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The Role of Cloud Microphysical Processes in Climate: An Assessment From a One-Dimensional Perspective

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The potential link between cloud microphysical processes and climate is investigated and theorized. We base our theory on results simulated from a one-dimensional climate model with an interactive cloud formation and precipitation program. This cloud program includes temperature-dependent parameterization equations for condensation, evaporation, and precipitation derived from growth equations for water droplets. We show that the cloud liquid water content is directly related to precipitation processes, which are governed by the mean cloud particle radius. In particular, we illustrate that the rate of precipitation generation is directly proportional to the fourth power of this radius. A doubling of CO_2 is used as the radiative forcing. If the perturbed mean cloud particle radii for model high, middle, and low clouds are less than the climatological mean values, precipitation decreases because of the presence of smaller cloud particles, leading to an increase in the cloud liquid water content. Cloud solar albedo effects are enhanced, resulting in a reduction of temperature increases due to CO_2 doubling (negative feedback). If, however, the perturbed mean cloud particle radii are larger than the climatological mean values, the availability of larger cloud particles would increase precipitation, leading to a decrease in the cloud liquid water content. The temperature increase in the case of CO_2 doubling is amplified because of a reduction of cloud solar albedo effects (positive feedback). In the model the particle sizes are not directly related to radiative transfer, but they are indirectly related through precipitation and condensation processes, which determine the cloud liquid water content. We hypothesize that there are uncertainties in cloud microphysical processes and that a possible key to climate stability due to external radiative perturbations is the availability of larger or smaller cloud droplets (in reference to the climatological mean values). Smaller cloud droplets may be produced by additional condensation nuclei over the oceans as a result of greenhouse warming and pollution over land. The existence of larger cloud droplets could be caused by the removal of cloud-forming nuclei, resulting from enhanced precipitation due to greenhouse perturbations. It is critically important to have a global climatology of the cloud particle radii for various cloud types in the investigation of the role of clouds in climate.

1. INTRODUCTION

The importance of clouds in climate and climatic perturbations has been recognized as a result of a number of observational and modeling studies. It has been found (1) that the radiation budgets at the top of the atmosphere, observed from satellites, are closely related to the cloud field, (2) that a small change in cloudiness can significantly amplify or offset climatic temperature perturbations due to external radiative forcings, such as the anticipated increase in CO_2 and other greenhouse gases, and (3) that certain clouds (for example, stratus) are primarily responsible for the reflection of sunlight, referred to as the solar albedo effect, whereas others (for example, cirrus) are predominantly greenhouse elements. It is clear that the stability or instability of the climate depends on the role that clouds play in climatic perturbations. At this point, clouds remain one of the least understood components of the weather and climate systems.

There have been numerous speculations about the influence of cloud variations on the sensitivity of climate. Using a general circulation model (GCM), *Smagorinsky* [1978] suggested that the increase in downward IR fluxes due to the increase in CO_2 will enhance evaporation from the Earth's surface. This in turn will increase the amount of low clouds and thus exert a cooling effect on the climate. *Schneider et al.* [1978], on the other hand, speculated that cloud variations may have a positive feedback effect on the sensitivity of the global mean climate due to decreasing cloud cover in the model when the sea surface temperature is increased. This view was supported by *Hansen et al.* [1984] and *Washington and Meehl* [1984] in their GCM experiments for a doubling of CO_2. *Wetherald and Manabe* [1980] concluded that the influence of cloud feedback on the sensitivity of the global mean climate may not be as large as originally suspected because of compensation from cloud solar albedo and IR greenhouse effects. More recently, *Wetherald and Manabe* [1988] undertook a more comprehensive GCM study on the role of clouds in CO_2 perturbations. This model produced more cloudiness at the tropopause, but less cloudiness in the upper troposphere. In both instances the solar albedo effects are reduced, leading to a positive feedback to the temperature increase due to the doubling of CO_2. This conclusion appears to deviate from that presented in their previous paper [*Wetherald and Manabe* [1980]. Wetherald and Manabe pointed out that the formulations of cloud formation and feedback processes in GCMs are extremely idealized. For example, in both of their pioneering studies, the albedo and emissivity of various types of model clouds were fixed.

Numerical experiments using one-dimensional radiative-convective models, in which the transfer of solar and IR radiative fluxes can be treated more comprehensively, have been carried out in order to understand the role of clouds in climate. Based on one-dimensional experiments with fixed clouds, *Charlock* [1982] and *Somerville and Remer* [1984] showed that the specific humidity, and hence the cloud liquid

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water content (LWC), increase as a result of greenhouse warming. As a result, clouds reflect more incoming solar radiation because of a larger LWC, leading to a negative feedback to temperature perturbations. Using an interactive cloud model, which included the formation of cloud cover and liquid water in connection with a one-dimensional climate model, *Liou et al.* [1985] and *Ou and Liou* [1987] also found that overall, clouds exert a negative feedback to temperature increases produced by positive radiative forcings. On the basis of results derived from a cloud-climate model, they concluded that clouds appear to stabilize temperature perturbations.

In view of the preceding discussion, there appear to be conflicting views concerning the role of clouds in climate among researchers using results derived from GCMs and one-dimensional models. In all of the GCM experiments, the method for cloud prediction is highly primitive, and the radiative properties of various cloud types generated in the model may not be sufficiently realistic for the investigation of cloud-radiation interactions and feedbacks. The one-dimensional climate models developed for investigation of cloud-radiation interactions and feedbacks have not incorporated cloud microphysical processes adequately enough to link these processes to climate. In particular, precipitation processes, as they relate to cloud liquid water content, have not been dealt with in the models and model simulations.

The objective of the present paper is to study the role of clouds and precipitation in climate by using a one-dimensional model in which detailed radiative transfer and cloud microphysical processes can be incorporated. Section 2 presents the basic model structure and parameterizations for condensation, evaporation, and precipitation. The results simulated from the cloud-climate model are discussed in section 3, where the potential link between microphysical cloud processes and climate is theorized. Conclusions are given in section 4. We postulate in this section that there is a probability for either larger or smaller cloud droplets (compared to the climatological mean) to be available in the atmosphere. Finally, we point out the importance of a global climatology for mean particle radii for various cloud types to investigate the role of clouds in climate.

2. The Cloud and Climate Model

The present model for the investigation of the role of clouds and precipitation in climate is based on the one-dimensional climate model developed by *Liou et al.* [1985]. However, we have modified the model by incorporating cloud liquid water and precipitation equations. In addition, we have developed parameterization equations for condensation, precipitation, and evaporation terms, based on fundamental cloud microphysical processes, in connection with the climate model. The basic one-dimensional equilibrium equations for the temperature T, specific humidity q, cloud liquid water mixing ratio q_m, and precipitation flux $\bar{P}$ may be written in the forms

$$\rho C_p k_h\left(\frac{\partial T}{\partial z} + \gamma_s - \gamma'\right) + \int_0^z \sigma T^4(z')K(|z - z'|)\, dz' = F_s(z) \tag{1}$$

$$\frac{1}{\rho}\frac{\partial}{\partial z}(\rho\langle w'q'\rangle) = -\eta Q_c + (1 - \eta)E_r \tag{2}$$

$$\frac{1}{\rho}\frac{\partial}{\partial z}(\rho w_c q_m) = \eta Q_c - \eta P \tag{3}$$

$$\frac{1}{\rho}\frac{\partial}{\partial z}\bar{P} = \eta P - (1 - \eta)E_r \tag{4}$$

where ρ is the air density, C_p the specific heat at constant pressure, k_h the thermal eddy diffusion coefficient, γ_s the moist adiabatic lapse rate, γ' the countergradient lapse rate, σ the Stefan-Boltzmann constant, K the infrared kernel, which is a function of temperature, F_s the solar flux, η the cloud cover, Q_c, E_r, and P the rates of condensation, evaporation, and precipitation generation (per second), respectively, w_c the vertical velocity in the cloudy region, and $\rho\langle w'q'\rangle$ the eddy flux of the specific humidity. Note that the precipitation flux $\bar{P}$ is defined as the precipitated water from any model layer falling into the layer directly below. The total precipitation flux is obtained by integration of (4) from the surface to the top of the model layer.

Let w_0 and q_0 denote the vertical velocity and specific humidity, respectively, in the clear region. It is assumed that the model is composed of uniform clear and cloudy regions. Thus the eddy flux of the specific humidity $\langle w'q'\rangle = \eta w_c q_c + (1 - \eta)w_0 q_0$, where q_c is the specific humidity in the cloudy region, which can be computed through an equation for the water balance [*Haltiner and Williams*, 1980, p. 309]. The horizontal averages of temperature T, specific humidity q, and vertical velocity w, may be expressed by $\chi = \eta\chi_c + (1 - \eta)\chi_0$, where χ can be T, q, or w. This assumption has been widely used in the parameterization of cumulus convection [*Kuo*, 1974]. For large-scale cloud formation we may safely assume that $T_c \cong T_0 \cong T$. From the general circulation statistics compiled by *Oort* [1983], the globally averaged (clear plus cloudy areas) vertical velocity w ranges from a minimum of 0.91×10^{-3} cm s^{-1} close to the surface to a maximum of 0.83×10^{-2} cm s^{-1} at about 400 mbar. On the basis of this information, the vertical velocity in the present one-dimensional model is assumed to be 0. Thus $w_0 = -\eta w_c/(1 - \eta)$. The vertical velocity in the cloudy region can be derived from Richardson's equation in the manner described by *Liou et al.* [1985]. Finally, based on the horizontal averaging procedure, the cloud cover is related to the specific humidity in the form $\eta = (q/q_s - h_0)/(1 - h_0)$, where $h_0 = q_0/q_s$ denotes the threshold relative humidity. The threshold relative humidity is parameterized in terms of its surface value in the form, $h_0 = h_0(p_*)[(p/p_* - 0.02)/0.98]$ [*Manabe and Wetherald*, 1967]. From Oort's general circulation statistics, the global mean relative humidity at the surface $h_0(p_*)$ is about 0.8. We use this value to close the present one-dimensional cloud-climate model.

On the basis of the steady state, one-dimensional diffusion theory for water vapor and latent heat transports, the rate of condensation for a given particle size distribution with a mean radius $\bar{r}_a$ may be expressed by

$$Q_c = k_c(q_c/q_s - 1) \tag{5}$$

where the condensation rate coefficient

$$k_c = 4\pi\bar{r}_a N/\rho(A + B) \tag{6}$$

and the mean radius $\bar{r}_a$ is defined by

$$\bar{r}_a = \frac{1}{N}\int_r r n(r)\, dr \tag{7}$$

In these equations, $n(r)\,dr$ denotes the number of droplets per unit radius range r and $r + dr$, N is the number concentration, $A = L^2/(R_v K T^2)$, and $B = R_v T/[D e_s(T)]$, with L being the latent heat, R_v the gas constant for water vapor, D the mass diffusion coefficient for water vapor in air, K the thermal diffusivity, and $e_s(T)$ the water vapor saturation vapor pressure at temperature T. The values of D and K are taken from *Weast* [1977] and may be expressed in terms of a linear function of temperature. On the basis of the values for A and B, the condensation rate coefficient increases as the temperature increases.

The rate of precipitation generation, according to the collision theory, may be written in the form

$$P \cong q_m \bar{E} \int_r \pi r^2 w(r) n(r)\, dr \tag{8}$$

where $\bar{E}$ denotes the mean collision efficiency, and $w(r)$ denotes the fall velocity of the particles. The first stage of precipitation processes begins with the conversion of cloud droplets to raindrops and is referred to as autoconversion. In this process, the collector drops must be larger than about 20 μm in order to effectively initiate collisions. For droplet radii less than 50 μm, the fall velocity is governed by the Stokes law and is proportional to the square of the droplet radius, namely, $w(r) = kr^2$, where the constant of proportionality $k \cong 1.19 \times 10^6$ cm^{-1} s^{-1} [*Rogers*, 1979]. Thus the rate of precipitation generation due to autoconversion (from equation (8)) is directly proportional to the cloud liquid water in the form

$$P_1 \cong k_1 q_m \tag{9}$$

where the autoconversion rate coefficient

$$k_1 = \pi \bar{E} k N \bar{r}_w^4 \tag{10}$$

and the mean droplet radius is defined by

$$\bar{r}_w = \left[\frac{1}{N}\int_r r^4 n(r)\, dr\right]^{1/4} \tag{11}$$

On the basis of the preceding analysis, the initiation of precipitation is a linear function of the mean collision efficiency and droplet concentration but depends on the mean droplet radius $\bar{r}_w$ to the fourth power. A small variation in $\bar{r}_w$ will significantly affect the autoconversion rate coefficient and hence the rate of precipitation generation. As defined in (11), the mean droplet radius is related to the droplet size distribution $n(r)$.

The second stage of precipitation processes involves large raindrops and is referred to as accretion. The raindrop size distribution has been measured in terms of the rainfall rate at the surface. On the basis of these measurements, *Marshall and Palmer* [1948] suggested that the raindrop size distribution can be fitted with an appropriate negative exponential form, given by $n(r) = n_0 \exp(-2\Lambda r)$, where the slope factor is defined by $\Lambda = 41R^{-0.21}$, with R being the rainfall rate, and the intercept parameter $n_0 = 0.08$ cm^{-4}. According to Marshall and Palmer, this size distribution is valid for a small rainfall rate of about 1 mm h^{-1}. The rainfall rate generated in the present one-dimensional model is about 0.5 mm h^{-1} in the cloudy region. The averaged cloud cover for three cloud types generated in the model is about 0.25. Thus the averaged annual rainfall rate for all areas is about 1000 mm yr^{-1}. This value is smaller but is of the same order of magnitude as the observed data. For the raindrop fall velocity we use the form proposed by *Liu and Orville* [1969], that is, $w(r) = a(2r)^b(\rho_0/\rho)^{1/2}$, where $a = 2115$ cm^{1-b} s^{-1}, $b = 0.8$, and the reference air density is $\rho_0 = 1.2 \times 10^{-3}$ g cm^{-3}. Using these values, the rate of precipitation generation due to accretion (from equation (8)) may be written in the form

$$P_2 = k_2 \bar{P}^{0.791} q_m \tag{12}$$

where $k_2 \cong 0.931\,\rho^{-0.105}$ and the precipitation flux $\bar{P} = \rho \bar{w}_r q_r$, where q_r is the liquid water content mixing ratio for raindrops and $\bar{w}_r$ is the bulk terminal velocity for raindrops with mass $m(r)$, defined by the size distribution $n(r)$. The precipitation flux is linearly related to the rainfall rate R. Combining (9) and (12), the total rate of precipitation generation is given by

$$\begin{aligned} P &= P_1 \text{ (autoconversion)} + P_2 \text{ (accretion)} \\ &= (k_1 + k_2 \bar{P}^{0.791}) q_m \end{aligned} \tag{13}$$

This parameterization equation is similar to that developed by *Kessler* [1969] and *Soong and Ogura* [1973] for thunderstorm clouds, except that k_1 in the present formulation is a function of the mean radius to the fourth power.

In the cloudy condition, evaporation of cloud droplets is generally insignificant [*Sundqvist*, 1978; *Ogura and Takahashi*, 1971]. However, evaporation of raindrops is important in the consideration of the water budget. The time rate of change of mass for raindrops due to evaporation may be expressed by an equation analogous to the one for condensation. However, a ventilation factor V_e must be included. Following *Beard and Pruppacher* [1971], $V_e = \alpha + \beta S_c^{1/3} (\rho/\mu)^{1/2} (\rho_0/\rho)^{1/4} r^{1/2}$, where $\alpha = 0.78$, $\beta = 0.31$, the Schmidt number $S_c = \mu/\rho D$, μ is the viscosity of air, and D has been defined previously. Using the Marshall-Palmer size distribution and the aforementioned ventilation factor, the rate of evaporation may be expressed by

$$E_r = (k_{e1} \bar{P}^{0.417} + k_{e2} \bar{P}^{0.604})(1 - q/q_s) \tag{14}$$

where $k_{e1} = 7.493 \times 10^{-2} \rho^{-0.792}/(A + B)$, and $k_{e2} = 0.617 \times \rho^{-1.006}/(A + B)$.

The rates of condensation, evaporation, and precipitation generation are now parameterized in terms of the specific humidity q, cloud liquid water mixing ratio q_m, and precipitation flux $\bar{P}$. The rate coefficients k_c, k_{e1}, and k_{e2} are functions of temperature and are therefore interactive with the perturbation due to radiative forcings, through the thermodynamic equation containing temperature and solar and IR fluxes.

In the derivation of the condensation and autoconversion rate coefficients, we have introduced two mean droplet radii, $\bar{r}_a$ and $\bar{r}_w$, defined in (7) and (11). It would be desirable to express these two values in terms of a mean radius, which is related to the optical depth. The optical depth for a cloud with a thickness Δz and a droplet size distribution $n(r)$ is given by

$$\tau = \Delta z \int_r Q_{\text{ext}}(r) \pi r^2 n(r)\, dr \tag{15}$$

where Q_{ext} denotes the extinction coefficient. In the visible wavelengths, $Q_{\text{ext}} \approx 2$ for cloud droplets. We may define an optical mean cloud particle radius in the form

TABLE 1. Cloud droplet size, mean radius, and concentration

Cloud Type	N, cm^{-3}	r_{mode},* μm	Δ,† μm	$\bar{r}_a$, μm	$\bar{r}$, μm	$\bar{r}_l$, μm	$\bar{r}_w$, μm
St I (ocean)	464	3.5	0–16.0	4.1	4.5	5.0	5.4
As	450	4.5	0–13.0	4.6	5.3	6.0	6.8
Sc	350	3.5	0–11.2	4.1	4.6	5.0	5.6
Ns	330	3.5	0–19.8	7.1	8.2	9.1	9.9
Cu (fair)	300	3.5	0–10.0	4.1	4.5	4.9	5.2
St II (land)	260	4.5	0–20.0	5.9	6.7	7.4	8.0
Cu (congestus)	207	3.5	0–16.2	7.2	8.2	9.1	9.9
Cb	72	5.0	0–30.2	10.7	13.2	15.3	17.0

The mean radii $\bar{r}_a$, $\bar{r}$, $\bar{r}_l$, and $\bar{r}_w$ are defined in equations (7), (16), (18), and (11), respectively.
*Radius corresponding to the maximum concentration.
†Radius interval.

$$\bar{r} = \left[\frac{1}{N}\int_r r^2 n(r)\, dr\right]^{1/2} \qquad (16)$$

Hereafter, we shall refer to this radius simply as the "mean radius." The optical depth may then be expressed by

$$\tau \cong 2\pi \Delta z N \bar{r}^2 \qquad (17)$$

Thus the optical depth is proportional to the mean radius to the second power. Equation (17) is correct for the visible wavelengths.

We shall attempt to relate $\bar{r}_a$ and $\bar{r}_w$ to the mean radius, so that the latter value may be used as a reference radius in the discussion of the effects of cloud microphysical processes on climatic temperature perturbations. *Carrier et al.* [1967] summarized the droplet size distributions for eight types of clouds (St I and II, Sc, Cu, Cb, Cg, Ns, and As). In Table 1, we list the pertinent parameters for the droplet size distributions of these clouds, including the concentration, mode radius, radius interval, and four mean radii. The third-order mean radius $\bar{r}_l$ is defined by

$$\bar{r}_l = \left[\frac{1}{N}\int_r r^3 n(r)\, dr\right]^{1/3} \qquad (18)$$

which is proportional to the LWC.

Using these distributions, we find that $\bar{r}_a \cong 0.852\bar{r}$, $\bar{r}_w \cong 1.247\bar{r}$, and $\bar{r}_l \cong 1.132\bar{r}$. When $r = 0$, $\bar{r}_a = \bar{r}_w = \bar{r}_l = \bar{r} = 0$. Since the droplet size distributions are skewed toward larger radii, the mean vlue increases as the radius moment increases.

The droplet concentrations shown in Table 1 are about 300–400 cm^{-3}, except in the case of Cb, whose concentration is a factor of about 5 lower than other clouds. The fourth-order mean radius $\bar{r}_w$ varies from about 5 to 17. Thus the difference between these values to the fourth power is more than a factor of 100. It is quite clear that the precipitation generation rate depends more significantly on the radius than on the concentration.

3. NUMERICAL RESULTS AND THEORY ON THE ROLE OF CLOUD MICROPHYSICAL PROCESSES IN CLIMATE

In order to simulate the present mean annual condition (control run), we have used the following input data: a solar constant of 1360 W m^{-2}, average cosine of the solar zenith angle of 0.5, duration of sunlight of 12 hours, surface albedo of 0.13, and CO_2 concentration of 330 parts per million by volume (ppmv). The ozone and molecular profiles used correspond to the standard atmospheric condition. The parameterizations of the radiative properties of clouds and the scheme for cloud compaction to obtain high, middle, and low clouds and the total cloud cover follow those described by *Liou et al.* [1985].

On the basis of the cloud droplet size distributions presented by *Carrier et al.* [1967], we used mean radii $\bar{r}_0$ of 4.5 and 5.3 μm for low (Cu, St) and middle (As) clouds, with number concentrations of 300 and 450 cm^{-3}, respectively. For high clouds an equivalent mean size of 35 μm, with a concentration of 0.2 cm^{-3}, was used. These values approximately correspond to the properties of cirrostratus presented by *Heymsfield* [1977]. The radii are defined here as the "climatological mean radii." The mean radii enter the cloud and climate model through the condensation and precipitation processes denoted in (7) and (11). The radiative properties of various types of clouds are parameterized in terms of the vertical LWC [*Liou and Wittman*, 1979]. Thus the particle size distribution is not directly related to the transfer of radiation, but it is indirectly related through precipitation and condensation processes, which determine the cloud LWC.

Temperature and specific humidity profiles produced from the one-dimensional model are first verified through the climatological data presented by *Oort* [1983]. The model temperature deviations from the observed climate data are less than about 0.5°C in the troposphere. The differences between the model specific humidities and observed climate values are within about 10%. In the experiment for the present climate, the eddy thermal diffusivities were tuned in order to achieve the best accuracies possible. They remain constant in the perturbation experiments. The vertical velocities in clear and cloudy areas generated from the present model are ~0.7 and ~1.5 cm s^{-1}, respectively, at the low cloud base. The averaged vertical velocity is $\bar{w} \approx 0$. The present one-dimensional model does not generate the different types of clouds that occur in realistic atmospheres. However, the cloud fractional cover and LWC are computed in each model layer, from which the position, cover, and LWC for high, middle, and low clouds are derived based on statistical averaging procedures [*Liou et al.*, 1985]. This allows us to compare the model cloud results with the cloud climatology presented by *London* [1957]. From London's data we find that the cloud covers for high, middle, and low cloud types are 0.156, 0.188, and 0.350, respectively, with a total cloud cover of 0.511. The present model, without perturbations, produces values of 0.127, 0.201, and 0.389 for high, middle, and low cloud covers, respectively, with a total cloud cover of 0.516, which differs from the climatological value by about 1%. Finally, the global albedo, computed from the model, is 30.9%. According to the analysis of satellite radiation budgets, *Stephens et al.* [1981] derived a value of 30.4% for the global albedo.

We then examine the model LWC profile for the present climate condition. Shown in Figure 1 is the computed LWC profile expressed in terms of temperature (or height, from the climatological temperature profile). The observed LWC profile presented by *Matveev* [1984] is also depicted in Figure 1 for comparison purposes. The observed profile was derived from data gathered between 1957 and 1968 at various locations in the Soviet Union, using aircraft measurements. Both the computed and observed LWCs increase with increasing temperature and show a slight decrease for temperatures higher than about 5°C. This is due to the fact that higher temperatures correspond to the cloud base region where a discontinuity in the LWC occurs [*Simpson and Wiggert*, 1969; *Yanai et al.*, 1973]. The observed LWCs, which represent the only available data of this kind, are limited to a specific region of the globe. Nonetheless, it is quite encouraging that the computed LWCs from the present model are within the range of observed values. The total LWC computed from the model is about 64 g m^{-2}. On the basis of the retrieval of microwave measurements of LWC over the oceans, the total observed LWC is of the order of about 60 g m^{-2} [*Prabhakara and Short*, 1984]. Finally, the total rate of precipitation from the control run is 2.4 mm

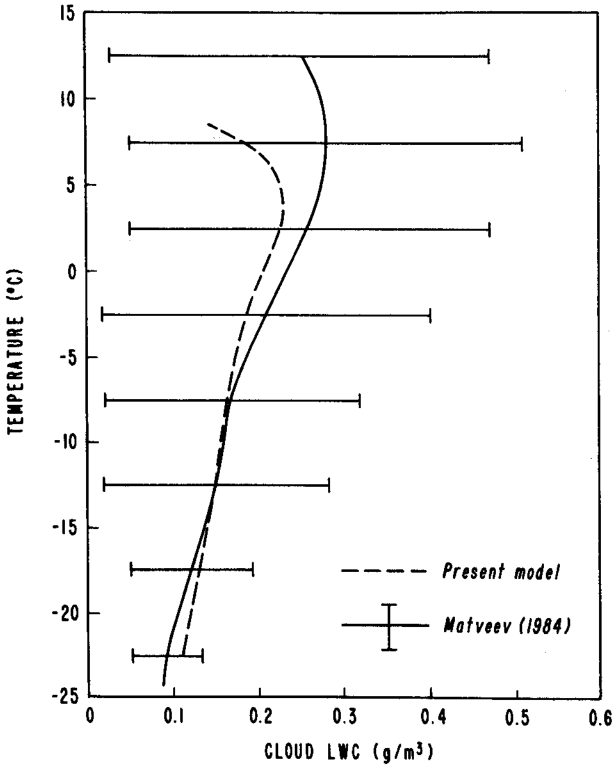

Fig. 1. Cloud liquid water content as a function of temperature computed from the one-dimensional cloud-climate model described in the text. Measured values presented by *Matveev* [1984] are also shown. These values are derived from data gathered between 1957 and 1968 at various locations in the Soviet Union from aircraft measurements. The vertical bars denote deviations from the mean.

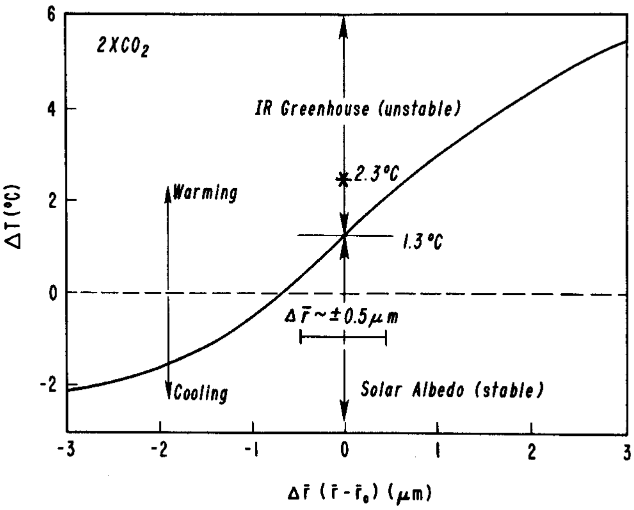

Fig. 2. Surface temperature perturbation ΔT due to doubling of CO_2 as a function of $\Delta\bar{r}$, defined as the deviation of the mean radii $\bar{r}$, for high, middle, and low clouds, from the climatological means $\bar{r}_0$ (see equation (16) for the definition of the mean radius). The bar denotes the standard temperature change ΔT = 1.3°C, corresponding to $\Delta\bar{r} = 0$. At values larger than this, the temperature increase is amplified owing to the prevalence of IR greenhouse effects, whereas at values smaller than this, the temperature increase is reduced because of the domination of the solar albedo effects. For $\Delta\bar{r}$ within 0.5 μm, the surface temperature increase is within 2.3°C, denoted by an asterisk. This value is produced by using a constant cloud liquid water content and mean radius in the model.

day^{-1} (~1000 mm yr^{-1}). This value compares well with the climatological data of 981 and 1097 mm yr^{-1} given by *Sellers* [1965] and *Budyko* [1982], respectively. In order to obtain this precipitation value, we have selected mean radii of 4.5, 5.3, and 35 μm for low, middle, and high clouds, respectively, as denoted previously. The surface evaporation is calculated from the temperature and humidity gradients, with the eddy coefficients adjusted to match the value for the present climate condition presented by *Budyko* [1982]. The mass balance requires that the total precipitation must be balanced by the surface evaporation. For this reason, whether the Bergeron process is included in the model or not would not affect the total precipitation generated for the present climate condition. If this process is incorporated in the model, an adjustment of the mean particle radius for ice clouds must be made in order to obtain a model precipitation that is close to the climatological value. However, in the perturbation experiments it is anticipated that the inclusion of the ice processes would remove more water vapor to become precipitation.

In the perturbation experiments we uniformly increased and decreased the climatological mean radii $\bar{r}_0$ by a value of $\Delta\bar{r}$ (= $\bar{r} - \bar{r}_0$), ranging from −3 to +3 μm, with $\bar{r}$ the perturbed mean radii. We used a doubling of the CO_2 concentration as the initial radiative forcing in order to investigate the effects of the mean radius on the climatic temperature perturbation. The results are illustrated in Figure 2. For the fixed cloud cover, LWC, and mean radius, a doubling of CO_2 produces a surface temperature increase ΔT of 2.3°C. In our previous studies we illustrated that the introduction of an interactive cloud cover program [*Liou et al.*, 1985] and/or an interactive cloud LWC program [*Ou and Liou*, 1987], in connection with the climate model, leads to negative feedbacks. Increased temperatures will cause the surface evaporation to increase. Subsequently, the cloud cover and LWC also increase, and less solar radiation is absorbed by the atmosphere and surface. Thus clouds appear to suppress the temperature increase because of the anticipated increase in CO_2 concentration. In the GCM experiments performed by *Wetherald and Manabe* [1988], the high cloud cover increases in the troposphere but the middle cloud cover decreases in the troposphere. The present results, without the consideration of the variation in particle sizes, show that low and middle cloud covers increase. A direct comparison between the present one-dimensional cloud results and those from GCMs would appear to be misleading. This is in view of the fact that one-dimensional models do not have latitudinal variations in cloud parameters and that the cloud formation scheme used in GCMs is highly primitive. It seems that a more realistic, but simplified, cloud parameterization scheme including the generation of cloud LWC for radiation calculations could be developed for use in GCMs.

If we vary the mean radius in the interactive cloud and precipitation program, several scenarios for temperature perturbations occur. Using the climatological mean radii $\bar{r}_0$, the total cloud cover increases from 0.516 (control run) to 0.530 and the surface temperature increases by 1.3°C, which is referred to as the standard temperature change. The cloud cover and temperature increase agree with those derived in our previous studies [*Ou and Liou*, 1987]. If the perturbed mean radii $\Delta\bar{r}$ are reduced to within about 0.5 μm, $0 < \Delta T <$ 1.3°C, and the temperature increases due to a doubling of CO_2 are offset (negative feedback). Moreover, if $\Delta\bar{r}$ are smaller than 0.5 μm, cooling instead of warming takes place when the CO_2 concentration is doubled. The surface temperature could be cooled by as much as −2°C owing to a significant increase in the LWC. The model results reveal that the total cloud cover decreases by only about 2% in reference to the control run. However, the LWCs of low, middle, and high clouds are increased by 50, 128, and 200%, respectively. These increases are associated with an about 3% decrease in precipitation because of small cloud droplets. Owing to an increased LWC, the solar albedo prevails and less solar fluxes are available at the surface.

However, if $\Delta\bar{r} > 0.5$ μm, temperature increases due to a doubling of CO_2 are amplified (positive feedback). For $\Delta\bar{r}$ of 3 μm, a surface warming of 5.6°C (compared to the standard temperature change of 1.3°C) could be produced. The LWCs for low, middle, and high clouds are significantly reduced by 81, 80, and 50%, respectively. These reductions result from an about 9% enhancement in precipitation, which is caused by the existence of larger cloud droplets. In this case the effective cloud optical depth decreases significantly, leading to a reduction in the solar albedo effects and, at the same time, an enhancement of the IR greenhouse effects. In the present sensitivity experiments we have uniformly increased and decreased the climatological mean radii $\bar{r}_0$ by a set of values. While the results derived from these experiments represent only limited possibilities for changes in cloud particle sizes, the significance of particle sizes in climate and climate changes is demonstrated. At this point we do not have observational or theoretical bases on which to vary the particle radius according to cloud type.

In Figure 3 the interactions and feedbacks involving the particle size, precipitation, cloud LWC, surface evaporation, and radiation due to greenhouse perturbations are schematically illustrated. The key to these interactions and feedbacks is the availability of larger or smaller cloud particles in reference to the climatological mean values. We shall speculate on the possibilities of the existence of larger or smaller droplet sizes in section 4.

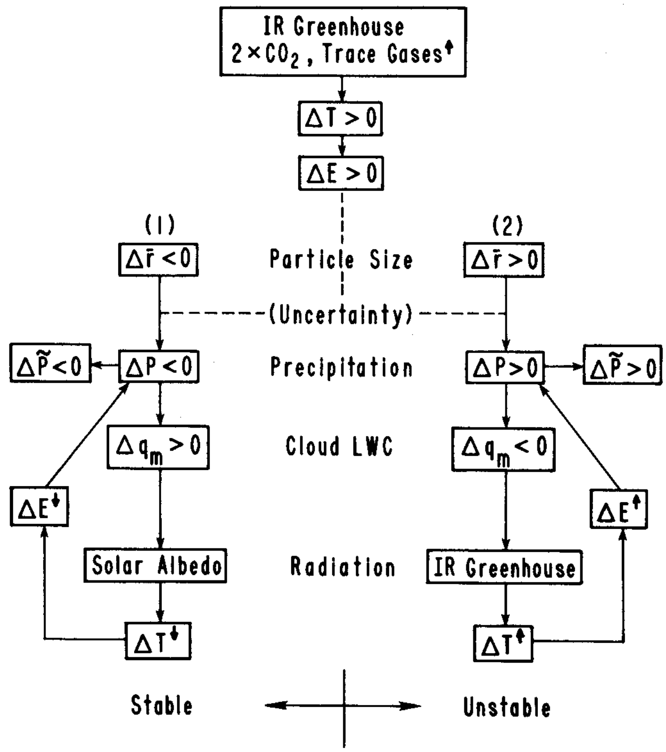

Fig. 3. A schematic illustration of interactions and feedbacks involving cloud particle size, liquid water content (LWC), precipitation, and radiation. In this illustration, T is the surface temperature, E the surface evaporation, $\bar{r}$ the mean radius (see equation (16)), P the precipitation generation rate, $\tilde{P}$ the precipitation flux, and q_m the LWC. The Δ denotes the change due to climatic perturbations; the arrows indicate that the perturbation parameters (ΔT or ΔE) are increased or decreased. It is postulated that there are uncertainties in the cloud particle size in the atmosphere. If the perturbed mean radii are increased because of greenhouse warming, then the precipitation generation rate is enhanced, resulting in a decrease in the LWC. In this case the IR greenhouse effects outweigh the solar albedo effects, leading to a positive feedback to the surface temperature increase. The reverse is true if the perturbed mean radii are decreased because of greenhouse warming.

On the basis of the preceding results, derived from the present climate model with an interactive cloud and precipitation program, the potential link between cloud microphysical processes and the climate and climatic perturbations is theorized.

Theory 1. If the perturbed mean radii $\bar{r}$ are less than the climatological mean values $\bar{r}_0$, precipitation decreases, leading to increases in the LWC. Thus the solar albedo effects outweigh the IR greenhouse effects, and the perturbed temperature due to a positive radiative forcing is stabilized.

Theory 2. If the perturbed mean radii $\bar{r}$ are larger than the climatological mean values $\bar{r}_0$, precipitation increases, leading to decreases in the cloud LWC. Thus the IR greenhouse effects outweigh the solar albedo effects, and the perturbed temperature due to a positive radiative forcing is amplified.

4. CONCLUSIONS AND HYPOTHESES ON THE UNCERTAINTIES IN CLOUD MICROPHYSICAL PROCESSES

In section 3 we theorized about the effects of clouds/radiation on climatic temperature perturbations, based on the deviation of the perturbed mean radii from the climatological mean values. We pointed out that the cloud LWC is directly related to precipitation processes, which depend on the mean radius to the fourth power. We further illustrated that the stabilization or amplification of temperature increases because of greenhouse warming is controlled by the particle mean radii and precipitation.

In connection with our theories on the link between cloud microphysical processes and the stability of the climate and climatic perturbations, we propose the following two possibilities for perturbations of the climatological particle mean radii due to temperature feedbacks.

Hypothesis 1 (for smaller cloud droplets in the atmosphere). *Charlson et al.* [1987] pointed out that the major source of cloud condensation nuclei (CCN) over the oceans is non-sea-salt sulphate, which is produced from the emission of dimethylsulfide (DMS) by marine organisms. They suggested that the highest rate of DMS emission to the atmosphere is associated with the warmest, most saline, and most intensely illuminated regions of the oceans. Thus an increase in the surface temperature could cause an increase in DMS emission, and hence CCN. Theory and experiments indicate that the cloud droplet concentration is approximately proportional to the CCN and that the size of the droplets decreases as the CCN in water clouds increase [*Pruppacher and Klett*, 1978; *Warner and Twomey*, 1967; *Hudson*, 1983]. From a recent satellite study, *Coakley et al.* [1987] showed that the stratocumulus clouds associated with underlying ship-tracks were consistently brighter in the visible wavelengths. This brightness was not due to particulates from the ship's smoke, but to enhanced CCN from the sulfur in the smoke. Over land, numerous observations have verified that pollution increases the number of CCN [*Warner and Twomey*, 1967; *Hobbs et al.*, 1974; *Braham*, 1974]. The increase in CCN over land will lead to more small cloud droplets per unit volume [*Twomey et al.*, 1984]. This increase is caused by anthropogenic sources and is not directly related to greenhouse temperature perturbations.

The preceding discussions illustrate the possibility for the existence of smaller cloud droplets (compared to the climatological mean) in the global atmosphere. Moreover, *Hobbs et al.* [1974] pointed out that precipitation from nonfreezing clouds may be modified by efficient CCN. A low concentration of very efficient CCN will tend to increase precipitation, whereas a large concentration of CCN might decrease precipitation due to competition for the available water vapor. Our proposed theory concerning the dependence of the precipitation rate on the mean radius to the fourth power is in line with these findings.

Hypothesis 2 (for larger cloud droplets in the atmosphere). We suggest the following competing mechanism for the potential existence of larger cloud droplets (compared to the climatological mean) in the atmosphere. Using the climatological mean radius in the perturbation run, we find that precipitation from the present one-dimensional cloud model increases by 1.4% as the CO_2 concentration is doubled. Moreover, all GCM experiments appear to show that precipitation would be increased in almost all latitudes with a doubling of CO_2 (see, for example, *Manabe and Wetherald* [1980, Figure 8]; *Washington and Meehl* [1984, Figure 14]).

Precipitation is considered to be the primary mechanism for the removal of atmospheric aerosols, including CCN. The process is referred to as wet removal [*Prospero et al.*, 1983]. Wet removal includes the incorporation of CCN in precipitation droplets within the cloud (rainout) and the capture of CCN in precipitation occurring below the cloud base (washout). Because of the increase in precipitation, the number of CCN may be reduced. In accordance with the discussion in hypothesis 1, larger cloud droplets could be formed from a low concentration of efficient CCN. This process provides a means for positive feedbacks involving precipitation, as well as temperature.

In the present model, neither aerosols nor the removal of aerosols were accounted for in the formation of clouds and precipitation. It is not known, based on this model study, which of the two competing mechanisms is more efficient. On the one hand, smaller cloud droplets could be produced from the additional CCN over the oceans as a result of greenhouse warming and over land as a result of pollution. Both provide a restoring mechanism (negative feedback) to the potential runaway greenhouse effect and stabilize the temperature perturbation. This mechanism appears to have received some support from aerosol researchers [*Charlson et al.*, 1987]. Also, *Charlock and Sellers* [1980] pointed out that changes in aerosol concentrations could imply changes in CCN. An addition of CCN would increase the low cloud reflectivity and reduce the surface temperature. On the other hand, larger cloud droplets could be generated through the removal of CCN by the enhanced precipitation caused by greenhouse warming. This would lead to a positive feedback and the temperature increase could be significantly amplified. A possible key to the greenhouse feedbacks appears to rely on the cloud microphysical processes. There are uncertainties in these processes for the formation of precipitation. These uncertainties, in our view, are statistical and stochastic in nature and cannot be predicted entirely by the thermodynamic and dynamic laws that govern the formation of clouds and precipitation.

There remains the question of how to minimize the uncertainty in cloud microphysical processes in relation to the climate and climatic perturbations. To begin with, it appears that a global climatology must be developed for the mean cloud particle radii for various cloud types, perhaps in terms of high, middle, and low clouds, in the investigation of the role of clouds in climate. The determination of particle sizes over the globe requires satellite measurements of the reflected solar radiation. The polarization technique appears to have had some success in the sizing of Venus cloud decks [*Hansen and Hovenier*, 1974]. Also, there is a significant information content in the reflected polarization with respect to the shape of cloud particles [*Takano and Liou*, 1989]. The multiwavelength scanning radiometer proposed by *King et al.* [1987], which is designed for the measurement of the single-scattering albedo of clouds, appears to have some potential for particle sizing. Obviously, a global definition of particle sizes for various cloud types from satellites requires in-depth research and development.

In the present study we followed our earlier work in the parameterization of the radiative properties of clouds in terms of the LWC for three types of clouds (high, middle, low). The effects of the variation of particle sizes on the cloud radiative properties were not accounted for. There is some evidence that cloud absorption depends significantly on large droplets and that the LWC, which is related to the third moment of the particle radius, may not be sufficient to define the radiative properties of clouds [*Wiscombe et al.*, 1984]. The importance of the mean radius defined in (16), in addition to the LWC, in cloud-climate feedback problems has also been noted by *Bohren* [1985]. The incorporation of some aspects of particle radius in the parameterization of the radiative properties of clouds would be a subject requiring further research.

We have not considered the role of ice phase in the analysis and discussion of greenhouse perturbations. The incorporation of ice crystal formation and the Bergeron precipitation process would become extremely complicated even in the context of a one-dimensional model. However, ice crystal size distributions are unlikely to be affected by variations in the CCN.

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