JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 92, NO. D7, PAGES 8483–8485, JULY 20, 1987

Thermodynamic Constraint on the Cloud Liquid Water Feedback in Climate Models

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The cloud liquid water feedback in climate models consists of the increase (decrease) in optical depth of clouds resulting from higher (lower) liquid water contents that might accompany tropospheric warming (cooling). The change in cloud liquid water with temperature is shown to depend on the rate of change of the slope of the moist adiabat with respect to temperature, and it is a strong function of temperature. The value of this rate of change in the tropics is about half that in mid and high latitudes and is much less than the value obtained by assuming that liquid water scales with the saturation mixing ratio.

BACKGROUND

There are several ways in which cloudiness could feed back on the climate system. This is one reason why any quantitative conclusions regarding the change in climate parameters like surface temperature accompanying atmospheric trace gas increases are usually qualified by uncertainties regarding possible changes in the cloudiness. Although estimates of feedbacks relating to changes in the areal extent of cloudiness and the mean cloud top height go back to the work of *Schneider* [1972] and others, there is also a body of literature concerning what may be termed the cloud liquid water feedback [*Petukhov et al.*, 1975; *Paltridge*, 1980; *Charlock*, 1982; *Somerville and Remer*, 1984]. Whereas changes in cloud amount and height are strongly dependent on the cloud generation mechanism in the climate model and therefore subject to challenge, the cloud liquid water feedback has been considered reasonable on thermodynamic grounds.

The feedback argument operates in the following manner. A warmer troposphere will contain more water vapor (because of the increase in the saturation mixing ratio) and hence more condensate. Clouds of higher liquid water content will be optically thicker for the same depth and therefore will have higher albedos at solar wavelengths. They will also be more opaque in the infrared. For low- and mid-level water clouds, the infrared opacity saturates very quickly, and any increase in liquid water content will produce a negative feedback (stabilizing effect) if all other cloud parameters are unchanged. It has been suggested in the previously mentioned papers that the increase in liquid water content might scale with the saturation mixing ratio. The purpose of this note is to show that moist thermodynamic relationships relate the change in cloud liquid water content to the change in slope of the moist adiabat with temperature, not to the saturation mixing ratio.

CLOUD LIQUID WATER

If we assume the cloud is between fixed pressure levels (p_1, p_2) and is produced by ascent along a moist adiabat, then its liquid water content l (g/g), is given by the change of saturation mixing ratio q_s, with pressure along the moist adiabat: constant θ_{ES}. Consider the linearization [e.g., *Betts*, 1982]

$$l = \langle(\partial q_s/\partial p)_{\theta_{ES}}\rangle \Delta p \tag{1}$$

where Δp is the thickness of the cloud and the angle brackets denote a mean value for the pressure interval p_1–p_2. Now, the moist adiabat satisfies

$$\delta\theta_{ES} = 0 = \frac{\delta\theta}{\theta} + \frac{L}{C_p T}\,\delta q_s \tag{2}$$

so that

$$\langle(\partial q_s/\partial p)_{\theta_{ES}}\rangle = -\langle(C_pT/L\theta)\rangle\langle(\partial\theta/\partial p)_{\theta_{ES}}\rangle = \langle(C_pT/L\theta)\rangle\Gamma_W \tag{3}$$

where the slope of the moist adiabat is defined as

$$\Gamma_W = -\langle(\partial\theta/\partial p)_{\theta_{ES}}\rangle \tag{4}$$

Hence the liquid water content is

$$l = \langle(C_pT/L\theta)\rangle\Gamma_W\,\Delta p \tag{5}$$

Now consider the cloud base temperature to change to a new moist adiabat while preserving the same cloud base and top pressures. The fractional change in liquid water content per degree Celsius change in mean cloud temperature, as defined by *Somerville and Remer* [1984] is

$$f = \frac{1}{l}\left(\frac{\partial l}{\partial T}\right)_{p_1,p_2} = \frac{1}{\Gamma_W}\frac{\partial\Gamma_W}{\partial T} \tag{6}$$

from (5), since (T/θ) is a fixed function of pressure and C_p and L are approximately constant. This, of course, is not the same as $(1/q_s)(\partial q_s/\partial T)$, and therefore liquid water content should not be expected to scale with the saturation mixing ratio.

Table 1 shows f tabulated against temperature and pressure as computed from (6) for 100-mbar thick cloud layers. For example, for a cloud between 900 and 800 mbar and a cloud base at $T = 15°\text{C}$, $f = 0.025$. The dependence on pressure and

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Paper number 7D0473.
0148-0227/87/007D-0473$02.00

TABLE 1. Dependence of $f = (1/l)(\partial l/\partial T)$ on Pressure and Temperature

	Pressure at Cloud Base, mbar	Temperature at Cloud Base, °C												
		−30	−25	−20	−15	−10	−5	0	5	10	15	20	25	30
$(1/\Gamma_W)(\partial\Gamma_W/\partial T)$	500	0.094	0.087	0.076	0.065	0.057	0.048	0.039	0.029					
	600	0.087	0.082	0.079	0.064	0.055	0.047	0.040	0.032	0.025				
	700			0.074	0.068	0.061	0.049	0.042	0.035	0.028	0.015			
	800					0.064	0.052	0.044	0.041	0.029	0.024	0.018		
	900						0.057	0.045	0.037	0.031	0.025	0.021	0.015	
	1000							0.048	0.042	0.032	0.026	0.021	0.017	0.012
$(1/q_s)(\partial q_s/\partial T)$	all pressures	0.094	0.090	0.086	0.083	0.079	0.076	0.073	0.071	0.068	0.066	0.064	0.062	0.060

temperature is considerable. The quantity f decreases somewhat with decreasing pressure but decreases rapidly with increasing temperature. In contrast, $(1/q_s)(\partial q_s/\partial T)$ decreases slowly with increasing temperature and is almost independent of pressure. Representative values are shown in the bottom line of Table 1. Moreover, it is greater than f given by (6) at all temperatures.

Table 2 shows f replotted as a function of moist adiabat and cloud-base pressure for 100-mbar thick clouds. Moist adiabats from 280 to 360 K are given, representing a characteristic range from high latitudes to a typical upper limit in the tropics (higher values are reached only in the hurricane eye wall). Corresponding wet-bulb potential temperatures are given as the bottom line, and pressure-averaged values of f are tabulated for each moist adiabat.

DISCUSSION

Somerville and Remer [1984] present data on cloud liquid water content from *Feigelson* [1978] based on over 20,000 measurements made in the U.S.S.R. When grouped in terms of temperature ranges, the data indicate that $f = 0.04$–0.05 for temperatures between −25° and +5°C. Also, at higher temperatures the value of f is very small, with virtually no change in liquid water content. The observational results appear to be similar to the values of f obtained from (6) given in Table 1. The close correspondence between the observational value of f and the values in Table 1 indicate that the mixing process which reduces liquid water may not be sensitive to changes in temperature, so that the rate of change of adiabatic liquid water content is a good measure of the fractional change in liquid water for clouds even in the presence of entrainment.

TABLE 2. Dependence of $f = (1/l)(\partial l/\partial T)$ on Pressure and Moist Adiabat

	Moist Adiabat, θ_{ES}				
	280 K	300 K	320 K	340 K	360 K
Pressure at cloud base, mbar					
500	0.111	0.087	0.065	0.050	0.037
600	0.092	0.063	0.052	0.038	0.028
700	0.082	0.052	0.041	0.030	0.023
800	0.066	0.046	0.032	0.025	0.021
900	0.061	0.039	0.028	0.024	0.018
1000	0.048	0.035	0.023	0.020	0.015
Average for all pressures	0.077	0.054	0.040	0.031	0.024
1000-mbar wet bulb temperature, °C	−2.1	8.1	15.5	21.1	25.5

This has two implications for climate modeling. First, this particular cloud feedback can be included in detailed climate models that have prognostic cloud liquid water. It is anticipated that the next generation of global models will incorporate this feature. At present, even if cloud liquid water is not computed in the model, the rate of change of cloud liquid water with temperature and pressure can be used to parameterize cloud optical properties. Second, the quantiy f varies considerably with temperature, and hence latitude. Note that all the data from *Feigelson* [1978] are for observations made in the U.S.S.R. at mid-latitudes. In the tropics the value of f is quite small, such that the cloud liquid water feedback will operate to a greater extent in mid and high latitudes and for colder clouds. The value of f to be used in arriving at a global estimate of this feedback is therefore probably closer to 0.02 or 0.03 rather than the value of 0.04–0.05 inferred from the cloud data or the value of 0.07–0.08 obtained using $(1/q_s)(\partial q_s/\partial T)$. The consequence is striking. *Somerville and Remer* [1984] estimated the surface temperature warming due to a doubling of CO_2 concentration using a radiative-convective model with this feedback included. For $f = 0.02$ the model surface warming is reduced to 64% of that for $f = 0$ (no feedback), whereas for $f = 0.04$ and 0.08, it is reduced to 49% and 32%, respectively.

The preceding discussion involves only one possible cloud liquid water feedback. The depth of the cloud will determine the total liquid water path. Moreover, the location of the freezing level and precipitation processes will also influence the cloud liquid water in precipitating clouds. Here again, detailed global models can accommodate most of the physics involved, such that there is hope for including this cloud feedback in climate models. The relationship between cloud liquid water and optical properties is also being built into the current generation of climate models and it is possible to model subtle changes in cloud droplet size distribution that might accompany tropospheric warming [*Bohren*, 1985].

A final point: only water clouds have been considered in this analysis. The question of change in cirrus properties resulting from a warmer troposphere is important, since models indicate that for high, thin clouds, the infrared greenhouse effect dominates over the albedo effect [*Stephens and Webster*, 1981]. The cloud ice feedback therefore could be of opposite sign.

Acknowledgments. We wish to thank David Randall of NASA Goddard Space Flight Center for helpful discussions of the subject. This research was supported by the National Aeronautics and Space Administration through contract NAS5-28800 to Atmospheric Research and grant NAG5-783 to the University of Maryland.

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(Received February 19, 1987;
revised May 22, 1987;
accepted May 25, 1987.)