the altitude (or pressure). This conclusion is largely based on the work of Cess (1974) who illustrated that outgoing flux calculations based on fixed cloud altitude were incompatible with the empirical flux results of Budyko (1969). Cess went on to show that a consistent outgoing flux model is one for which the effective cloud-top temperature is fixed as the surface temperature varies.

In a version of the Manabe–Wetherald (1967) radiative-convective model [which we have used for some time (Reck, 1974)] the model atmosphere approaches a steady-state temperature profile by a forward time-marching technique while several layers of water clouds (usually three) are held at fixed cloud pressures (or altitudes), (fcp). Which cloud approximation (fctt or fcp) is closer to reality is somewhat difficult to resolve (Fig. 1). If the temperature of the cloud is allowed to change its black-body radiation changes and it is also possible that its physical and optical properties could change, as for example, in the melting of ice crystals in a cirrus cloud. Holding the temperature constant means the cloud changes altitude as the temperature changes at a given pressure level during the calculation.

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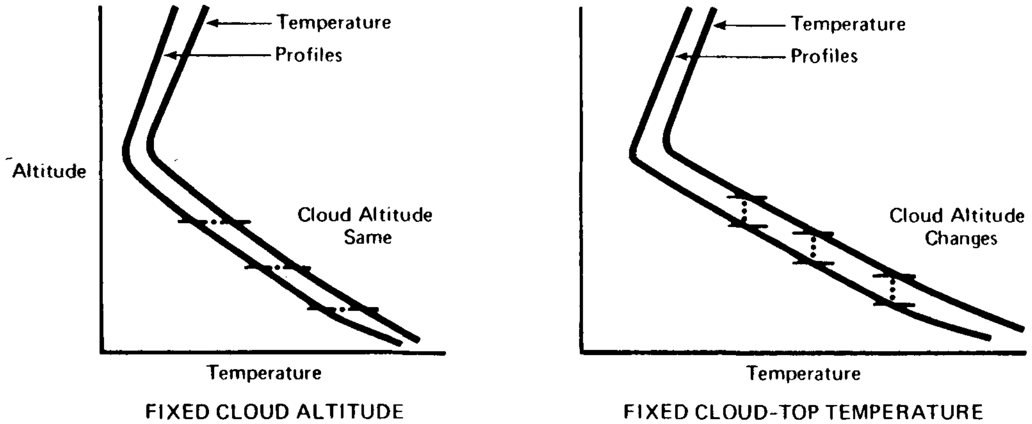

Fig. 1. Comparison of cloud altitude for the fixed cloud altitude model and the fixed cloud-top temperature model.

This approximation implies there is a related physical mechanism which causes either the transport of the cloud or the evaporation at one level with simultaneous reformation at another level. Wetherald and Manabe (1975) suggest that an increase in the abundance of low clouds may be correlated with a decrease in middle and high cloud abundances. If this is the case this would imply an internal cloud feedback mechanism and neither approximation might be entirely appropriate for one of the clouds when considering multiple layers of clouds. So far, all models which have included the fctt approximation have treated only one effective cloud layer. With the inclusion of the fctt approximation the models are more sensitive to other parameter variations. Hence the matter is critical for more detailed cloud models in order to adequately assess the temperature influence of increases in atmospheric constituents such as CO_2 and particles.

Wang et al. (1976) have pointed out that the fctt approximation is valid for Venus. This author believes the fact that Venus is totally cloud covered [as well as differing from earth in many other respects (see Table I)] makes the extension of its use in the earth's atmosphere less obvious. Wang et al. also mention that a partially cloudy atmosphere (such as earth has) is much more complicated but still state their preference for the fctt approximation for earth.

Table 1. *Atmospheric properties of earth and Venus*

	Earth	Venus
Cloud composition	H_2O	H_2SO_4
Surface pressure	1 bar	95 bars
Surface temperature	288 K	700 K
Equator to Pole temperature contrast	24%	2%
Percentage cloud cover	50%	100%
Atmospheric composition	N_2/O_2	CO_2

Smagorinsky (1960) has shown that high, middle and low cloud amounts depend on relative humidity which, in a dynamic hydrological cycle, is fixed by temperature. Based on Smagorinsky's work it would be possible to fix cloud altitude but vary the amount as the relative humidity changes. This treatment would require a full hydrologic cycle with detailed balance at all pressures for proper application of the fctt approximation.

In the present work we have calculated the change in surface temperature with cloud-top temperature, first for each cloud layer alone in the atmosphere and then for one cloud-top temperature fixed at a time, while the other two layers are held at constant pressure (altitude). Because the results are so simple they may be readily used to determine the differences in the two cases.

2. The atmospheric model

The Manabe–Wetherald radiative-convective model was developed over many years by workers at the Geophysical Fluid Dynamics Laboratory at Princeton University and was brought to its present form by Manabe and Wetherald (1967) and Stone and Manabe (1968). It was modified by us to include the role of airborne particles. In this model, solar radiation is considered to be absorbed by ozone, carbon dioxide, and water, and absorbed and backscattered by water clouds, airborne particles, and the earth's surface. The ozone, carbon dioxide, water, water clouds, airborne particles, and the earth's surface also radiate and absorb infrared radiation. A temperature is initially assumed for each of nine vertically-aligned points in the atmosphere. If the temperature decrease with altitude is greater than the critical adiabatic lapse rate, energy is removed from the lower altitudes and placed higher up. A forward time integration of the solar and infrared flux imbalance is performed until a radiative-convective steady-state temperature is asymptotically approached at each of the nine points.

The water vapor content is allowed to vary with temperature during the time integration so that the relative humidity remains fixed. The particle layer was assumed to have an extinction coefficient of 0.1 km^{-1} because this is in the range of the average global value.

By comparison with the real atmosphere this model is very simplified and neglects the general circulation of the atmosphere and all the detailed mechanisms by which energy and momentum are transferred by different scale processes in the atmosphere. It does not provide a full hydrologic cycle and also neglects important but complicated feedback mechanisms such as changes in ice-extent. The present work evaluates only the response of the calculated surface temperature for fixed cloud-top temperatures.

3. Calculation of surface temperature, T_s for fixed cloud-top temperature, T_t

We have calculated $\partial T_s/\partial T_t$ for clouds at three levels, holding cloud abundances and cloud optical properties fixed (Table 2). One cloud layer temperature is varied at a time to calculate $\partial T_s/\partial T_t$ and the same calculations are repeated both with and without the presence of two other clouds, while holding the pressures (altitudes) of the other clouds fixed. For the thick low cloud we have also considered the fctt but with a bottom fixed at a constant altitude. The results of these calculations are illustrated in the next section.

Table 2. *Average cloud properties*

	Upper cloud	Middle cloud	Lower cloud
Fraction cloud cover	0.181	0.079	0.302
Cloud level (mb)*	336	664	811–926
Solar reflectivity	0.21	0.48	0.63
Solar absorptivity	0.005	0.02	0.035
Infrared absorptivity	0.50	1.00	1.00

* The corresponding altitudes in a standard atmosphere are 336 mb = 8.4 km, 664 mb = 3.4 km, 811 mb = 1.9 km, 926 mb = 0.75 km.

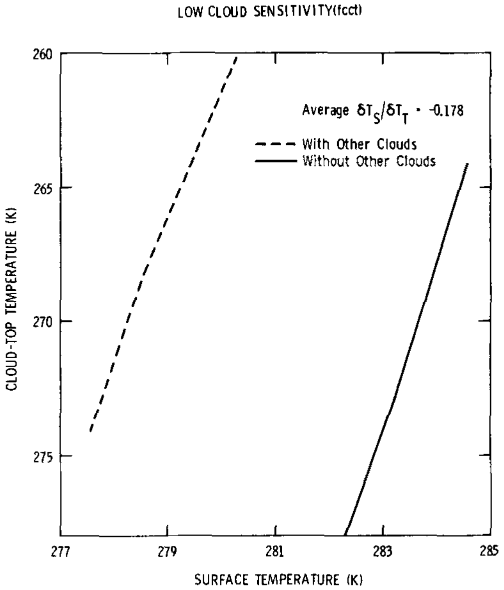

Fig. 2. Calculated changes in surface temperature as a function of low-cloud top temperature for a low cloud having a 30.2% abundance. The smooth curve is for no other clouds present and the dashed curve with middle and high equilibrium clouds present.

4. Results

Fig. 2 shows two curves of low cloud-top temperatures versus calculated surface temperature. The dotted curve is calculated with other clouds fixed in altitude and the continuous line curve considers an atmosphere with only the lower cloud-layer present. With other clouds present, $\partial T_s/\partial T_t = -0.196$, and with only the low cloud present, $\partial T_s/\partial T_t = -0.16$, with an average value for both cases of $\partial T_s/\partial T_t = -0.178$. If the bottom of the

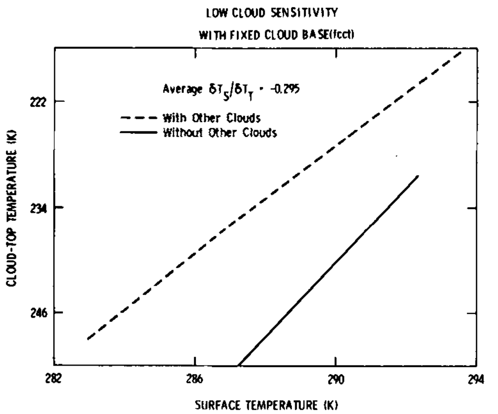

Fig. 3. Calculated changes in surface temperature as a function of low-cloud top temperature for a low cloud having a 30.2% abundance. The smooth curve is for no other clouds present and the dashed curve with middle and high equilibrium clouds present and a fixed lower cloud base situated at 811 mb.

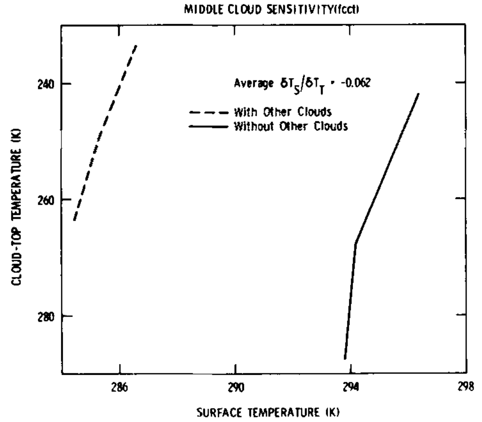

Fig. 4. Calculated changes in surface temperature as a function of middle-cloud top temperature for middle clouds having a 7.9% abundance. The smooth curve is for no other clouds present and the dashed curve with lower and high altitude clouds present.

low cloud is held fixed we obtain the two comparable curves in Fig. 3. Here the slopes are not quite as similar. In Fig. 4 are the values of middle cloud-top temperature versus calculated surface temperature. A least-square fitting of both sets of calculated T_s gives $\partial T_s/\partial T_t = -0.062$. In Fig. 5 are shown the values of fixed high cloud-top temperature versus calculated surface temperature. For these cases also the least-squares fitting to obtain the slope is identical either with or without other clouds present, but giving the value $\partial T_s/\partial T_t = -0.204$.

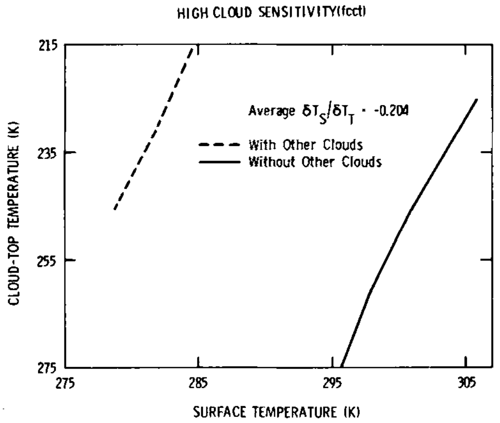

Fig. 5. Calculated changes in surface temperature as a function of high-cloud top temperature for a high cloud having a 18.1% abundance. The smooth curve is for no other clouds present and the dashed curve with middle and low altitude clouds present.

5. Discussion

Our results show that the calculated surface temperature decreases as the cloud-top pressure increases (i.e. altitude decreases). The largest thermal effect is produced by a thick low-lying cloud with a fixed bottom altitude and a changing top temperature. High (cirrus) clouds also produce a relatively large effect on the surface temperature when their cloud-top temperature varies. The presence of other cloud layers produces a complicating and enhancing effect only for the low cloud layer.

For the present study we have considered half-black cirrus clouds at 336 mb and below and have avoided the complication of cirrus cloud effects changing from cooling to heating. Manabe and Strickler (1964) studied this effect to some extent and showed that full black cirrus clouds produce heating above 9 km (336 mb). Since most cirrus clouds (unless associated with thunderstorms) are probably below this altitude and since the cirrus clouds are most likely far from black we have chosen to avoid this complication in this simple analysis.

A qualitative physical explanation of these results is possible. If during the course of the calculation the cloud-top temperature is allowed to increase the blackbody radiation emitted from the top of the cloud will *increase* and more infrared radiation will be lost to space. In addition the mean shortwave planetary albedo will change (Reck, 1975) as well as the water vapor thickness for this constant relative humidity model. Since the boundary condition requires a net radiation balance, the calculated surface temperature (i.e. emission of infrared radiation from the surface) *decreases*. This qualitatively explains the negative slopes in each of the plots in Figs. 2–5. An additional complication arises when the cloud bottom is held fixed. If the cloud thickness changes during the course of the calculation this corresponds to a change in the cloud's optical depth and an additional contribution to the infrared flux divergence of the upward flux. Very little significance should probably be attached to the degree of nonlinearity in the curves in Figs. 4–5 largely because of the sensitivity of T_s to cloud optical properties (Reck, 1978; JOC Study Conference, Oct. 1978), which at the present time are still very uncertain.

It is clear that the fcct approximation will give a larger calculated ΔT_s for any "greenhouse" type parameter change than the fcp because in the fctt case the surface emission is the principal contribution to maintain the radiation balance at the top while in the fcp case it is both the cloud-top and surface emission.

If we include the combined effects of three fctt clouds in our calculation we find $0.426 \leq \partial T_s/\partial T_t \leq 0.561$. This implies that in all our results published to date for fcp, the calculated ΔT_s for changing a parameter constituent should be multiplied by a factor in the range 1.43–1.56 to obtain the calculated temperature for fixed cloud-top temperature.

How does the sensitivity of our model to the fctt approximation compare with that of other models? Cess (1975) illustrates the $\partial T_s/\partial T_e$ where T_e is the effective temperature of the earth-atmosphere system and obtains a factor of 1.88 for the ratio of the two cases of fctt and fch (fixed cloud height[1]). If we consider the average ratio (changes in surface temperature for fctt to changes in surface temperature for fcp) for changes in the concentrations of all gases reported by Wang et al. (1976) in their Table III, we obtain 1.46 for their radiative-convective model with average clouds.

While we feel it was important to determine the sensitivity of the Manabe–Wetherald radiative-convective model for the fctt case, it should still be stressed that the treatment of clouds within the model is very primitive and much work needs to be done to study the effects of cloud formation and multiple cloud layers.

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[1] This is a minor point but fixed cloud height and pressure is not exactly identical since the height pressure relationship can vary with season and latitude.

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СРАВНЕНИЕ ПРИБЛИЖЕНИЙ ФИКСИРОВАННОЙ ТЕМПЕРАТУРЫ НА ВЕРШИНЕ ОБЛАКА И ФИКСИРОВАННОЙ ВЫСОТЫ ВЕРШИНЫ ОБЛАКА В РАДИАЦИОННО-КОНВЕКТИВНОЙ МОДЕЛИ МАНАБЕ-УЭЗЕРАЛД

Эта работа демонстрирует эффект фиксирования температуры на вершине облака при числовом расчёте атмосферного температурного профиля с использованием атмосферной модели Дж.М.Р. Во всех предыдущих моделях Дж.М.Р. расчеты температурной реакции выполнялись на фиксированных высотах вследствие изменения параметра бесконечно тонких верхних и средних слоёв облака и толстого нижнего слоя. Поскольку недавние исследования облаков показали, что более реалистичным будет принятие фиксированной температуры на вершине облака, мы сравнивали температурную реакцию модели Дж.М.Р., используя фиксированную высоту облака и фиксированные температуры на вершине облака.

Если три наших слоя облака поддерживать так, чтобы температура вершины каждого слоя была фиксированной, а нижний слой самого нижнего облака при этом подогнан под одинаковую оптическую толщину, то в этом случае рассчитанные температурные различия вследствие изменения параметров больше на 1,43, чем в случае, когда облака брались на фиксированных высотах в этой модели.

Тем не менее, если нижний слой нижнего облака рассматривается при фиксированной высоте, в то время как вершины облаков рассматриваются при фиксированной температуре, рассчитанная температура выше на 1,56. Эти величины сравнимы с величиной 1,46, полученной при помощи радиационно-конвективной модели, разработанной ВЭНГОМ и др./1976 г./. Механизмы обратной связи между протяжённостью различных облаков не были включены, но могли быть важными при наличии детальной информации о взаимосвязях между различными облаками.