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Comparison of radiative-convective models with constant and pressure-dependent lapse rates

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ABSTRACT

In the current generation of radiative-convective models a constant value for the critical atmospheric lapse rate, generally 6.5 K/km, is used. However, the moist adiabatic lapse rates are a better approximation for use in simple climate models. Thus, a comparison of temperature profiles with critical constant and moist adiabatic lapse rates has been made for a one-dimensional radiative-convective model.

The commonly used lapse rate of 6.5 K/km yields surface temperatures some 1 to 3 K higher than with the use of moist adiabatic lapse rates for both clear sky conditions and a single effective cloud. When multiple clouds are included the constant lapse rate of 6.5 K/km yields the lower surface temperatures. More importantly, the surface temperature generated from the constant lapse rate formulation is more sensitive to changes in carbon dioxide, relative humidity, cloud cover, and surface albedo. For a doubling of CO_2 the moist adiabatic lapse rate formulation yields surface temperature changes 25 to 60% smaller than does a constant 6.5 K/km lapse rate depending on the cloud treatment.

1. Introduction

As a result of the increased attention focused on climate and climatic changes, both natural and anthropogenic, many models are available for studying climatic processes. One of the most commonly used models is the convective adjustment radiation model.

It is well known that an atmosphere in pure radiative equilibrium produces a temperature profile that is super-adiabatic in the troposphere (e.g. Manabe and Moller, 1961), the reason being that convection and latent heat releases are not included. In the present generation of radiation models, stable temperature profiles are maintained with a convective adjustment in which the temperature lapse rate is set equal to a critical lapse rate (usually 6.5 K/km) whenever the computed lapse rates exceed the critical value. First introduced by Manabe and Strickler (1964), a variety of convective adjustment models are now in use (e.g. Manabe and Wetherald, 1967; Rasool and Schneider, 1971; Schneider, 1972; Ramanathan, 1976).

As recently reported by Rennick (1977), models incorporating the 6.5 K/km lapse rate consistently produce colder temperature profiles, as shown in Fig. 1. This is also true for the constant 0.12 K/mb lapse rate used by Sellers (1973). Also, fixed lapse rate models cannot be used to study seasonal and latitudinal variations. Convective adjustment models with a constant critical lapse rate but allowing the lapse rate to vary up to this critical value still produce colder profiles and are of questionable value when used in one-dimensional radiative convective equilibrium calculations.

Historically, the value of 6.5 K/km was based on an average of lapse rates from a limited set of atmospheric measurements. As noted by Stone and Carlson (1979), this value is too high. They suggest a value of about 5.16 K/km would represent a reasonable average lapse rate for the entire lower atmosphere.

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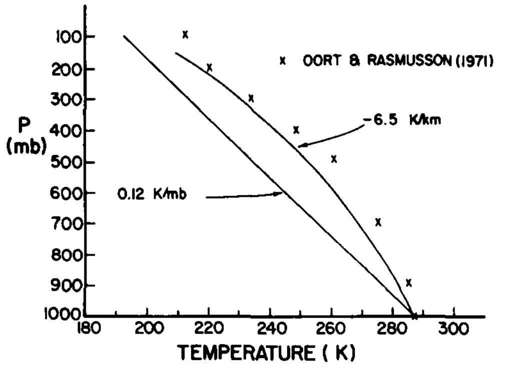

Fig. 1. Comparison of observed temperatures (Oort and Rasmusson, 1971) with the standard convective adjustment lapse rate (6.5 K/km) and that of Sellers (1973) (0.12 K/mb). (Based on Fig. 2 of Rennick, 1977.)

The actual atmospheric lapse rate is dominated by moist convective transport and baroclinic eddies. In zonally averaged models both processes must be included. Stone and Carlson (1979) presented critical lapse formulations for both baroclinic and moist convective processes. For hemispherical and global annual conditions, however, moist convective processes dominate and can be used to compute appropriate critical lapse rates.

2. Methodology

As a moist parcel of air rises adiabatically, water vapor can condense releasing latent heat to the atmosphere. Therefore, the lapse rate will be less than that in a dry atmosphere; the moist adiabatic lapse rate, γ_m, is given by (see e.g. Iribarne and Godson, 1973):

$$\gamma_m(T,p) = \gamma_d[(1 + \varepsilon L(T)e_s(T)/pRT)/ (1 + \varepsilon^2 L^2(T)e_s(T)/c_p\, pRT^2)] \quad (1)$$

where $\varepsilon = 0.622$, the ratio of the molecular weights of water vapor and dry air; L, the latent heat of condensation; e_s, the saturation water vapor pressure; p, the atmospheric pressure; R, the specific gas constant for air; T, the temperature; and c_p, the specific heat at constant pressure. The latent heat is computed from (Stone and Carlson, 1979),

$$L(T) = 2510 - 2.38(T - 273) \quad (2)$$

where L has units of Joules/gram. The saturation water vapor pressure is determined from the Clausius–Clapeyron equation. From the temperatures computed in the radiation calculation, and with γ_m given by (1) the moist adiabatic lapse rate is computed at each pressure level to insure atmospheric stability.

In Fig. 2 the moist adiabatic lapse rates applicable for the mid-latitude U.S. Standard Atmosphere are plotted. Also shown are the 6.5 K/km and dry adiabatic lapse rates. As shown in the figure the moist adiabatic lapse rate approaches the dry adiabatic value in the upper troposphere where the water vapor content is low. In the lower troposphere where the water vapor content is high, the moist adiabatic lapse rate is less than 6.5 K/km. In the lowest kilometer or so the differences are large and can lead to significant surface temperature sensitivity differences in radiative-convective models.

The moist adiabatic lapse rate formulation was introduced into a detailed radiation model based on the work of Kuhn (1978). The atmospheric transmission functions were computed from a quasi-random band model (Wyatt et al., 1962) that includes a Voigt profile (Drayson, 1976). A total of 31 spectral intervals was used for the solar absorption by CO_2 and H_2O, 106 for O_2 and O_3, and 30 spectral intervals for the infrared absorption by O_3, CO_2, and H_2O. The absorption due to the water vapor continuum was also included (Bignell, 1970). The spectral data for CO_2, H_2O, and O_3 are from McClatchey et al. (1973). The absorption cross sections for O_2 and O_3 are from Ackerman (1971). The surface albedo is 14% (Hummel and Reck, 1979).

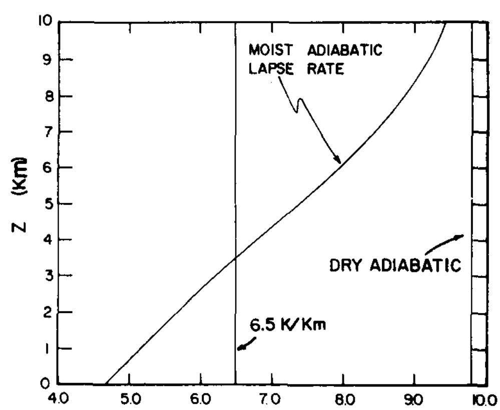

Fig. 2. Moist adiabatic lapse rate as a function of height.

The temperature profile for the model atmosphere was evaluated at the 12 levels listed in Table 1. The ozone mixing ratios are from Dopplick (1972) and the carbon dioxide mass mixing ratio is 4.56×10^{-4}. Calculations were made for a constant relative humidity atmosphere (Manabe and Wetherald, 1967). A profile given by (1) was only used when a lapse rate produced in the radiative-convective model exceeded the moist adiabatic value at the pressure level.

There are two ways in which convective adjustment can be computationally applied. The entire tropospheric lapse rate can be specified to be 6.5 K/km (Rasool and Schneider, 1971; Ramanathan, 1976) or individual lapse rates can be compared with a critical lapse rate such that convective adjustment may only be necessary over a portion of the troposphere. We have used this latter procedure; the computed lapse rates are compared against the critical lapse rate, given by (1) and if found to be unstable, adjusted to this critical value. This comparison is made from the top of the model atmosphere working downward. (Manabe and Wetherald, 1967, initiated their calculations from the bottom of the atmosphere.) When the first convectively unstable layer is found, the temperature profile down to the surface is adjusted to that given by (1). The transmission functions are then recomputed, a new temperature profile generated and the lapse rates again compared with (1). The procedure is continued until the net incoming solar and outgoing terrestrial radiation balance, the stratosphere is in radiative equilibrium, and no convectively unstable layers exist, i.e., the computed lapse rates are equal to or less than the critical lapse rates.

Table 1. *Pressure levels used in the model calculations*

Level	Pressure (mb)
1	10
2	50
3	100
4	200
5	300
6	400
7	500
8	650
9	800
10	900
11	950
12	1000

In the following, all results are presented for equinox conditions at approximately 35 N which correspond to conditions used by Manabe and Wetherald (1967) in their radiative-convective study against which most 1-D models are compared. In addition, one might expect such a latitude and season to crudely represent a "mean global condition" since the out-going infrared radiation and absorbed solar radiation are in balance at approximately this latitude (Vonder Haar and Suomi, 1971). The model parameters are summarized in Table 2.

3. Results

Standard atmosphere calculations were made for clear skies and average cloud conditions with one, two, and three cloud layers. Under clear sky conditions the surface temperature calculated using critical moist adiabatic lapse rates is 291.90 K as compared with 294.04 K for a critical 6.5 K/km lapse rate. Although the average tropospheric lapse rates are nearly equal, 6.17 K/km (moist adiabatic) versus 6.24 K/km (6.5 K/km), the surface temperatures differ by 2 K. In a clear atmosphere the bulk of the infrared radiation comes from the surface and the lowest kilometer or so of the atmosphere. In this region the moist adiabatic lapse rates are less than 6.5 K/km (see Fig. 2) so that a relatively larger amount of the out-going infrared radiation is emitted with a moist adiabatic lapse rate than with the 6.5 K/km lapse rate. Thus, in order to have flux balance between net incoming solar and outgoing infrared radiation the surface temperature in the atmosphere limited to 6.5 K/km must be higher.

When a single cloud with an assumed cover of 50% is included at 500 mb, the surface temperature

Table 2. *Model parameters*

Surface albedo	14%
Rayleigh scattering	7%
Cloud location (fixed)	500 mb
Cloud fraction	50%
Cloud albedo	32%
Surface relative humidity	77%
Solar zenith angle	60°

is still lower in the moist adiabatic case, being 289.79 K, while for a critical 6.5 K/km lapse rate it is 291.14 K. The complete profiles are given in Fig. 3. When clouds are present the infrared flux is controlled primarily by surface temperature and cloud top temperature. With a single cloud at 500 mb the cloud top temperatures are nearly the same for both a critical moist adiabatic lapse rate and one of 6.5 K/km. Thus the near surface contribution to the outgoing infrared radiation is primarily responsible for the different surface temperatures for the two critical lapse rate formulations.

The "dip" in the pressure-dependent lapse rate profile near the cloud top is artificial and is produced by the fixed cloud height and the black body assumption imposed on the cloud. Heating and cooling occur near a cloud base and top respectively and this effect becomes computationally more exaggerated the finer the vertical resolution. Such an effect can be minimized by vertically smoothing the radiative heating/cooling rates although we have not done this since the effect is not crucial to our discussions (see, e.g., Katayama, 1967; Haurwitz and Kuhn, 1974).

Multiple cloud layers were also introduced into the model atmosphere. The cloud parameters used are given in Table 3. For both the two and three cloud cases the surface temperatures are about 2 K lower for a constant 6.5 K/km lapse rate than for critical moist adiabatic rates, which is reversed from the clear sky or single effective cloud models. The reason for the reversal is the cloud top temperatures. As shown in Fig. 2, above about 3 to 4 km, the moist adiabatic lapse rates exceed 6.5 K/km and the atmosphere is generally cooler. The top cloud in the two cloud case and the two higher clouds in the three cloud case are found in this region of the atmosphere. Therefore, the infrared radiation emitted is less from the cloud tops and the surface temperature must be higher in the moist adiabatic case.

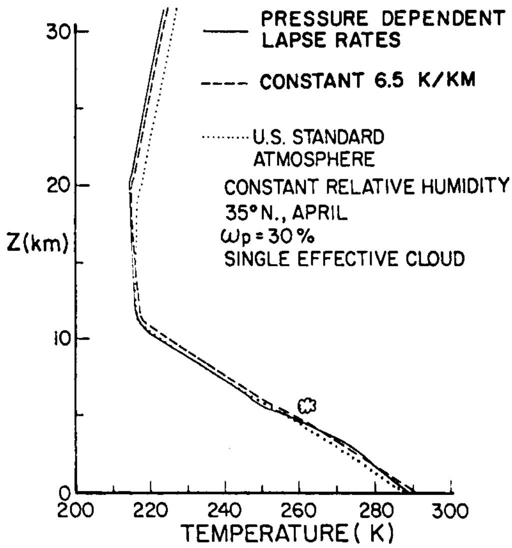

Fig. 3. Comparison of equilibrium temperature profiles from the model using two critical lapse rate formulations: pressure dependent and a constant 6.5 K/km.

Calculations were also made to determine surface temperature sensitivities for changes in

Table 3. *Cloud parameters used and surface temperatures calculated for multiple cloud conditions*

				Surface temperature (K)	
Cloud top	Cloud base	Cloud fraction	Cloud albedo	Moist adiabatic	6.5 K/km
		Two cloud case			
650	650	0.079	0.480	271.83	270.17
650	800	0.320	0.690		
		Three cloud case			
300	300	0.181	0.210		
650	650	0.079	0.480	283.30	280.87
650	800	0.320	0.690		

carbon dioxide content, relative humidity, cloud cover fraction, and surface albedo. A single effective cloud was included. The results are summarized in Table 4. It is important to note that the reductions in sensitivity shown in Table 4 apply only to the single effective cloud model used in this study. The reductions in sensitivity are different with multiple clouds, the results of which will be given in a forthcoming paper by one of us (J.R.H.).

A single cloud model was chosen in favor of a multiple layer model for two reasons. First, multiple cloud models yield significantly different climate sensitivities than do models with only one cloud (Kuhn, 1978; Reck, 1978). These different sensitivities arise from the effects which cloud parameters such as altitude, thickness, amount, optical properties, and the nature of the cloud overlap have on surface temperature calculations.

Second, the cloud amounts, albedos, and absorptivities suggested for three-cloud models (Manabe and Wetherald, 1967) when used with the recently revised surface albedo value of 14% (Hummel and Reck, 1979) produce a planetary albedo of 37%. A single, effective cloud was used because it was found that using the cloud amounts and albedos of Manabe and Wetherald (1967) in a three cloud model along with the realistic surface albedo of 14% based on the recent detailed surface albedo model of Hummel and Reck (1979) will not give realistic surface temperatures (289 K). With the cloud amounts and albedos suggested by Manabe and Wetherald (1967) and the applicable surface albedo of 14%, a surface temperature of 286.66 K is obtained, but the resulting planetary albedo is 37%. By reducing the surface albedo and modifying the Manabe and Wetherald (1967) cloud amounts the planetary albedo can be forced to 30%. Under these conditions, the resulting surface temperature is about 296 K, in good agreement with the 294.9 K value of Reck (1975). These conditions are applicable for a completely ocean-covered earth. Even with an adjustment of the cloud amounts to achieve a planetary albedo of 30% and fractional coverage of 50%, realistic surface temperatures cannot be obtained without an unrealistic adjustment of the other physical parameters such as ozone abundance, surface albedo, cloud albedos, etc. Therefore, in order to focus on the effects of the lapse rate formulations alone, a single effective cloud was used.

Table 4. *Surface temperature changes from changes in physical parameters using moist adiabatic lapse rates and a constant 6.5 K/km*

	Constant 6.5 K/km (K)	Moist Adiabatic lapse rates (K)
300–600 ppmv CO_2	1.94	0.79
77–87% RH	0.96	0.33
77–67% RH	−0.86	−0.43
50–45% A_c	0.30	0.05
50–55% A_c	−0.20	−0.04
14–12% ω_s	1.71	0.65
14–16% ω_s	−2.14	−1.07

RH—surface value of relative humidity. A_c—fractional cloud cover. ω_s—surface albedo.

As noted in Table 4 the surface temperature sensitivities are larger in all cases when a constant 6.5 K/km critical lapse rate is imposed. In the case of doubled carbon dioxide, the moist adiabatic lapse rate formulation gives a 0.79 K increase in the surface temperature while the use of a constant 6.5 K/km rate yields 1.94 K. Hunt and Wells (1979) reported an increase of 1.82 K for a radiative-convective model with moist adiabatic lapse rates and oceanic heat capacity. The details of their radiation calculations are not given, so direct comparison is difficult. We note, however, that their surface temperature and temperature differences agree with ours for clear sky conditions.

The moist adiabatic lapse rate gives a greater variation in sensitivity with respect to a doubling of CO_2 for a change in cloud height than does a 6.5 K/km lapse rate. A comparison is shown in Table 5 for single clouds located at either 500 or 800 mb.

For a critical lapse rate of 6.5 K/km, the

Table 5. *Comparison of surface temperatures for critical lapse rates of 6.5 K/km and moist adiabats*

		Cloud height (mb)	
		500	800
6.5 K/km,	present CO_2	291.14	282.87
	twice CO_2	293.08	284.69
Moist adiabatic,	present CO_2	289.79	282.52
	twice CO_2	290.58	284.05

temperature increase for a doubling of CO_2 is nearly the same for a cloud located at 500 (1.94 K) or 800 mb (1.82 K). However, if the moist adiabat represents the critical lapse rate, then the temperature increase for a doubling of CO_2 is 1.53 K for the single lower cloud while for the cloud at 500 mb, the temperature increase is only 0.79 K. For higher surface temperatures such as occur with the cloud at 500 mb, the difference in air temperature between the moist adiabat and the 6.5 K/km lapse rate is larger than the air temperature differences for the lower surface temperatures corresponding to the cloud at 800 mb since the atmosphere contains less water vapor. Thus the sensitivities between the two lapse rate formulations differ by only 16% for a cloud at 800 mb.

With the cloud at 500 mb, the moist adiabatic lapse rate yields a smaller sensitivity than does a 6.5 K/km lapse rate (1.94 K vs. 0.79 K). In the latter case, i.e., with a constant lapse rate formulation, the air temperature differences cannot exceed the surface temperature differences. This is not the case for the moist adiabatic lapse rate however, since it depends on temperature and air temperature differences do indeed exceed the surface temperature differences. Thus in the moist adiabatic case, a greater contribution to the outgoing radiation occurs from the atmosphere relative to the surface so that the surface temperature need not increase as much as with the 6.5 K/km lapse rate formulation in order to maintain a constant outgoing infrared flux.

Clearly, the difference in sensitivity that occurs between the constant 6.5 K/km lapse rate or a critical moist adiabatic value is because a constant lapse rate decouples the stability characteristics of the model atmosphere from the temperature profile. The lowest few kilometres is where convective stabilization occurs and by limiting the lapse rate to 6.5 K/km the surface is forced to undergo larger temperature changes in order to maintain flux balance.

4. Conclusions

On a global scale, moist adiabatic processes, and thus moist adiabatic lapse rates approximate the atmospheric temperature profile. Comparisons of profiles from a one-dimensional radiative-convective model have been made using the conventional 6.5 K/km as the critical lapse rate and the pressure-dependent moist adiabatic lapse rates. For a clear sky and a single effective cloud the surface temperatures are 1 to 3 K higher with the constant 6.5 K/km critical lapse rate. However, when multiple cloud layers are included the 6.5 K/km critical lapse rate yields surface temperatures 1 to 3 K lower than when pressure-dependent moist adiabatic lapse rates are used. For changes in physical parameters such as carbon dioxide, relative humidity, fractional cloud cover, and surface albedo, the 6.5 K/km critical lapse rate formulation consistently gives larger surface temperature differences. In the case of doubled CO_2, a critical lapse rate of 6.5 K/km gives a temperature increase of 1.94 K while the moist adiabatic formulation gives 0.79 K. For the physical parameters studied the relative difference in estimates between the two lapse rate formulations ranged between 33–65%, significantly larger than the uncertainty in input data.

The reductions in surface temperature sensitivity reported here from the use of pressure-dependent moist adiabatic critical lapse rates apply only for a model with a single, effective fixed cloud. These results demonstrate the influence which the choice of critical lapse rate can have on model calculations. The magnitude of the reduction may not apply to multiple cloud models.

Radiative convective models employing a constant critical lapse rate have been successful in helping us understand some of the physical principles involved in climate change. However, there are some cases where a scheme which couples the temperature profile to the lapse rate, such as demonstrated in this work, should be an improvement. A climate model, for example, that is self-consistent among cloud height, water vapor amount, and temperature should employ a moist adiabatic lapse rate as the critical lapse rate, since it is this lapse rate that limits the temperature and thus water vapor and cloud height.

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СРАВНЕНИЕ РАДИАЦИОННО-КОНВЕКТИВНЫХ МОДЕЛЕЙ С ПОСТОЯННЫМИ И ЗАВИСЯЩИМИ ОТ ДАВЛЕНИЯ ВЕРТИКАЛЬНЫМИ ГРАДИЕНТАМИ ТЕМПЕРАТУРЫ

В текущем поколении радиационно-конвективных моделей используется постоянная величина для критического вертикального градиента температуры в атмосфере, обычно 6,5 К/км. Однако влажноадиабатические вертикальные градиенты температуры являются лучшим приближением для использования в простых климатических моделях. Таким образом, сделано сравнение температурных профилей с критическим постоянным и влажноадиабатическим вертикальными градиентами температуры для одномерной радиационно-конвективной модели.

Обычно используемый вертикальный градиент температуры 6.5 К/км дает несколько, на 1–3 К, более высокие поверхностные температуры, чем с использованием влажноадиабатических вертикальных градиентов температуры как для безоблачных условий, так и для одного эффективного облака. При включении многослойных облаков постоянный вертикальный градиент температуры 6.5 К/км дает более низкие поверхностные температуры. Более важно, что поверхностная температура, получаемая при постоянном вертикальном градиенте температуры, более чувствительна к изменениям двуокиси углерода, относительной влажности, облачного покрова альбедо и поверхности. Для удвоения CO_2 с влажноадиабатическим вертикальным градиентом температуры изменения поверхностной температуры меньше на величину от 25 до 60%, чем при постоянном вертикальном градиенте температуры 6.5 К/км, в зависимости от трактовки облачности.