Tellus (1982), *34*, 203–208

Surface temperature sensitivities in a multiple cloud radiative-convective model with a constant and pressure dependent critical lapse rate

By JOHN R. HUMMEL, *Physics Department, General Motors Research Laboratories, Warren, Michigan 48090, U.S.A.*

(Manuscript received August 12, 1980; in final form June 25, 1981)

ABSTRACT

A comparison is made of the surface temperature sensitivities in the Hummel–Kuhn radiative–convective model with fixed clouds, but without water vapor transport, using first the constant critical lapse rate of 6.5 K/km and then with pressure-dependent moist adiabatic critical lapse rates. The moist adiabatic critical lapse rate formulation is shown to yield consistently smaller surface temperature sensitivities to parameter variations than those yielded from using the traditional 6.5 K/km.

For a doubling of carbon dioxide (300 p.p.m.v. to 600 p.p.m.v.). the surface temperature increase is 1.29 K with moist adiabatic lapse rates compared with 1.83 K for the 6.5 K/km formulation. In addition, the surface temperature sensitivities to changes in surface relative humidity, surface albedo, and cloud amounts are shown to be nonlinear with pressure-dependent critical lapse rates rather than linear as with the constant 6.5 K/km.

1. Introduction

In simple energy balance climate models, the vertical atmospheric temperature profile is computed as a function of radiative heating rates and convective adjustment. The model atmosphere is forced to remain stable by requiring that the atmospheric lapse rate γ, the variation in temperature with altitude, never exceeds a critical value, γ_c.

Traditionally, the value of γ_c most commonly used has been 6.5 K/km. Based on an early analysis of limited atmospheric temperature data, the value of 6.5 K/km as the critical lapse rate has been assumed to be independent of altitude, latitude, and season (Manabe and Strickler, 1964). This value of γ_c is used in most radiative–convective models currently in use (e.g. Manabe and Wetherald, 1967; Schneider, 1972; Weare and Snell, 1974; Ramanthan, 1976) and has allowed the model atmosphere's sensitivity to changes in physical parameters alone to be evaluated (e.g. Reck, 1978). The value of 6.5 K/km is *not* based on a physical analysis of atmospheric processes and will not reproduce observed atmospheric lapse rates (Rennick, 1977). While 6.5 K/km has been traditionally taken as the average tropospheric lapse rate, recent results indicate that about 5 K/km is a more representative average annual lapse rate for the troposphere (Stone and Carlson, 1979). The observed average lapse rate does indeed vary with altitude, latitude, and season. As discussed by Hummel and Kuhn (1981) radiative–convective models that employ 6.5 K/km as the critical lapse rate tend to overestimate surface temperature sensitivities to changes in model physical parameters when compared to a pressure-dependent critical lapse rate formulation.

Hummel and Kuhn (1981) only examined the effects of a pressure-dependent moist adiabatic

0040-2826/82/020203-06$02.50/0

critical lapse rate formulation in a radiative–convective model with a single effective cloud with fixed cloud properties and a single water vapor profile based on the assumption of a constant distribution of relative humidity. The present study extends the research to multiple cloud layers, such as those found in the Manabe and Wetherald model (1967), using the Hummel and Kuhn model (1981) without water vapor transport.

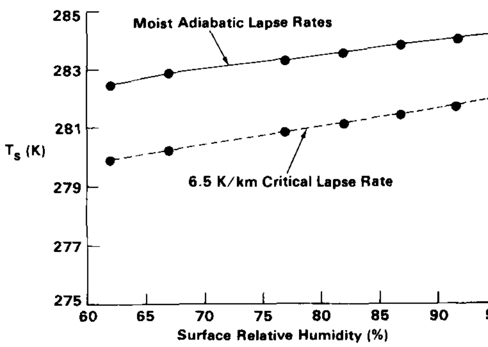

Fig. 2. Surface temperatures for different surface relative humidities.

2. The atmospheric lapse rate

In the atmosphere, the temperature at an altitude z is determined by physical processes such as radiative heating or cooling, latent heat release, and the type of air being transported into or out of a unit volume. The dominant transport processes above the planetary boundary layer are convection and baroclinic processes. In tropical regions, moist convective transport is the dominant transport mechanism.

In Fig. 1 a plot of the moist adiabatic lapse rates in a mid-latitude U.S. standard atmosphere is given. The dry adiabatic lapse rate and 6.5 K/km value are also shown for comparison. Annual average lapse rates for 35 N are also shown based on Fig. 2 of Stone and Carlson (1979). Below about 3.5 km, the moist adiabatic lapse rates are less than 6.5 K/km. Above 3.5 km the moist adiabatic lapse rate exceeds 6.5 K/km, meaning that in this region energy balance models do achieve absolute stability. One of the properties of energy balance radiative–convective models is that they achieve stability everywhere, so the choice for a critical lapse rate should not be a constant value of 6.5 K/km or any other constant value but the appropriate pressure-dependent value at each altitude. The critical lapse rate should be based on which atmospheric process or processes dominate.

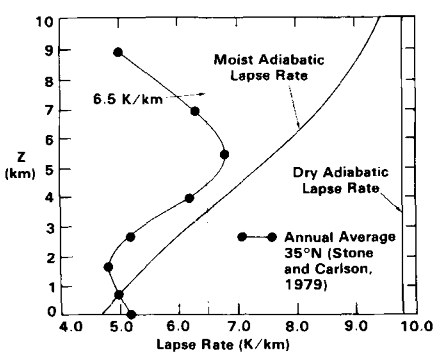

Fig. 1. Moist adiabatic lapse rates in a mid-latitude standard atmosphere.

For global and hemispheric conditions, however, the lower tropospheric vertical temperature structure (above the planetary boundary layer) is well represented by moist adiabatic lapse rates. The use of moist adiabatic lapse rates, however, will not provide the correct seasonal change in the lapse rate. The divergence of the observed annual average lapse rate from the moist adiabatic lapse rate above about 5 km indicates the lessening contribution of moist convective processes above this altitude. For zonally averaged conditions, especially for mid and high altitudes, pressure-dependent moist adiabatic lapse rates insure that the model atmosphere is absolutely stable but severly underestimate the contributions from baroclinic processes (Stone and Carlson, 1979). Strictly speaking, moist adiabatic lapse rates are only applicable under saturated conditions. By using the moist adiabatic lapse rates the intent is to allow the model to reproduce mean observed conditions, not to imply that the thermodynamics of moist convection are included. Stone and Carlson (1979) have presented a critical lapse rate formulation for baroclinic processes, but seeing that it depends on a latitudinal temperature gradient, it is unsuited for one-dimensional models. However, using climatological average data or parameterizations, such as the one developed by Rennick (1977), their formulation may be useable in simple, one-dimensional climate models.

3. Methodology

The radiative–convective model includes solar absorption by O_2, O_3, CO_2, and H_2O and infrared absorption by O_3, CO_2, and H_2O, and anomalous water absorption (Bignell, 1970). A temperature is initially assumed at each of twelve vertically aligned points. A forward time integration of the solar and infrared heating rates is performed until a balance between the net incoming solar and outgoing infrared radiation fluxes exists at the top of the atmosphere. In addition, the stratosphere is required to be in radiative equilibrium and no convectively unstable layers are allowed to exist in the lower atmosphere. Whenever the net flux at the top of the atmosphere is not in balance the surface temperature is adjusted. Lapse rates are then compared against the critical lapse rates and adjusted if the critical lapse rates are exceeded. Results will be presented for surface temperature sensitivities from changes in physical parameters using both pressure-dependent moist adiabatic critical lapse rates and the conventional constant 6.5 K/km critical lapse rate. The assumed standard atmosphere conditions are given in Table 1.

Table 1. *Assumed standard atmosphere conditions. The cloud properties are assumed to be fixed and the water vapor profile is based on a constant distribution of relative humidity (Manabe and Wetherald, 1967)*

Surface albedo, ω_s			14%
Rayleigh scattering, ω_R			7%
Aerosols			None
Carbon dioxide content			300 p.p.m.v.
Surface relative humidity, h_0			77%
Cloud properties			
	High	Middle	Low
Pressure levels (mb)	300 (thin)	650 (thin)	650–800
Fractional cloud cover, a_c	0.181	0.079	0.302
Cloud reflectivities	0.210	0.480	0.690
Cloud absorptivities	0.0	0.0	0.0
Infrared emissivity	1.0	1.0	1.0

4. Discussion of results

4.1. *Standard atmosphere conditions*

Calculations were performed for changes in carbon dioxide content, surface relative humidity, surface albedo, and cloud cover. The surface temperatures for the standard atmosphere conditions and the surface temperature differences for the CO_2, relative humidity, and surface albedo changes are given in Table 2.

Table 2. *Surface temperatures for standard conditions and surface temperature differences for changes in* CO_2 *content, surface relative humidity, and surface albedo,* ω_s

	Constant 6.5 K/km	Pressure-dependent moist adiabatic lapse rates
	T_s (K)	
Standard conditions (300 p.p.m.v. CO_2, 77% h_0, 14% ω_s, clouds as in Table 1)	280.87	283.30
	ΔT_s (K)	
300–450 p.p.m.v CO_2	0.93	0.72
300–600 p.p.m.v. CO_2	1.83	1.29
77%–67% RH	−0.61	−0.47
77%–87% RH	0.55	0.45
14%–12% ω_s	1.78	1.33
14%–16% ω_s	−1.66	−1.25

For the same standard conditions, the surface temperature described by pressure-dependent moist adiabatic lapse rates is 2.43 K warmer than the surface temperature with the constant 6.5 K/km critical lapse rate. This is due to the distribution of the clouds in the atmosphere. When clouds are in a model atmosphere the outgoing infrared flux is controlled by the surface and cloud top temperatures. In the model atmospheres considered, the middle and low clouds in the two cases (i.e., moist adiabatic and 6.5 K/km lapse rate calculations) have essentially the same cloud top temperatures. As shown in Fig. 1 above about 650 mb (~3.5 km) the pressure-dependent moist adiabatic lapse rates exceed 6.5 K/km. This means that the atmosphere above this level is colder when pressure-dependent moist adiabatic critical lapse rates are used. The outgoing infrared flux is then less than if 6.5 K/km was used as the critical lapse rate. In order to have flux balance, the surface temperature must be larger in the moist adiabatic lapse rate atmosphere. As discussed by Hummel and Kuhn (1981) the opposite occurs when only a single effective cloud is used or if clear sky conditions are assumed. That is, the 6.5 K/km lapse rate atmosphere is warmer.

4.2. *Carbon dioxide*

For both 50% and 100% increases in atmospheric carbon dioxide content the model atmosphere with a constant 6.5 K/km critical lapse rate yields larger surface temperature sensitivities than if pressure-dependent moist adiabatic lapse rates were used (Table 2). This result is consistent with the clear sky and single effective cloud results of Hummel and Kuhn (1981) and the coupled ocean–atmosphere model of Hunt and Wells (1979).

When there is a change in a physical parameter the flux balance is maintained by changes in the temperature profile. As the temperature profile changes, the contributions from moist convection also change. Therefore, the critical lapse rate for moist convection should change. By using a constant critical lapse rate of 6.5 K/km this is not accounted for. The use of pressure-dependent moist adiabatic critical lapse rates forces the requirement for convective adjustment to change as the model atmosphere changes. When the CO_2 increases, the lower atmosphere warms as a result of infrared absorption. As the temperature increases, the critical pressure-dependent moist adiabatic lapse rates decrease. This means that the atmospheric temperatures increase more than if the critical lapse rate was held fixed. In fact, the change in temperature for a change in CO_2 content increases with altitude instead of decreases as with constant critical lapse rate models (e.g. Reck, 1978). This can be seen by referring to Table 3, which lists the critical moist adiabatic lapse rates as a function of altitude for both the standard and doubled CO_2 model atmospheres. As this table shows, the critical moist adiabatic lapse rates are less in the doubled CO_2 case up to about 8 km. Above 8 km the lapse rates are larger in the doubled CO_2 case. The temperature change at a level Δz above the surface is, then, the surface temperature change plus the change in lapse rates times Δz. The maximum temperature change occurs at about 8 km and then decreases from there to a net cooling in the stratosphere. The net result is that by allowing the critical lapse rates to be coupled to the temperature profile surface, temperature sensitivities are, in general, less than if the critical lapse rate were fixed.

4.3. *Relative humidity*

Fig. 2 details the effects of the critical lapse rate assumptions on surface temperature. Decreasing the relative humidity at the surface leads to a decrease in the amount of water vapour and a cooling of the atmosphere. Again, the magnitude of the cooling is less with the pressure-dependent moist adiabatic lapse rates. As the atmosphere cools, the critical atmospheric lapse rates increase,

Table 3. *Critical moist adiabatic lapse rates as a function of altitude for the standard and doubled carbon dioxide atmospheres*

Altitude (km)	Standard	Doubled CO_2
25	7.72	8.17
18	9.50	9.56
14	9.65	9.66
11	9.80	9.80
8	9.73	9.71
7	9.42	9.34
5	8.75	8.59
3	7.38	7.15
2	6.22	6.03
1	5.68	5.52
0	5.50	5.35

meaning that the atmosphere can sustain a larger lapse rate without triggering convection. As with the carbon dioxide results the greatest change in temperature is not at the surface but at about 500 mb. Increasing the relative humidity increases the water vapour amount. The increased water vapor absorption leads to an atmospheric heating and surface temperature increase. Again, the surface temperature sensitivities to changes in relative humidity are less when pressure-dependent moist adiabatic lapse rates are used. This is true for all relative humidities examined as shown in Fig. 2. The surface temperature sensitivity to changes in relative humidity is nearly linear with a constant critical lapse rate of 6.5 K/km, in agreement with Reck (1978). As the figure shows, the sensitivity is not linear when the pressure-dependent moist adiabatic lapse rates are used. The nonlinear response is due to the coupling between temperature and the moist adiabatic critical lapse rates.

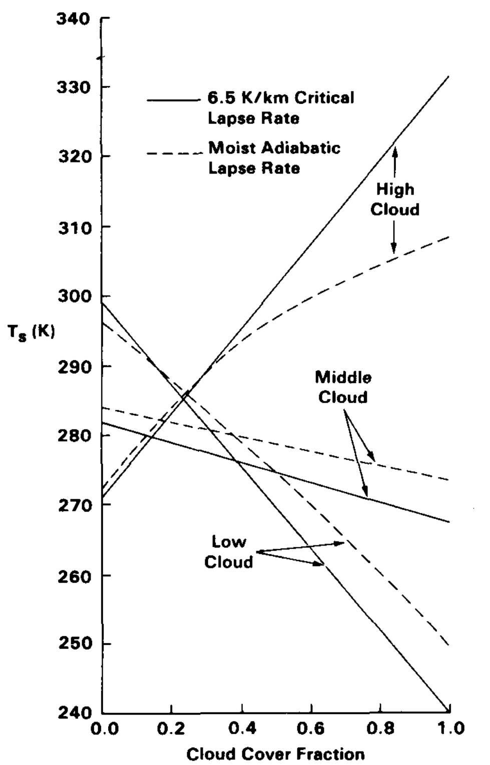

Fig. 3. Surface temperatures for changes in high, middle, and low cloud amounts.

4.4. *Surface albedo*

As with the previous results, the surface temperature changes from variations in surface albedo are less when pressure dependent moist adiabatic lapse rates are used as the critical lapse rates. Again the reason is that the critical lapse rates are coupled to the temperature profile.

4.5. *Cloud cover amount*

Fig. 3 displays the surface temperatures for changes in high, middle, and low cloud amounts, respectively. In each case, one cloud cover amount was varied while the other two were held fixed. In all cases, the results from using a constant critical lapse rate of 6.5 K/km exhibit a linear relationship between surface temperature and cloud cover. The results from employing the pressure-dependent moist adiabatic critical lapse rates are non-linear with respect to cloud cover. As with the other parameter variations, the moist adiabatic results exhibit less sensitivity to cloud cover variations than do the 6.5 K/km results.

5. Conclusions

This study examined the implications of using pressure-dependent moist adiabatic critical lapse rates in a radiative–convective model with multiple clouds. For the same standard conditions the surface temperature described by the pressure-dependent moist adiabatic critical lapse rate is 2.4 K warmer than the model atmosphere with the constant 6.5 K/km critical lapse rate. Surface temperature sensitivities to changes in carbon dioxide, surface relative humidity, surface albedo, and cloud cover amounts are smaller by 7 to 64% with pressure-dependent moist adiabatic critical lapse rates rather than the constant value of 6.5 K/km. In addition, the surface temperature sensitivities to changes in surface relative humidity, surface albedo, and cloud cover amounts are non-linear when pressure-dependent moist adiabatic critical lapse rates are used rather than linear as with the traditional constant value of 6.5 K/km. The reductions in surface temperature sensitivities and the non-linear relationships from using pressure-dependent moist adiabatic critical lapse rates are due to the coupling between the temperature profile and the critical lapse rates. By reducing the surface temperature sensitivities the conclusion that climatic sensitivities are also less cannot, as of yet, be made. The reductions in surface temperature changes are made by coupling the critical lapse rates, i.e. dynamical contributions, to the temperature profile. The dynamical contributions lead to other climatic characteristics such as mass and momentum transport that cannot be examined in a one-dimensional framework. The inclusion of pressure-dependent critical lapse rates, utilizing both moist adiabatic and baroclinic lapse rates (e.g. Stone and Carlson, 1979), does provide the groundwork, however, for the development of a two-dimensional climate model that can be used to model realistic climate sensitivities.

REFERENCES

Bignell, W. J. 1970. The water-vapour infrared continuum. *Quart. J. Roy. Meteorol. Soc. 96*, 390–403.

Hummel, J. R. and Kuhn, W. R. 1981. Comparison of radiative–convective models with constant and pressure-dependent lapse rates. *Tellus 33*, 254–261.

Hunt, B. G. and Wells, N. C. 1979. An assessment of possible future climatic impact of carbon dioxide increases based on a coupled one-dimensional atmospheric oceanic model. *J. Geophys. Res. 84*, 787–791.

Manabe, S. and Strickler, R. F. 1964. Thermal equilibrium of the atmosphere with a convective adjustment. *J. Atmos. Sci. 21*, 361–385.

Manabe, S. and Wetherald, R. T. 1967. Thermal equilibrium of the atmosphere with a given distribution of relative humidity. *J. Atmos. Sci. 24*, 241–259.

Ramanathan, V. 1976. Radiative transfer within the earth's troposphere and stratosphere: A simplified radiative–convective model. *J. Atmos. Sci. 33*, 1330–1346.

Reck, R. A. 1978. Global temperature changes: Relative importance of different parameters as calculated with a radiative–convective model. In *Carbon Dioxide Climate and Society* (ed. Jill Williams). New York: Pergamon Press, 193–200.

Rennick, M. A. 1977. The parameterization of tropospheric lapse rates in terms of surface temperature. *J. Atmos. Sci. 34*, 854–862.

Schneider, S. H. 1972. Cloudiness as a global climatic feedback mechanism: The effects on the radiation balance and surface temperature of variations in cloudiness. *J. Atmos. Sci. 29*, 1413–1422.

Stone, P. and Carlson, J. 1979. Atmospheric lapse rate regimes and their parameterization. *J. Atmos. Sci. 36*, 415–423.

Weare, B. C. and Snell, F. M. 1974. A diffuse thin cloud structure as a feedback mechanism in global climatic modeling. *J. Atmos. Sci. 31*, 1725–1734.