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Cirrus Clouds and Climate Feedback: Is the sky falling and should we go tell the king?

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1. Introduction

Global warming is a contemporary topic of great scientific interest. With the projected rise in sea level and the anticipated effects of climate change on agriculture among others, global warming has escalated to a major societal issue. At the grass-roots scientific level however, global warming has not yet been proclaimed as an accepted truth and it has been realized for some time that potential feedbacks via the effect of cloud on the Earth's radiation budget make nonsense of any prediction of a global temperature rise. A number of recent scientific studies have attempted to investigate the perplexing effects of cloud feedback in the context of a global warming. Some climate model results suggest that the feedback may even accentuate the warming induced by a CO_2 increase largely due to the enhancement of cirrus clouds in the models (e.g., Roeckner *et al.*; 1987).

It is a widespread belief that thin cirrus clouds act to enhance the 'greenhouse effect' owing to a particular combination of their optical properties (Manabe and Wetherald, 1967; Cox,1971; Stephens and Webster, 1981). It is demonstrated in this study how this effect is perhaps based on inadequate resolution of the physics of cirrus clouds and that the more likely impact of cirrus to climate change remains somewhat elusive. These conclusions are developed within the context of a specific feedback mechanism incorporated into a simple 'mechanistic' climate model. A specific scientific question addressed here is whether or not the observed relationship between the ice water content and temperature of cirrus provides any significant feedback to the CO_2 greenhouse warming. A related question is also examined concerns the specific role of cloud microphysics and radiation in this feedback. This raises several pertinent issues about our understanding of cirrus clouds and their likely role in climate change as there presently exists a considerable uncertainty about the microphysics of these clouds (e.g. size and shape of ice crystals) and their radiative influences.

2. Cloud microphysics and ice water content

Characterization of the shape and size of ice crystals in terms of their environmental parameters continues to be a heavily researched area of cloud physics. It is a topic crucial to the cloud climate problem. The observations of Heymsfield and Platt (1984) indicate that both the size of these ice crystals and the ice water content increases with increasing cloud temperature. Their results are reproduced in Fig. 1 together with the empirical relationship

$$w = 0.0007e^{0.041(T+60)} \qquad (1)$$

where w is in $g.m^{-3}$ and T is in $°C$. This relationship forms the basis for the ice water feedback studied in this paper.

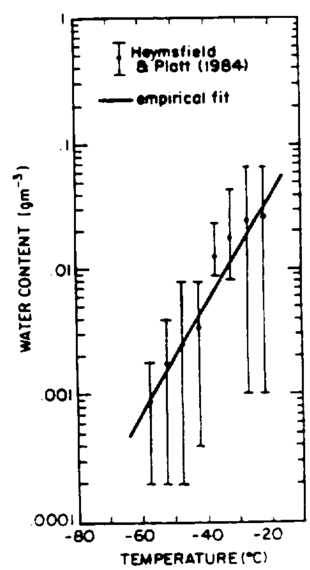

Fig. 1. The relationship between cirrus cloud ice water content and cloud temperature (after Heymsfield and Platt, 1984) and the relationship expressed by (1)

3. Cloud optical properties

The optical properties of the ice crystals were assumed to be spherical in shape and parameterized in the manner described by Stephens *et al.* (1989). A simple diffraction theory was adopted as the framework for this parameterization and the relevant properties of volume extinction and single scatter albedo were derived as functions of the effective radius of the size distribution (r_e) and the bulk absorption coefficient of ice. Typical values of r_e were chosen to be consistent with the observations reported by Platt and Harshvardhan (1988). Figure 2 shows the values of α_{abs} derived from a series of lidar-radiometer measurements (LIRAD) (e.g., Platt *et al.*, 1987) together with additional aircraft observations. Shown as curves are three relationships calculated from Mie scattering theory for a wavelength of 10.8 μm assuming an analytic size distribution with $r_e = 4, 16$ and 64 μm. The three theoretical relationships included on the diagram are therefore based on the assumption that crystal size is invariant to temperature change and that the increase of ice water content with increasing cloud temperature occurs through an associated increase in total particle concentration. This is, by necessity, an overly simple assumption as already noted and a better understanding of the role of cirrus cloud microphysics in relationships like that shown in Fig. 2 is sorely needed.

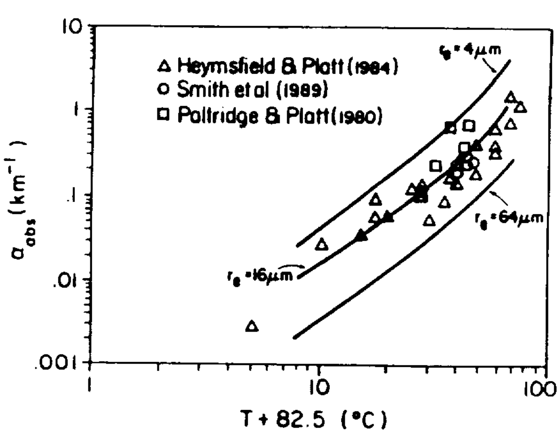

Fig. 2. The observed relationship between the volume absorption coefficient and cloud temperature taken from the sources indicated. The three curve were derived from Mie theory for the values of r_e indicated.

The asymmetry parameter was selected in the following way. Combined analyses of aircraft radiometric data and satellite data were employed to obtain albedo ($\mathcal{R}$)-emittance (ϵ) relationships that are then matched to theory in such a way as to provide a value of the asymmetry parameter. The values of $\mathcal{R}$ and ϵ derived from the satellite data and the values obtained from the near coincident aircraft measurements are shown in the form of a scatter diagram in Fig. 3. Two theoretical relationships between albedo and emittance were also derived and are shown on Fig. 3. The relationship depicted by the solid curve is that derived from Mie theory with $r_e = 16$ μm and the value of the solar zenith angle corresponding to the time of observation ($\mu_o = 0.496$). The broadband average g determined from Mie theory and used to produce the solid curve is 0.87. The second relationship (dashed curve) provides a better fit to the observations and was obtained with $g = 0.7$. The difference between the Mie value of g and the value chosen to fit the observations is both significant and expected. It is straight forward to show that the reflectance of thin clouds is directly proportional to the backscatter fraction b_o and hence a function of $1 - g$. The albedo of a cloud estimated using $g = 0.7$ is therefore greater than the albedo calculated using $g = 0.87$ (the emittance is largely independent of g). We show below that this difference in albedo significantly influences the predicted response of a climate model to the presence of cirrus cloud. It is also expected that real cirrus clouds, composed of irregularly shaped particles, have values of g that are smaller than the values of g associated with the more ideal spherical particles (e.g., Stephens, 1980).

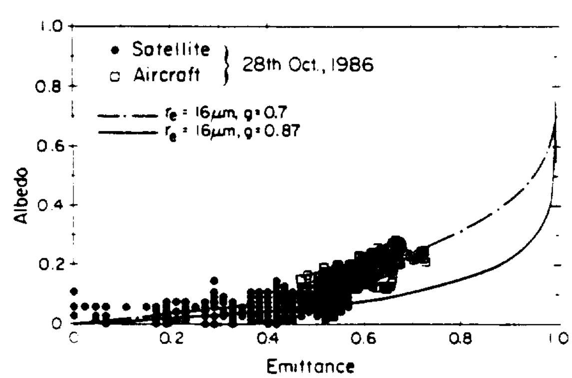

Fig. 3 . The relationship between cirrus cloud albedo and emittance derived from aircraft and coincident satellite data obtained for the 28th October FIREcirrus case. For explanations of the curves consult the text.

4. The effects of cirrus optical properties in a simple climate system

The effects on a simple climate system of the cloud optical properties and their relation to ice water content on a simple climate system defined by a radiative equilibrium climate model which are examined. The radiative properties of the clouds were determined using the optical properties as specified above in a two stream model. Details are provided in Stephens *et al.* (1989).

(a) Simulations with fixed ice water

The results of a series climate equilibrium experiments are shown in Fig. 4 and 5 expressed as the difference between overcast and clear skies of the surface temperature ΔT_g, cloud temperature ΔT_c (upper panel), cloud albedo $\mathcal{R}$ and emittance ϵ (lower panel) as a function of r_e. The ice water path prescribed for these experiments was 3 $g.m^2$ which corresponds to a $1km$ thick cloud at a temperature of $229°K$. The model simulations were carried out using the two values of g mentioned above. The resultant surface warming reported in earlier studies like that of Stephens and Webster (1981) is also reproduced in this study. However, the magnitude of this warming is strongly dependent on both the value of g and the value of r_e which is assumed for $\mathcal{R}$ and ϵ. For example, the surface warming tendency is enhanced by either decreasing the particle size or by assuming more forwardly scattering cloud particles.

A principal driving force of the surface warming is the radiative heating of the cloud layer that results primarily from the absorption of infrared radiation. According to the analysis shown in Fig. 4, the cloud warming is more than twice the warming calculated at the surface. This is seen in the time evolution of the model solutions displayed on Fig. 5. The simulations were carried out with the following prescribed values; $r_e = 16\ \mu m, g = 0.7$ and $W = 4.7\ g.m^{-2}$. The simulated surface temperature undergoes a slight cooling during the first few simulation days and only significantly differs from the clear sky equilibrium value after about ten days into the simulation. By contrast, the cloud temperature systematically increases during the early stages of the simulation and after about 10 days of the simulation the increased emission from cloud base due to this temperature increase is enough to drive a surface warming.

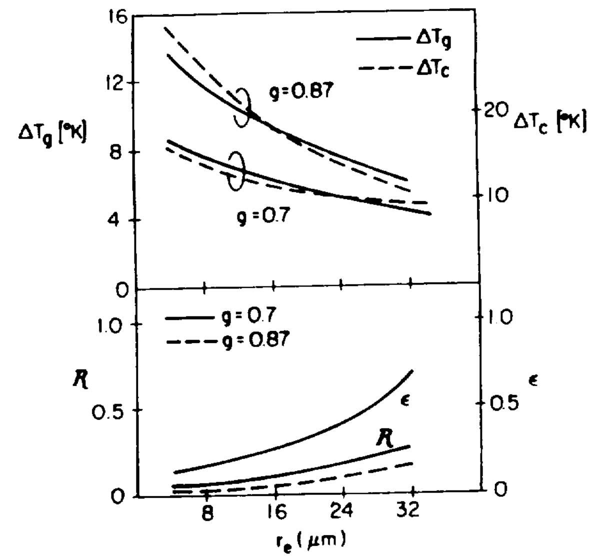

Fig. 4 The difference in equilibrium surface (T_g) and cloud (T_c) temperatures as a function of r_e for two values of g (upper panel) and the respective variation in albedo ($\mathcal{R}$) and emittance (ϵ) with r_e (lower panel).

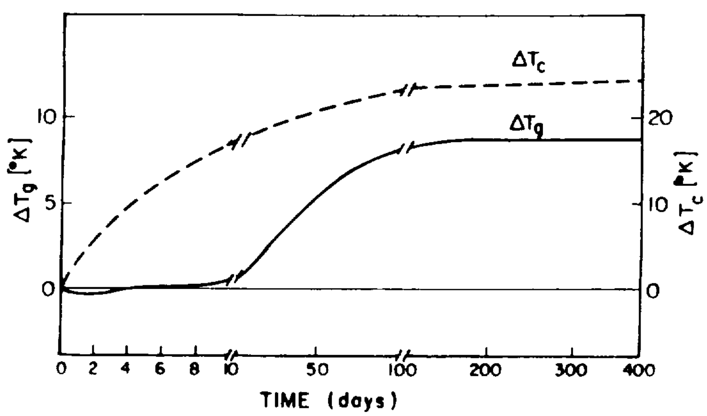

Fig. 5 Time evolution of the surface (solid) and cloud (dashed) temperatures predicted by the model.

(b) Simulations with ice water feedback

The ice water feedback was examined by analyzing pairs of control/perturbation simulations with the radiative equilibrium model. The perturbation experiment represents the simulations with twice the present day CO_2 concentration and the control simulations were run with the present day concentrations of CO_2. The notation Δx is used to represent the difference between the perturbation and control simulations of a particular climate parameter of interest (say surface temperature). Two pairs of perturbation/control experiments are then compared; one pair was conducted with the ice water feedback included in the model and the second pair assumed fixed values of ice water path. These comparisons are presented in terms of the parameter $\delta x = \Delta x$(with feedback) $-\ \Delta x$(fixed). Positive values of δT_g therefore indicate that the ice water feedback acts to reinforce the simulated CO_2 warming and negative values of δT_g indicate a buffering effect against such a warming.

Values of $\delta T_g, \delta T_c$ (upper panel), δW (middle panel) and $\delta\epsilon$ and δR (lower panel) are presented as a function of r_e in Fig. 6. All simulations were performed with $g = 0.7$. These results indicate that the sign of the ice water feedback varies according to the value of r_e used in the model to obtain the cloud optical properties. According to these simulations, the feedback is negative when $r_e < 24\mu m$ and positive for larger crystal clouds. The explanation for this is revealed by comparison of $\delta\mathcal{R}$ and $\delta\epsilon$.

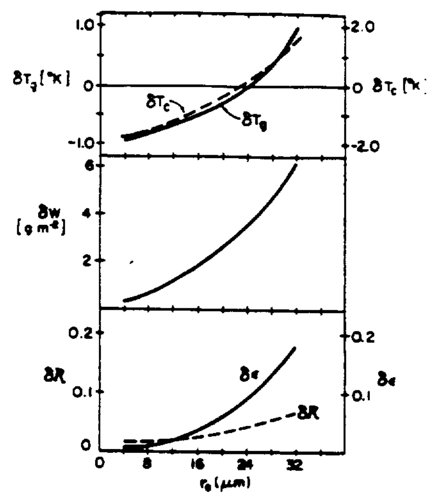

Fig. 6 The feedback parameter as defined in the text as a function of r_e.

5. Summary and Conclusions

Is the sky falling and do cirrus clouds make it worse? While the first part of this question was not explicitly addressed in this study it is clear that, from a scientific viewpoint, the potentially large but not well understood effects of cloud feedbacks cast serious doubts over any proclamations of impending climate change. The focus of this paper was directed towards the second question; is there overwhelming scientific evidence in support of a positive cirrus cloud feedback? Despite accepted wisdom to the contrary, the results demonstrate that the sign of the cirrus feedback is uncertain, let alone its magnitude, and is influenced by cloud (microphysical and dynamical) properties that are presently neither well known nor well understood. The results also suggest that the surface warming induced by cirrus clouds as predicted previously by several others (including the author) may be model dependent and unrealistic. It was shown how the cirrus warming was governed by the radiative budget of the cloud itself. The absorbed infrared radiation gave rise to a direct warming of the cloud layer and it was shown that this warming was largely responsible for the associated surface warming. This scenario is clearly artificial as dynamical and turbulent motions, induced by the radiative warming, will likely act to alter the structure of real cirrus and perhaps even the character of the feedback. Thus an understanding of the dynamical aspects of cirrus, coupled to the microphysical and radiative properties, are likely to be important to the problem of understanding cirrus cloud feedback to climate.

6. Acknowledgements

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