Cloud Forcing and Feedback:

1. Introduction

A long history exists regarding attempts to estimate the albedo of Earth (e.g. Hartmann, 1993). From early on it was recognized that clouds made an important contribution to the albedo of Earth. With artificial, Earth-orbiting satellites it became possible to measure the albedo of earth directly, and later the contribution of clouds to this albedo. Estimates from ERBE (Ramanathan, et al. 1989, Harrison, et al. 1990) showed that clouds approximately double the albedo of Earth from an estimated clear-sky value of 0.15, to its average value with clouds of 0.3. This makes a change in the global energy balance of about 50 Wm^{-2} that is reflected by clouds that would not be reflected by the planet if clouds were not there, all else being equal. We often use the following linear approximations in back-of-the-envelope calculations.

$$\alpha_p = A_c\, \alpha_{cloudy-sky} + (1 - A_c)\, \alpha_{clear-sky} \qquad (1)$$

where A_c is the fractional area coverage of clouds, which is estimated to be about 0.6 from International Satellite Cloud Climatology Project data analysis (e.g., Rossow and Schiffer, 1991; Rossow, et al. 1993, Rossow and Schiffer, 1999). If we plug the clear-sky (0.15) and average (0.3) albedos into (1) we get an implied average cloudy-sky albedo of 0.4.

Clouds also increase the greenhouse effect of the atmosphere, and this is estimated by ERBE to add about 30 Wm^{-2} to the global energy balance at the top of the atmosphere. Therefore, the net effect of the current population of clouds on the global energy balance adds up to about -20 Wm^{-2}. This is actually fairly modest, compared to the global average greenhouse effect.

$$G = \sigma\,(T_s^4 - T_e^4) = \sigma\, T_s^4 - \mathrm{OLR} = 390 - 240 = 150\ Wm^{-2} \qquad (2)$$

where T_s = 288K and T_e = 255K.

On the other hand, when we come to consider climate sensitivity, we see that the individual solar and longwave components of cloud forcing, and even their sum, are large compared to the direct forcing of, say, doubled carbon dioxide, ~4 Wm^{-2}. If the cloud albedo, for example, were to be sensitive to global mean surface temperature, then you could produce a very strong feedback. For example, if the average cloudy-sky albedo were to increase from its current value, of about 0.4, by some amount $\Delta\alpha_{cloudy-sky}$, then we would get a global energy balance change of,

$$\Delta R_{\mathrm{net}} = \frac{S}{4} A_c\, \Delta\alpha_{cloudy-sky} = -344\, Wm^{-2}\, 0.6\, \Delta\alpha_{cloudy-sky} \qquad (2)$$

To get a change in net radiation of -4 Wm^{-2}, we need to increase the cloudy-sky albedo from 0.4 to 0.42, 0.02 or five percent of the current value.

Hartmann et al. (1992) showed using ISCCP and ERBE data that the net effect of clouds on the global energy depends sensitively on the type of cloud. Low clouds in well insolated conditions have a strong negative feedback, whereas thin, high clouds can have a positive feedback. One striking thing brought out by recent satellite observations is the very high albedos that can be associated with tropical convective clouds. Hartmann(1993) suggested from ISCCP and ERBE data that deep convective clouds in the tropics can have a strong negative effect on the planetary energy balance despite their cold tops, because they are very reflective and well insolated. On the other hand, high but optically thin clouds in the tropics can warm the surface. On average, these two effects cancel, so that clouds in convective regions change the net radiation balance very little from that of surrounding subsiding regions. This is one of the interesting puzzles of cloud climatology. I think this results from the feedback of top of atmosphere radiative effects of clouds and the large-scale circulations that support convective regions in the tropics.

2. Early GCM Cloud Sensitivity studies

Hansen, et al.(1984) were the first to do a really thorough and logical sensitivity analysis of a GCM. One of the things that they investigated carefully was the impact of clouds on the sensitivity of their model. The model they had was one of the most sensitive at the time, and produced a temperature response to a doubling of CO_2, or almost equivalently a 2% increase in solar constant, of 4.2C. The only cloud properties that were predicted were cloud fractional coverage and cloud height. This is often described as a diagnostic cloud scheme, because cloud microphysical properties are not conserved, optical properties are specified and spatial location is predicted from average thermodynamic properties in grid boxes. The average cloud height went up in response the surface temperature increases and the average cloud fractional coverage went down. Together these two positive feedbacks produced a significant warming enhancement when multiplied by the strong water vapor feedback in the model. These two feedbacks seem reasonable within the confines of such a model. The increased SST will give larger moist static energies, so clouds can penetrate higher. Because the moist energy of air near the surface goes up exponentially with temperature and radiative cooling is more nearly linear in temperature, you can balance the radiative cooling with a smaller area of convective flux in a warmer Earth. Thus maybe it is reasonable to suppose that in a warmer world we would have more intense convection covering a smaller area that at present. These changes coupled with a decrease in the lapse rate of water vapor raised the emission level of the atmosphere, which we have seen in simple homework problems can reduce the requirement for convective fluxes with which convective clouds are associated (problems 5 and 6 of Chapter 3 of GPC).

At first Hansen et al.(1984) were alone in having such a sensitive model, but later Wetherald and Manabe(1988) did a cloud feedback analysis of the GFDL model in which clouds were allowed to change area and vertical extents, and they too found a rather strong positive feedback from the clouds. They went from a response to doubled CO_2 of 3.2 to 4.0, in good agreement with Hansen, et al(1984). The cloud positive feedback was caused by an increase of cloudiness near the tropopause and a reduction at lower levels, also similar at least in part to Hansen, et al. despite the cloud parameterizations being substantially different. On the other hand, both models had assumed fixed cloud optical depth and other optical properties; in the case of W&M 88, they used the OLD 65-45-21% albedos for low, middle and high cloud deriving from Haurwitz(1948). So the natural question arises, how well do we know the cloud properties, and how might they respond to climate change. The issue of cloud liquid water feedback will be raised in the next section.

3. Cloud liquid water feedback

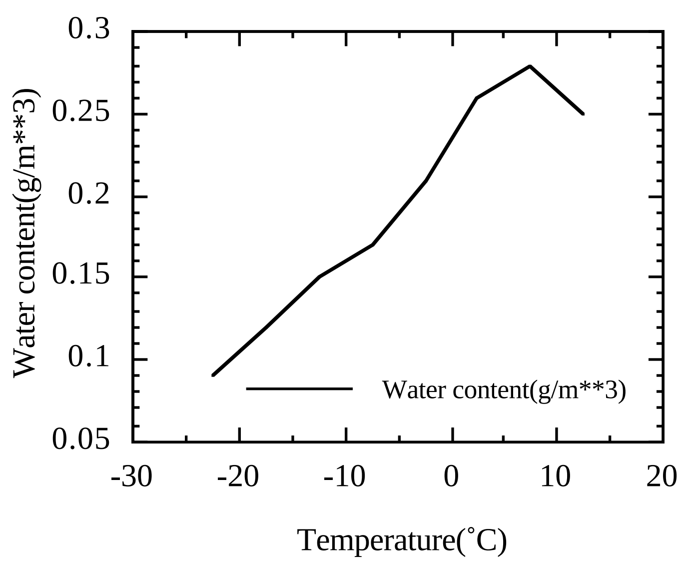
The optical depth of a cloud of water droplets, τ_d, which can be input into a radiative transfer scheme to calculate the cloudy-sky albedo, is given by the approximate formula,

$$\tau_d = 2\pi\bar{r}^2 Nh = \frac{3}{2}\frac{LWC}{\rho_w \bar{r}} \tag{3}$$

where $\bar{r}$ is the effective mode radius, LWC is the liquid water content (gm^{-2}), N is the number of cloud droplets per unit volume, ρ_w is the density of water, and h is the vertical extent of the cloud. There are a couple of lessons in (3). First. the optical depth increases linearly with the liquid water content, and second, for fixed liquid water content, the optical depth decreases with increasing effective droplet radius. Smaller drops give a higher optical depth and hence a higher albedo. Working with the first effect, we can imagine what would happen if the liquid water content retained in the atmosphere went up proportionally with the saturation vapor pressure. What sort of feedback would this give? A negative one, or course, since the cloud albedo would go up with temperature. Charlock(1981, 1982) tried this idea in a simple 1D model and later Charlock and Ramanathan(1985) looked at this effect in a GCM. The conclusion of Charlock(1981, 82) was that this would give a negative feedback with a gain of -0.28 or a feedback factor of 0.72, so that the temperature response was decreased by 28%. He reckoned that this would be an upper bound on the likely effect of such a feedback.

Somerville and Remer(1984) summarized a bunch of Soviet observations of cloud liquid water as a function of temperature. These data were mostly taken over the Soviet Union in the 60's and 70's. The data they showed in tabular form are plotted up below. You can see that the water content increases with temperature, at least up to a point, going pretty much linearly from 0.1g m^{-3} at -20˚C to about 0.28 g m^{-3} at 7.5˚C. It then turns down slightly at 12.5C, after peaking at 7.5C.

Soviet Cloud Water Data, Sommerville & Remer, 1984



Notice that the temperatures are rather cold, and remember this is data taken over the Soviet Union, all over land and largely continental climate.

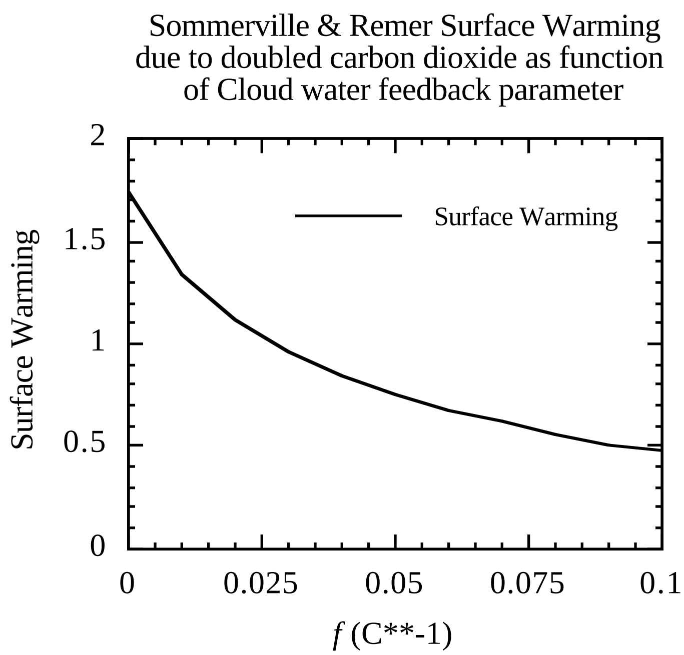
If we expect an exponential dependence as in that of the Clausius-Clapeyron equation for water vapor, then we postulate a sensitivity measured in terms of a parameter *f*, as follows.

$$f = \frac{1}{LWC}\frac{dLWC}{dT} \tag{4}$$

These data seem to fit an exponential scale with a logarithmic derivative of $f = 0.04$ to 0.05, which is half to 5/8 of the Clausius-Clapeyron value of 0.08 in the appropriate range of temperatures. Actually, from Clausius-Clapeyron, I get,

$$\frac{1}{e_s}\frac{de_s}{dT} \cong \frac{L}{R_v T^2} \approx 0.065 K^{-1} \;\; at \;\; 288K \tag{5}$$

The change of saturation vapor concentration is what is called the 'adiabatic assumption', which goes back to Paltridge(1980). When they put this factor into their 1D radiative/convective model, Somerville and Remer got a negative gain of -0.51 or a feedback factor of 0.48, so somehow they produced a very strong negative feedback that cut the effect of doubled CO_2 in half (See figure below.). This strong negative feedback is derived from the strong temperature dependence of the cloud liquid water derived from the Soviet data. (What do these data from Eurasia mean for global climate??). Their model with *f*=0, or no liquid water feedback, produces a warming of 1.72C in response to doubled CO_2. They got a bigger response than Charlock(1982) to liquid water feedback, for some reason, with the Soviet value of *f* reducing the temperature response to 0.85˚C, less than it would be without water vapor feedback.



In order to get such an effect, the water retained in clouds needs to increase with temperature in proportion to the saturation vapor pressure. It is certain that the amount of water processed in clouds will increase with surface temperature, but will the amount that is resident in the atmosphere as liquid and ice increase with temperature at such a high rate? One place to look would be warm boundary layer clouds in the current climate, where we expect that precipitation removal will be of less importance. One could look at the current distribution of cloud optical depth with surface temperature in the hope that the current climate may give some clues to feedback processes operating during climate change. This is a dubious assumption, since cloud type and structure tends to vary with SST, but little else can be done observationally.

Tselioudis and Rossow(1994) looked at the temperature dependence of optical depth estimates from ISCCP. They found a rather confusing picture, with some types of clouds showing an increase of optical depth with temperature and some not. In some cases the optical depth decreased with temperature. They related this to changes in the dynamical regime within which the clouds operate. Subtropical stratus, for example, tend to show an increase of optical depth and coverage with decreasing temperature(a positive feedback), which is related to the way in which they are formed and sustained, which depends on the stability of the PBL, the rate of large-scale subsidence, etc.(Klein and Hartmann 1993, Klein 1994, Klein, et al. 1995, Klein 1997, Norris and Klein 2000). These subtropical and tropical low clouds tend to dominate the global average, so that the global affect seems to be decreasing low-cloud optical depth with increasing temperature - just the opposite of the adiabatic expectation (adiabatic=Clausius-Clapeyron). For cirrus clouds the effect is a mixed again, but with positive sensitivities to temperature. However, since cirrus clouds tend to have a large greenhouse effect comparable or greater than their albedo effect, the effect on the climate may again be a positive feedback. None of these relationships may be especially applicable to climate change sensitivity calculations, however, since most of the variation you see is related to circulation changes. Subsidence over the cold water favors PBL stratocumulus cloud development, and rising over warm water favors cirrus development. Under these conditions, can looking at observed data for the current climate ever tell you anything about global climate change? Well . ., maybe, but one must be very careful.

Many intercomparisons of cloud feedback effects in global climate models have been conducted. In the first intercomparison the results were widely divergent (Cess, et al. 1989, Cess, et al. 1990). In later intercomparisons the differences were less, but the mechanisms whereby these net feedbacks were produced were divergent (Alekseev, et al. 1996, Cess, et al. 1997). Overall, we have a long way to go in this area, and most of these models used diagnostic cloud schemes. Small differences in the manner in which clouds are represented in GCMs can have a strong influence on CO2 response experiments (Senior and Mitchell 1993).

The trend in global climate modeling is toward using prognostic cloud schemes in climate models, where conservation laws are used to predict cloud water and ice content from 'first principles' (e.g Del Genio, (1996); Fowler and Randall, (1996b, 1996a, 1996); Das, et al. (1998)). Data to validate such models are inadequate, and the number of parameters to be tuned to observations is large. So far, no definitive results have come from these models, in my humble opinion. Experiments are being done with cloud-scale models, and with regional-scale models in which more cloud physics and mesoscale motions can be explicitly resolved to try to do the cloud interaction problem with brute force. A combination of these studies with global observations of cloud properties to come from future satellite (King, et al. 1992, Wielicki, et al. 1995, Wielicki, et al. 1996) and field programs should lead to greater confidence in the ability of global climate models to faithfully predict the role of clouds in global warming.

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