Notes and Correspondence

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On the role of clouds in the general circulation of the atmosphere

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1. Introduction

In recent years there has been considerable interest in examining the role played by clouds in climate, both from model studies and from satellite observations of the earth–atmosphere radiation budget. As a result of the 1974 JOC Study Conference on Climate (GARP 1974) it was noted that the cloud–radiation feedback problem was a key limiting factor in the development of physically realistic self-consistent climate models. This conclusion was reiterated by the 1978 JOC Study Conference on Parameterization of Extended Cloudiness and Radiation for Climate Models (GARP 1978) which recommended "that sensitivity and diagnostic studies be carried out to test the dependence of climate on cloudiness". Most model sensitivity studies are based on one-dimensional radiative–convective models (Manabe and Wetherald 1967, for example) which indicate that complete removal of clouds would increase the global surface temperature ($\overline{T}_s$) by about 15 K. Analysis of satellite radiation budgets by Ellis (1977) indicates that complete removal of clouds would enhance the radiative energy absorbed by the earth–atmosphere system by about $25\,\mathrm{W\,m^{-2}}$, roughly equivalent to an increase of 10% in the solar constant. In order to illustrate the significance of such a large increase in the solar constant we refer to Wetherald and Manabe's (1975) general circulation model (GCM) study, which estimates that a mere 2% increase in solar constant increases $\overline{T}_s$ by 3 K accompanied by a 9 K increase in polar T_s, and that the equator to pole temperature difference is decreased by 7 K.

The only three-dimensional GCM study of the cloud–climate problem to date is that by B. G. Hunt (1978), in which clouds were removed completely and GCM simulations, with and without clouds, compared. For the simulation with clouds, clouds were prescribed on the basis of annual mean observations; and, furthermore, the GCM simulations were performed for annual mean conditions. The significant conclusions from this comparison study were: (i) the global $\overline{T}_s$ increased by 7 K, as opposed to 15 K obtained by earlier studies; and (ii) the meridional forcing function for the general circulation was largely unaltered by the removal of clouds. Based on these results, Hunt suggested that the forcing function for the general circulation is independent of cloud cover and that clouds have a negligible role in providing radiative–dynamical coupling within the atmosphere.

The purpose of this note is to indicate quantitatively that the GCM used by Hunt, because of neglected feedback processes, underestimated the global forcing function by more than a factor of two and may have misrepresented the meridional forcing function caused by the removal of clouds. In addition it is shown that in order to examine the radiative–dynamical coupling provided by clouds it is necessary to take account of seasonal and land–ocean asymmetries in cloud radiative forcing – two effects which were neglected in Hunt's GCM. The principal conclusion of our paper, then, is that, while Hunt's study is an important first step towards defining the role of clouds in the general circulation, we need more detailed model and observational studies before arriving at definite conclusions.

2. Analysis of Hunt's study: neglected feedback processes

The major cause of the underestimation of the global forcing (due to removal of clouds) by Hunt is the neglect of the 'relative humidity feedback' in the radiation calculations. Hunt's GCM allows for a hydrological cycle, i.e. atmospheric H_2O is a prognostic variable in the model. As shown by this GCM, as well as by Wetherald and Manabe's (1975) GCM study, the atmosphere

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tends to conserve relative humidity by a change in temperature. Then, as the temperature increases, the H_2O amount increases and the consequent enhancement in the H_2O longwave radiation opacity (the so-called 'greenhouse effect') amplifies the initial increase in temperature. Manabe and Wetherald (1967) demonstrated that this relative humidity feedback doubles the increase in $\overline{T}_s$ when compared with a model which fixes absolute humidity. However, in Hunt's GCM this feedback is neglected since the GCM assumes the same absolute humidity in both simulations, with and without clouds, for the radiation calculations. Consequently, we estimate that the increase in $\overline{T}_s$ of 7 K computed by this model would have been $\simeq$ 14 K (in closer agreement with the results of Manabe and Wetherald 1967) had the GCM simulation included the relative humidity feedback in the radiative calculations.

Another important feedback neglected in the GCM is the ice albedo feedback. As suggested by several studies, for example Wetherald and Manabe (1975), in regions of ice and snow cover a warming of the surface might melt this surface cover, resulting in a decrease in surface albedo; this albedo decrease would in turn amplify the initial increase in the surface temperature. A summary of the numerous investigations on this feedback shows that the ice albedo feedback amplifies the change in $\overline{T}_s$ by a factor of about 1·25 (Lian and Cess 1977), and this contribution of 1·25 to global $\overline{T}_s$ comes from the increase in polar T_s, which is larger than the low to mid-latitude warming by a factor of about 3 (Wetherald and Manabe 1975). This result is in contrast with Hunt's GCM estimates, which suggest that increases in polar surface temperatures are much smaller than increases in mid-latitude surface temperatures. Consequently, because of the neglect of the ice albedo feedback, meridional forcing caused by the removal of clouds is substantially underestimated by the model, and perhaps more importantly is misrepresented with regard to the sign of the forcing.

3. Concluding remarks

There are important seasonal and land–ocean asymmetries in the radiative forcing of clouds that are neglected in Hunt's GCM which may limit the validity of his conclusions concerning the negligible role of clouds in providing radiative–dynamical coupling.

In polar regions complete removal of clouds during winter would radiatively cool the earth–atmosphere system but would cause radiative warming in summer. This is because solar insolation during winter is negligible in polar regions and hence removal of clouds would enhance longwave cooling to space. On the other hand, during summer solar insolation is larger and hence longwave cooling to space caused by the removal of clouds would be more than compensated by the increased absorption of solar radiation, particularly when considered in conjunction with the effects of ice–albedo feedback in reducing surface albedo. This seasonal asymmetry in cloud radiative forcing is clearly illustrated by Ellis (1977) who shows that at 60–70°N the parameter $\partial N/\partial c$ (where N is the net radiative energy budget of the earth–atmosphere system and c is fractional cloudiness) is $22\,\mathrm{W\,m^{-2}}$ during January and that it changes in sign to $-61\,\mathrm{W\,m^{-2}}$ during July. The resultant change in perturbation meridional radiative forcing due to cloud removal can play an important role in determining the effects on the general circulation.

In addition, as shown by Ellis, removal of clouds has a significantly larger effect on the ocean energy budget than on the land energy budget. Ellis's analysis of satellite radiation budgets indicates that removal of clouds would exert roughly a 50% larger effect on the ocean radiative energy budget, in mid-latitudes, than on the land energy budget. Such land–ocean contrast in cloud radiative effects, which are neglected in Hunt's GCM, can play an important role (because of their effects on excitation of planetary scale waves) in determining the radiative–dynamical effects of clouds.

The list of neglected cloud radiative processes given above, that may determine the role of clouds on climate, is by no means exhaustive. It should be pointed out that all current GCMs and other, less sophisticated climate models suffer from similar or different types of deficiencies, the reason for such deficiencies being lack of adequate observational data and theoretical framework regarding cloud distributions and their radiative effects. The existence of these deficiencies in current GCMs does not necessarily imply that the GCMs are unsuitable for climate studies; but that they may not yet be ready to enable a definite assessment to be made of the role of clouds in the atmospheric general circulation.

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