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Cloud optical feedback and climate stability in a radiative-convective model[1]

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ABSTRACT

A globally averaged, one-dimensional radiative-convective climate model is used to study the effect of clouds on both the climate and the sensitivity of climate to changes in incoming solar radiation. The model has been run with low, mid and high clouds of different areas, heights and liquid water contents (LWC). The cloud optics in both solar and terrestrial infrared wavelengths are a function of the cloud LWC.

In some runs the cloud properties are held fixed. Then the model temperature is strongly dependent upon the selected LWC of clouds, especially when the LWC is small. The model sensitivity to changes in the solar constant is not, however, so strongly dependent upon the selected cloud area, height, or LWC.

In other model runs the cloud LWCs are permitted to vary in direct proportion to the water vapor mixing ratio, which changes with temperature. This permits a rough evaluation of the feedback relations between cloud optical properties and climate. Under this hypothesis, variable cloud optics generally serve as a significant negative feedback mechanism in climate change. High thin cirrus can be a special positive feedback case.

1. Introduction

There is a continuing interest in understanding the role of atmospheric radiation in both short- and long-term climate changes (Hansen et al., 1978; Hart, 1978). Clouds exert a profound influence on the radiation balance in both solar (SW) and terrestrial infrared (IR) wavelengths (Schneider, 1972), with their cooling effects in SW generally exceeding their heating effects in the IR (Hartman and Short, 1980).

A change in the climate may be accompanied by a change in the height, amount, and optical properties of clouds, which may in turn feedback to enhance or diminish the original change in climate (Hunt, 1981). Cess (1974) has indicated that cloud height may vary with surface temperature so as to keep cloud top temperature constant, resulting in a positive feedback mechanism in climate change. Wetherald and Manabe (1980) have simulated climate change with a general circulation model and concluded that change in cloud amount is probably not a significant climate feedback mechanism in the global sense. An earlier theoretical study by Weare and Snell (1974) suggested that the feedback relations between climate and the optical properties of clouds (rather than variations in their amounts, as addressed in the valuable Wetherald and Manabe study) are significant.

Present uncertainty in how cloud optical properties may change with climate introduces a like uncertainty in our understanding of the first-order radiative stability of climate. This is the case even if variations in cloud amounts or heights are not significant in climate change. A change in surface temperature would change the absolute humidity of the atmosphere (Manabe and Wetherald, 1967), which may in turn be reflected by a change in cloud liquid water content (LWC), and hence also cloud optics and the radiation balance.

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We have a fairly accurate picture of the relation of cloud LWC to cloud optics (Stephens, 1978; Liou and Wittman, 1979). Because changes in aerosol optics have been somewhat successfully related to temperature variations (Hansen et al., 1978; Charlock and Sellers, 1980), it can also be assumed that changes in cloud optics can be related to changes in the radiation balance and temperature. A full understanding of the effects of temperature change on cloud LWC is needed, however, to complete the first-order climate-cloud optical property feedback loop. This may require the development of sophisticated microphysical-dynamical models for each cloud type and a highly detailed satellite climatology of cloud LWC as a function of height in different regions and seasons.

The present work examines the stability of globally averaged climate in a one-dimensional radiative-convective model with respect to changes in cloud optical properties, height, and amount, each of which is held constant in the given test of climate stability. In this radiative-convective model the surface relative humidity is fixed, causing the water vapor mixing ratio to vary with surface temperature. Calculations are also made with cloud LWCs which vary in direct proportion to the variation in mixing ratios at cloud height; changes in cloud LWC translate into changes in cloud optics, so this assumption permits a rough scaling of the feedback relations between cloud optical properties and climate.

Paltridge (1980) has followed a similar procedure in a study of cloud climate stability, scaling cloud LWC according to the surface water vapor saturation pressure. Here the work of Paltridge is extended by considering a wide variety of initial cloud LWCs and by explicitly calculating model equilibrium temperatures. A note by Charlock (1981) neglected variations in cloud IR optics, which are included here.

2. The model

A 12-layer, steady state, radiative-convective model, similar to that used by Charlock and Sellers (1980a) and fully documented by Charlock (1979), is employed. A vertical temperature lapse rate of 6.5 K km^{-1} is assumed, and the surface albedo is fixed at 0.150 (Robock, 1980). Rayleigh scattering, absorption due to water vapor, ozone, and carbon dioxide, and scattering and absorption due to clouds are calculated in several solar wavelength (SW) intervals. The disposition of solar radiation in direct and diffuse (scattered) beams is accounted for in a modified adding radiative transfer scheme. The terrestrial infrared (IR) radiative transfer routines include the absorption and emission of water vapor, carbon dioxide, ozone, and clouds. Water vapor e-type absorption is resolved in 5 wavelength intervals in the window.

The top 8 layers of the model are each 100 mb thick, and the lower 4 are 50 mb thick. When clouds occur they occupy an entire layer, swamping the optical properties of the gaseous constituents. The swamping approximation is regarded as somewhat tenuous for the case of very thin cirrus clouds. Some calculations were also made with infinitely thin clouds placed in the middle of the layer. The model sensitivity to changes in the incoming solar radiation did not drastically differ for cases of thin versus thick clouds. The thin cloud calculations, which retained the full IR optical depth of the atmospheric gaseous constituents, produced temperatures 3–4 K higher than did the thick (swamping) cloud calculations.

Low, mid, and high clouds with full overlap simulation are included in the model. The optical properties of low and mid clouds are obtained from Stephens' (1978) liquid water cloud parameterization. A computer program was used to perform interpolations in the Stephens' tables. Stephens' parameterization, which is validated by observations, permits a calculation of SW cloud optics from a form of the Coakley and Chylek (1975) zenith angle-dependent two-stream formulation. Cloud optical properties are given for wavelengths greater or less than 0.75 microns, and cloud IR emissivity can also be obtained.

The optical properties of high (cirrus) clouds are calculated as functions of ice content from the parameterization of Liou and Wittman (1979). In the terrestrial IR, Liou and Wittman give distinct emissivities, transmissivities and reflectivities for cirrus.

In the model runs which investigate the feedback relations between cloud optical properties and climate, the water vapor mixing ratio at cloud height is used to scale the cloud LWC. The water vapor mixing ratio in each vertical layer is obtained from the temperature of the layer and the relative humidity RH, which is given by Ramanathan and Coakley (1978) as

$$RH = RH_0[(p/p_0 - 0.02)(1 - 0.02)^{-1}]^{\Omega}$$
$$\Omega = 1.0 - 0.03(T - 288)$$

where RH_0 is the fixed surface relative humidity of 0.77, p and p_0 are the pressure at cloud height and the surface pressure, and T is the surface temperature.

As mentioned, a crude estimate of the feedback relations between cloud optical properties and climate is made by running the model with perturbed solar inputs for (1) fixed cloud LWC and hence fixed cloud optics and, alternately, (2) variable cloud optics, with cloud LWC varying in direct proportion to water vapor mixing ratio at cloud height. The result is intended to indicate the sign and possibly the magnitude of errors in a climate model which has fixed cloud optics. The physical arguments for increasing cloud LWC with mixing ratio at cloud height are simplistic. As we go up in the atmosphere, the water vapor mixing ratio decreases, and we can correspondingly note that the amount of condensed water in low level cumulus generally greatly exceeds that in high level cirrus. Also, the clouds with the highest LWC, cumulonimbus, are generally found in regions with high water vapor mixing ratio (as in the tropics or midlatitudes in summer).

While the model is run with various cloud heights and cloud areas, as well as various optical properties, cloud heights and areas are fixed within each particular run. Feedback effects involving interactive changes in cloud height or amount are not addressed in this paper.

3. Calculations

3.1. *Low cloud LWC*

Model surface temperature solutions as a function of low cloud LWC are shown in Fig. 1. Cloud amounts are fixed at 0.20 for low, mid, and high clouds which occupy the pressure levels 850–900 mb, 600–700 mb, and 300–400 mb, respectively. These cloud amounts and heights are used throughout the paper unless otherwise specified. Curves A and B (Fig. 1) for different mid and high cloud LWC both display the same sensitivity to low cloud LWC, which is especially strong for LWC less than 200 g m^{-2} (0.2 mm of liquid cloud water in a column).

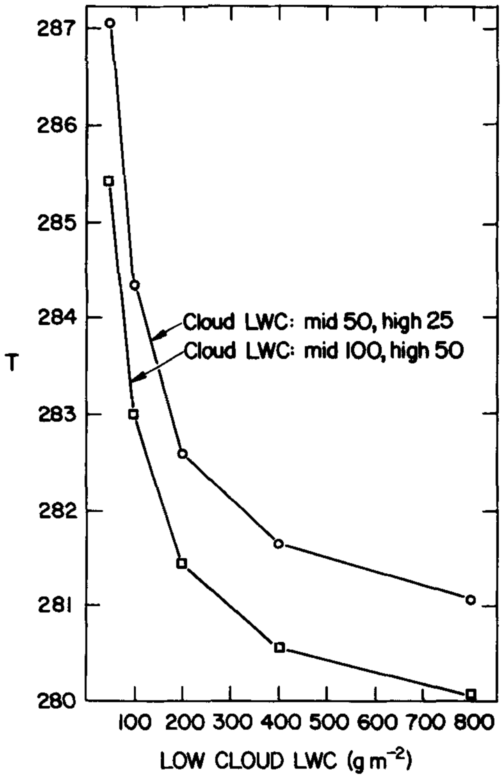

Fig. 1. Model temperature T (K) as a function of low cloud liquid water content LWC (g m^{-2}). Fractional area of each cloud type is 0.20.

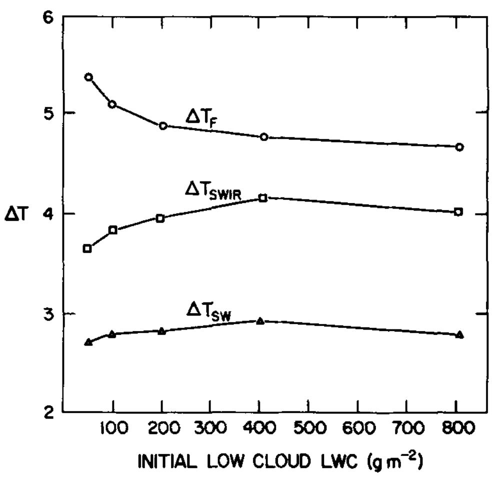

Fig. 2. Temperature change ΔT (K) for a 4% increase in the solar constant as ΔT_F (fixed cloud optics), ΔT_{SWIR} (cloud optics that vary in both SW and IR) and ΔT_{SW} (cloud optics that vary only in SW). Initial LWC for mid and high clouds of 50 and 25 g m^{-2}. Various initial LWC for low cloud.

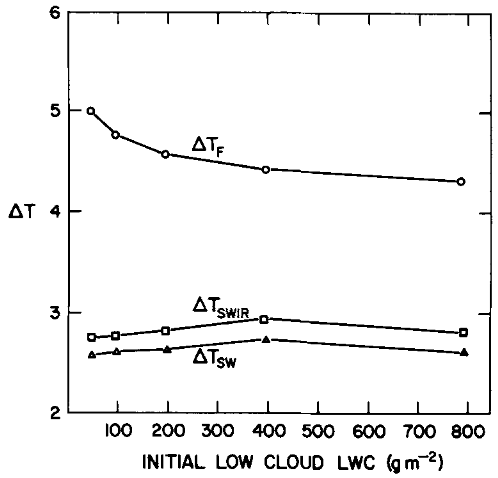

Fig. 3. As in Fig. 2, except that mid and high cloud initial LWC are 100 and 50 g m^{-2}.

The model temperature change ΔT for a 4% increase in the solar constant, specified originally as 1365 W m^{-2}, is indicated in Figs. 2 and 3. ΔT_F, the temperature change for fixed cloud optics, decreases as low cloud LWC increases because of decreasing absorption of solar radiation (Tables 1 and 2). The ΔT_F curves flatten out at high LWC for low clouds because low cloud reflectivity changes relatively little with an increase in LWC beyond 400 g m^{-2}. Table 3, which gives a diagnosis of the changes in cloud optics for the case of cloud LWC originally at 100, 50 and 25 g m^{-2}, shows that reflectivity for the 100 g m^{-2} cloud changes less than that for the 50 and 25 g m^{-2} clouds.

Table 1. *Model temperature T (K) and solar wavelength absorption SW ABS (W m^{-2}) as a function of low cloud liquid water content LWC (g m^{-2}). Temperature change ΔT for a 4% increase in the solar constant ΔT_F (fixed cloud optics), ΔT_{SWIR} (cloud optics that vary in both SW and IR) and ΔT_{SW} (cloud optics that vary only in SW). Initial LWC for mid and high clouds are 50 and 25 g m^{-2}*

	Low cloud LWC (g m^{-2})				
	50	100	200	400	800
T	287.07	284.29	282.57	281.63	281.05
SW ABS (W m^{-2})	232.94	227.49	223.96	221.96	220.67
ΔT_F	5.39	5.11	4.91	4.77	4.66
ΔT_{SWIR}	3.63	3.83	3.96	4.14	4.00
ΔT_{SW}	2.69	2.77	2.83	2.92	2.77

Table 2. *As in Table 1, except that the initial mid and high cloud LWC are 100 and 50 g m^{-2}*

	Low cloud LWC (g m^{-2})				
	50	100	200	400	800
T	285.45	282.98	281.43	280.54	280.01
SW ABS (W m^{-2})	225.87	220.86	217.57	215.68	214.44
ΔT_F	5.02	4.78	4.59	4.42	4.31
ΔT_{SWIR}	2.74	2.78	2.80	2.93	2.80
ΔT_{SW}	2.60	2.59	2.62	2.74	2.60

ΔT_{SW} in Figs. 1 and 2 has low, mid, and high cloud LWC and optics which vary in SW but are fixed in the terrestrial IR. Variable SW cloud optics are seen to provide roughly 40% (the difference of ΔT_F and ΔT_{SW}, divided by ΔT_F) of negative feedback on climate change. ΔT_F (fixed cloud optics) and ΔT_{SW} (variable SW cloud optics) are widely separated at small low cloud LWC because the reflectivity of clouds in the Stephens parameterization varies more at small LWC, giving a sharp negative feedback due to variable SW cloud optics at small LWC.

The optical properties of all clouds in both SW and IR vary in ΔT_{SWIR}. $\Delta T_F > \Delta T_{SWIR}$, so variable cloud optics is seen to be a negative feedback on climate change in all of the cases in Tables 1 and 2.

Table 3. *Model optics for (1) a solar constant of 1365 W m^{-2} and (2) a 4% increase in the solar constant with variable cloud SW and IR optics*

Solar constant (W m^{-2})	1365	1365 × 1.04
T	284.29	288.12 ($\Delta T_{SWIR} = 3.83$)
Cloud LWC (g m^{-2})		
low	100	132.6
mid	50	71.2
high	25	41.8
Cloud reflectivity		
low	0·702	0·728
mid	0.613	0.663
high	0.187	0.238
Cloud absorption		
low	0.128	0.131
mid	0.119	0.124
high	0.062	0.093
Cirrus IR properties		
emissivity	0.803	0.908
reflectivity	0.148	0.176
transmissivity	0.178	0.067

This is despite the relative positive feedback effect of variable cloud IR optics ($\Delta T_{SWIR} > \Delta T_{SW}$). At the LWCs used here, the IR emissivity of low and mid clouds are almost 1.0 and vary little with LWC, so the cloud IR climate feedback effects are due to variable high (cirrus) IR optics. As with SW cloud optics, most of the variability in cirrus IR optics is at small LWC. Thus Fig. 2, in which initial cirrus LWC is 25 g m^{-1}, has a larger ΔT_{SWIR} than Fig. 3, in which the initial cirrus LWC is 50 g m^{-2}. At about 25 g m^{-2} the positive feedback effects of cirrus IR changes exceed cirrus negative feedback effects in SW.

3.2. *Cloud altitude*

The effect of placing high and mid cloud in different pressure (vertical) levels is shown in Tables 4 and 5. The initial cloud LWCs are 100, 50 and 25 g m^{-2}. Cloud vertical pressure increments of 100 mb are used in both tables. This corresponds to larger height (in meters) variations for the high cirrus cloud in Table 4 as opposed to the mid cloud in Table 5, and causes the high cloud case to have a larger temperature increase with decreasing pressure than the mid cloud case. Changes in cloud height do not cause a drastic change in the sensitivity (ΔT) of the model to a 4% increase in the solar constant. ΔT_F for fixed cloud optics remains the largest ΔT, indicating that variable cloud optics is a negative feedback on climate change under the stated assumptions.

As high cloud altitude increases in Table 4, both SW absorption and climate sensitivity for fixed cloud optics ΔT_F increase. These variables decrease, however, as the mid cloud altitude increases in Table 5. Now ΔT_F in the model is generally proportional to the SW absorption. As cloud altitude increases, the SW absorption is affected by two main factors: (1) SW absorption decreases because more of the absorbing gases now have the reflecting cloud placed above them and (2) SW absorption increases because as cloud altitude increases so does surface temperature (Schneider, 1972), and higher surface temperatures mean higher water vapor mixing ratios with fixed relative humidity. Effect (1) dominates for the mid cloud because the amount of absorbing H_2O at mid cloud height is still fairly substantial. The greenhouse-water vapor effect (2) is the most important for high cloud altitude variations because of the smaller high cloud reflectivity and lower amount of absorbing H_2O at cloud level.

Table 4. *Model temperature T and solar wavelength absorption SW as a function of cirrus cloud height. Temperature change ΔT for a 4% increase in the solar constant ΔT_F (fixed cloud optics), ΔT_{SWIR} (cloud optics that vary in both SW and IR) and ΔT_{SW} (cloud optics that vary only in SW). Initial LWCs for low, mid and high clouds are 100, 50 and 25 g m^{-2}*

	High cloud pressure level (mb)		
	400–500	300–400	200–300
T	281.98	284.29	287.68
SW ABS (W m^{-2})	227.06	227.49	228.30
ΔT_F	4.95	5.11	5.37
ΔT_{SWIR}	3.48	3.83	4.17
ΔT_{SW}	2.75	2.77	2.72

Table 5. *As in Table 4, except that the height of mid cloud is varied*

	Mid cloud pressure level (mb)		
	700–800	600–700	500–600
T	283.52	284.29	285.33
SW ABS (W m^{-2})	228.08	227.49	227.03
ΔT_F	5.18	5.11	5.08
ΔT_{SWIR}	3.93	3.83	3.75
ΔT_{SW}	2.83	2.77	2.73

3.3. *High cloud LWC*

The temperature solutions for variations in cirrus cloud initial ice content are shown in Fig. 4. For both cases, with the cloud between 200–300 mb and 300–400 mb, the highest temperature is obtained for a cirrus ice content of about 50 g m^{-2}. As cirrus ice content increases, both the heating effect of its increased IR opacity and the cooling effect of its SW reflectivity increase as well. The heating effect generally dominates for cirrus (note following section on increase of high cloud amounts), but as cirrus ice content increases, IR opacity in the Liou and Wittman optics tends to maximize faster than SW reflectivity, so ice contents in excess of 50 g m^{-2} cause relative cooling.

This effect is qualitatively validated by the aircraft observations of Paltridge and Platt (1980),

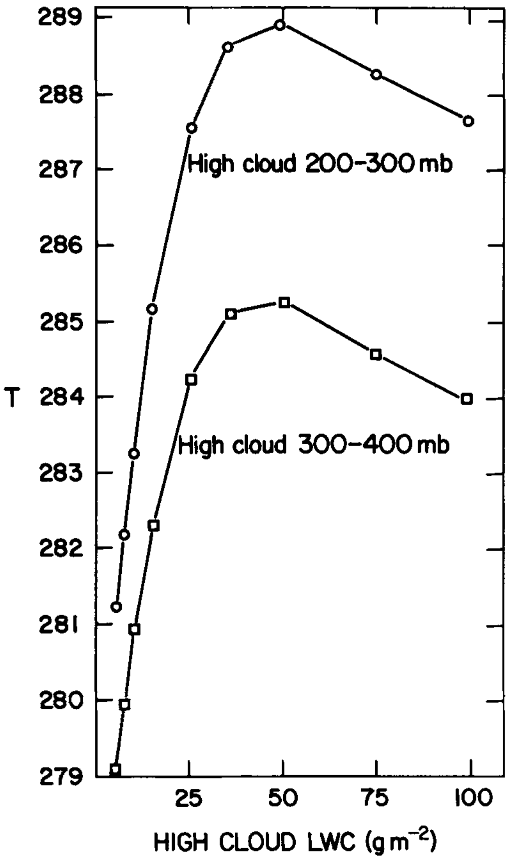

Fig. 4. Model temperature T (K) as a function of high cloud LWC with the high cloud at two different altitudes. Fractional area of each cloud type is 0.20.

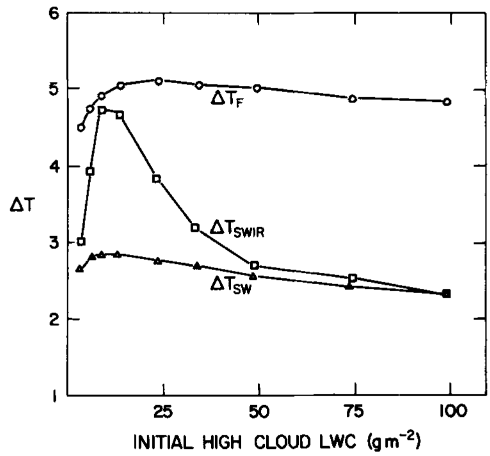

Fig. 5. Temperature change ΔT (K) for a 4% increase in the solar constant as ΔT_F (fixed cloud optics), ΔT_{SWIR} (cloud optics that vary in both SW and IR) and ΔT_{SW} (cloud optics that vary only in SW). Initial LWC for low and mid clouds of 100 and 50 g m^{-2}. Various initial LWC for high cloud, which is at pressure level 300–400 mb.

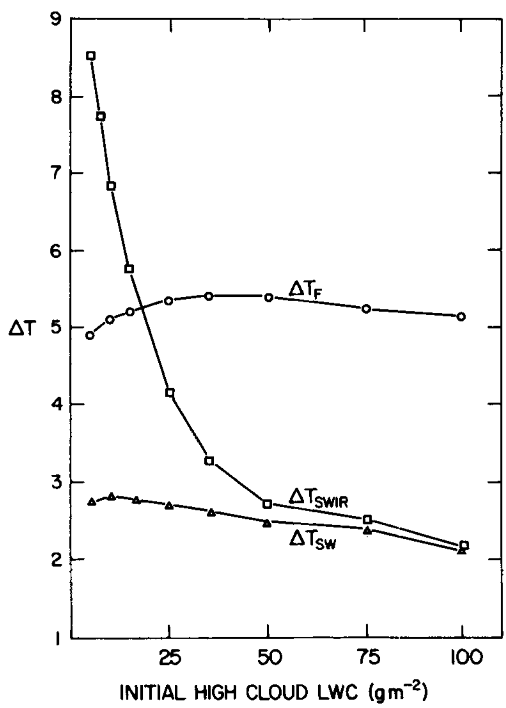

Fig. 6. As in Fig. 5, except that the high cloud is at 200–300 mb.

who note that cirrus infrared emissivity can approach one at ice paths just above 50 g m^{-2}. The solar wavelength albedo of cirrus is still small (and increasing) at 50 g m^{-2}. Radiation calculations by Platt (1981) also indicate that cirrus should cause heating for small optical depths and cooling for large optical depths. Radiative-convective model runs for winter conditions at latitudes 5 °N and 35° N by Stephens and Webster (1981) show that cirrus clouds cause surface heating when their ice contents are small, and cooling when their ice contents are large. The Stephens and Webster heating/cooling point for winter at 35 °N is obtained with a cirrus ice content of about 50 g m^{-2}.

At low ice contents the IR opacity of cirrus is quite variable. The interesting portions of the ΔT curves in Figs. 5 and 6 are below 50 g m^{-2}. The deviation of ΔT_{SWIR}, which includes variable SW and IR optics for clouds, from ΔT_{SW}, which includes variables cloud SW optics only, is due to the positive feedback effects of cirrus IR. In Fig. 6 the cirrus is at 200–300 mb, and the cirrus IR variability at low ice content is so large as to cause the variable cloud optics sensitivity (ΔT_{SWIR}) to exceed the fixed cloud optics sensitivity (ΔT_F). ΔT_{SWIR} for the cirrus at 200–300 mb (Fig. 6) exceeds ΔT_{SWIR} for cirrus at 300–400 mb (Fig. 5) because the RH parameterization is more temperature sensitive as altitude increases, causing the cirrus at 200–300 mb to have a larger variation in its ice content (and optics) than the cirrus at 300–400 mb. This last result should be regarded critically. The RH parameterization generally corresponds well with climatology (Oort and Rasmusson, 1971) below 500 mb, but begins to break down at high altitudes.

3.4. *Variations in cloud area*

Model results for various amounts of low and high cloud cover are given in Tables 6 and 7. Cloud amounts were fixed in each run, and initial LWCs were set at 100, 50 and 25 g m^{-2} for low, mid and high cloud. For cirrus ice content of 25 g m^{-2}, the SW and IR effects nearly balance, and temperature T increases by only 3 K for an increase in cirrus cloud amount from 0.10 to 0.25 (Table 7). The SW effects of low cloud dominate the IR effects of low cloud, and increasing the low cloud fraction for 0.10 to 0.25 decreases T by 9 K (Table 6). SW absorption and temperature sensitivity ΔT for fixed and variable cloud optics also decrease as low cloud amount increases.

Table 6. *Model temperature T and solar wavelength absorption SW ABS as a function of low cloud amount. Temperature change for a 4% increase in the solar constant ΔT_F (fixed cloud optics), ΔT_{SWIR} (cloud optics that vary in both SW and IR) and ΔT_{SW} (cloud optics that vary only in SW). Initial LWC for low, mid and high clouds are 100, 50 and 25 g m^{-2}. Mid and high cloud amounts are 0.20*

	Low cloud fractional area			
	0.10	0.15	0.20	0.25
T	290.80	287.52	284.29	281.25
SW ABS (W m^{-2})	240.93	234.21	227.49	220.82
ΔT_F	6.01	5.44	5.11	4.72
ΔT_{SWIR}	4.38	4.03	3.83	3.52
ΔT_{SW}	3.20	2.94	2.77	2.54

Table 7. *As in Table 6, except that the fraction of high cloud is varied. Low and mid cloud amounts are 0.20*

	High cloud fractional area			
	0.10	0.15	0.20	0.25
T	282.30	283.30	284.29	285.27
SW ABS (W m^{-2})	229.09	228.29	227.49	226.68
ΔT_F	5.21	5.18	5.11	5.05
ΔT_{SWIR}	3.52	3.70	3.83	3.96
ΔT_{SW}	2.98	2.87	2.77	2.69

ΔT_{SWIR} (cloud optics vary in SW and IR) > ΔT_F (cloud optics fixed) in all cases in Tables 6 and 7, indicating that variable cloud optics is a negative feedback. The relative feedback effects of cirrus are positive, however, as the gap between ΔT_F and ΔT_{SWIR} in Table 7 narrows for increasing cirrus amounts.

3.5 *Comparisons with other models*

A comparison of the present radiative convective model with others is easily made through the work of Chylek and Kiehl (1981), which lists the sensitivities of 4 models (Ramanathan, 1976; Coakley, 1977; Manabe and Wetherald, 1967; Wang et al., 1976) to various forcings. Chylek and Kiehl determine a mean temperature sensitivity $S\ \delta T/\delta S$ of 103.7 for the 4 models, where S is the solar constant. For fixed cloud optics (ΔT_F) and a 4% variation in S the present model gives a range of 108.0 to 150.0 for $S\delta T/\delta S$ (Tables 1–7). Thinner (or fewer) clouds generally permit more absorption of given incoming S, yielding a larger temperature sensitivity $S\ \delta T/\delta S$.

For the case of variable cloud optics (ΔT_{SWIR}), a rough comparison of the cloud optical feedback effect on model temperature sensitivity can be made with the present model and that of Paltridge (1980). The amount of negative feedback provided by cloud optics in the present globally averaged model is given by the difference between ΔT_F (fixed cloud optics) and ΔT_{SWIR} (variable cloud optics), divided by ΔT_F. For the solar constant variations and wide range in initial cloud LWCs noted in the tables, this negative feedback ranges from 13% to 45%. Paltridge's temperature sensitivities are calculated for a change in CO_2 at different latitudes. From a single initial set of cloud LWCs, he gives negative feedback effects to variable cloud optics of 31% to 41%. Paltridge scaled cloud LWC according to the surface water vapor saturation pressure. The present work scales cloud LWC to water vapor mixing ratio at cloud height, an assumption which produces a few cases of positive feedback (Fig. 6) for initially thin cirrus.

Wang et al. (1981) have also examined potential cloud feedbacks in a radiative convective model. (This latter study became available during revision of the present work.) The Wang model relates the vertical cloud distribution to a simulated mean vertical precipitation distribution, with increases in CO_2 and the solar constant generally increasing cloud optical thickness at some heights and decreasing it at others. Cases of positive and negative cloud optical feedback (a few tens of percent or less, as here) were reported. Both Wang et al. (1981) and Paltridge (1980) also included some calculations on the effects of cloud area, as well as cloud optical, feedback.

4. Conclusions

Most climate models are run with fixed optical properties for each cloud type. The temperature sensitivity ΔT_F (fixed cloud optics) in this model was shown to vary surprisingly little for a wide variety of cloud LWCs, heights and amounts. This indicates that if cloud properties (LWC, height, amount) undergo only small changes in a climate perturbation, then the climate perturbation ΔT could be modeled without the prior compilation of a detailed climatology of cloud properties.

If, however, cloud properties do significantly change with climate (and in the crude manner assumed here), then a detailed climatology of cloud properties will be needed to model the climate change ΔT. This is because the temperature sensitivity ΔT_{SWIR} for variable cloud optics was shown to be quite sensitive to the assumed initial LWC of clouds, especially of cirrus.

There is an interest in an accurate model calculation of the temperature T of climate, as well as in the climate sensitivity ΔT. T is a function of cloud properties (Hunt, 1977), and this study indicates that the most critical one is LWC. Presently available cloud climatologies can assess the amount of low cloud to within, for example, a fraction of 0.05 of sky cover. Table 6 shows that an error of 0.05 in low cloud cover would give an error of about 3 K in the calculation of T. Table 1 shows that a change in low cloud LWC from 50 to 400 g m^{-2} (and present cloud climatologies do not assess this) is larger (5.5 K). Fig. 4 shows the large dependence of T on high cloud LWC.

It should be noted that LWC is not the sole determinant of cloud optics. The optical properties of a cloud are a function of the cloud droplet distribution, as well as the LWC. The droplet distributions can be altered by changes in the cloud condensation nuclei concentrations (Twomey, 1977), and these concentrations are being affected by pollution (Hobbs et al., 1980). This is another mechanism for climate change (Twomey, 1974) which has been investigated with a one-dimensional radiative-convective model (Charlock and Sellers, 1980b).

There are considerable limitations in the application of this study's steady state, one-dimensional model to the complex, time-dependent, three-dimensional climate system (Ramanathan and Coakley, 1978). The impact of cloud optics on the radiation balance will vary with latitude and season (Potter et al., 1981). Even the one-dimensional system used here did not include a variety of effects such as, for example, a variable temperature lapse rate (Ramanathan, 1977). The parameterization for water vapor mixing ratio also has a crucial effect on T and ΔT as calculated in a one-dimensional model.

In view of the simplistic assumptions for scaling cloud LWC, the model conclusions regarding cloud optical feedback (ΔT_{SWIR}, ΔT_{SW}) should be guarded. Further surveys of cloud LWC and ambient water vapor mixing ratios with satellite microwave sensing (as in Grody et al., 1980) should indicate how cloud LWC does in fact vary. In the Grody et al. observations the cloud LWC seems to correlate with the precipitable water content, which would tend to validate the cloud LWC scaling assumption used in this model. Nimbus 5 observations by Staelin et al. (1976), however, show little correlation of cloud LWC with precipitable water, tending to invalidate the present scaling assumption. Even if total cloud LWC remained fairly constant in climate change, a vertical rearrangement of LWC could still imply a significant cloud optical feedback (Wang et al., 1981). Changes in the LWC of the thinnest clouds are the most significant for climate. A detailed program of cloud height and LWC observation and modeling, perhaps including ground based (Snider et al., 1980) as well as satellite measurements and large-scale dynamical simulations of cloud LWC development (Sundqvist, 1981), will be needed to address the emerging cloud-climate feedback question. Present modeling efforts have demonstrated the potential complexity of the issue, but they have not resolved it.

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