RCM study of cloud optical depth feedback

$\Delta\tau^*$	$\Delta\epsilon^*$	ΔN_t (W m^{-2})	ΔN_s (W m^{-2})	2% S_0 ΔT_s^* ($^{\circ}\text{C}$)	2 $\times\text{CO}_2$ ΔT_s^* ($^{\circ}\text{C}$)
0.41(0.65)	0.16(0.28)	2.4	-2.9	5.3(2.6)	5.3(2.8)
0	0	0	0	4.2(2.2)	4.4(2.5)

*For a fixed lapse-rate of $6.5^{\circ}\text{C km}^{-1}$ and for a variable moist-adiabatic lapse-rate (in parentheses).

results of the RCM study are presented in the table for two perturbations, a 2 per cent solar constant increase and a CO_2 doubling, both for a fixed lapse-rate of $6.5^{\circ}\text{C km}^{-1}$ and for a moist-adiabatic lapse-rate (shown in parentheses) which varies with temperature. The change in the surface air temperature ΔT_s for both perturbations is positive, and ΔT_s with cloud optical depth feedback ($\Delta\tau \neq 0$ and $\Delta\epsilon \neq 0$) is larger than ΔT_s without ($\Delta\tau = 0$ and $\Delta\epsilon = 0$). Consequently, this RCM analysis indicates that the cloud optical depth feedback is positive.

To show how this positive cloud optical depth feedback occurs, the time evolution of the RCM solutions for the solar-con-

stant perturbation with the moist-adiabatic lapse-rate is displayed in the figure in terms of $\delta(\Delta\psi) = [\Delta\psi \text{ (with cloud optical depth feedback)} - \Delta\psi \text{ (without cloud optical depth feedback)}]$, where $\Delta\psi = [\psi \text{ (perturbation)} - \psi \text{ (control)}]$ and ψ is any quantity. The surface of the RCM was taken to be ocean of 1 m depth. The timescale of the response of the RCM is related to this depth, and therefore has no physical significance. Initially the change in the net radiation at the tropopause, $\delta(\Delta N_t)$, is positive and the change in the net surface flux, $\delta(\Delta B_s)$, is negative. Here $B_s = N_s - H_s$, where H_s is the combined surface sensible and latent heat fluxes. As time increases both $\delta(\Delta N_t)$ and $\delta(\Delta B_s)$ approach zero as a result of the Earth-atmosphere system approaching equilibrium in each simulation. But

$\delta(\Delta B_s)$ does not approach zero monotonically from its initially negative value, but instead first becomes positive and then approaches zero monotonically. As a result, the change in the surface temperature $\delta(\Delta T_s)$ is negative initially but then becomes positive following the change in sign of $\delta(\Delta B_s)$.

Finally, I have investigated the fundamental assumption of Roeckner *et al.* that the change in sign of the surface temperature $\delta(\Delta T_s)$ is determined by the change in the net radiation at the surface $\delta(\Delta N_s)$ and is independent of the change in the net radiation at the top of the atmosphere $\delta(\Delta N_t)$. By varying $\Delta\tau$ and $\Delta\epsilon$ independently in the RCM for both the fixed and moist-adiabatic lapse-rate cases, we find that both the sign and magnitude of the temperature changes are determined by the change in the net radiation at the top of the atmosphere, $\delta(\Delta N_t)$, and are virtually independent of the change in the net radiation at the surface, $\delta(\Delta N_s)$, which is quite the opposite to the fundamental assumption made by Roeckner *et al.*

In conclusion, my RCM study indicates that the cloud optical depth feedback in the Roeckner *et al.* GCM simulations is positive. Of course the RCM is not the GCM, so the final, conclusive result will have to await a comparison of the appropriate GCM simulation with that in ref. 1. In any event, because of the complexity of cloud processes in nature, many additional modelling and observational studies will be required to determine the sign of the actual cloud optical depth feedback, let alone its magnitude.

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ROECKNER REPLIES—In response to Schlesinger's RCM feedback analysis of our GCM results, we performed another pair of GCM control/perturbation experiments, with cloud optical properties prescribed identically in both experiments using zonal/time averages as a function of height and latitude from the control experiment, in which the optical properties of the clouds were allowed to vary according to their dependence on the prognostically determined liquid water content¹.

The new pair of equilibrium-climate states serves as a reference for estimating the feedback that occurred in the earlier pair of experiments with variable cloud optics¹. As in Schlesinger's RCM analysis, the cloud optical depth feedback can now be evaluated directly as the difference δ of two equilibrium temperature changes ΔT that result from increasing the solar constant by 2 per cent in GCM simulations with and without the respective feedback.

Our results confirm Schlesinger's conclusion that the cloud optical-depth feedback in our GCM is positive, in contrast to our previous conclusion¹ and to earlier estimates⁴. The global and annual mean feedback $\delta(\Delta T)$ is largest in the upper troposphere (1.1°C) but is still positive at the surface (0.3°C) despite a negative net surface-radiation response. The chain of events creating the positive cloud optical depth feedback may be summarized as follows. The externally induced warming (solar constant increase by 2 per cent) causes a liquid-water increase in all types of cloud (but predominantly in high (cold) clouds) in accord with thermodynamic theory⁵. The associated increase of high-cloud infrared emissivity by approximately 15 per cent dominates the net planetary radiation change, that is, more long-wavelength radiation is trapped within the atmosphere than solar radiation is screened from the surface. The resultant upper tropospheric heating influences the surface by reduced convective overturning and less evaporative cooling at the surface. Thus, as Schlesinger infers, the cloud-induced negative surface-radiation change is not balanced by surface cooling¹ but instead by a decrease in the latent-heat flux at the surface.

Although our present GCM experiments cannot provide a final answer to the question of cloud feedback in the real world, they show that the negative cloud optical-depth feedback expected for optically thick clouds^{1,4} may be superseded by the positive feedback resulting from the emissivity change of optically thin cirrus clouds. Accordingly, the sign of the feedback may be crucially dependent on the spatial distribution of cloud amount and cloud optical properties in the control climate state.

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