THE ROLE OF CLOUDS IN THE GENERAL CIRCULATION OF THE ATMOSPHERE

D. A. Randall
Department of Atmospheric Science
Colorado State University
Fort Collins Colorado 80523 USA

1. INTRODUCTION

Clouds affect the dynamics of the atmosphere by creating complex couplings among radiative, thermodynamic, and dynamic processes (Arakawa, 1975). Clouds affect the large-scale circulation of the atmosphere by influencing radiative transfer, by releasing latent heat, and by producing small-scale turbulent and convective motions that vertically redistribute energy, moisture and momentum. Interactions between clouds and radiation, and between clouds and the dynamic-hydrologic cycle are only dimly understood, however. General circulation models (GCMs) are just now beginning to simulate microphysical processes and the three-dimensional, time-dependent distributions of cloud ice and cloud liquid water in the atmosphere (e.g., Sundqvist, 1978; Le Treut and Li, 1988; Tiedtk,e 1993; Fowler et al., 1994).

The discussion of the present paper is organized around the concept of "cloud feedback." A familiar example is as follows: Evaporation from a warm ocean leads to moist convection and high cloud formation. The high clouds trap longwave radiation and also reflect solar radiation back to space. Suppose, then, that increasing atmospheric greenhouse gas concentrations tend to produce a warming of the ocean. It has been argued (e.g. Ramanathan, 1981) that this would lead to increased surface evaporation and a general intensification of the hydrologic cycle. An altered hydrological cycle would be expected to lead to a change in cloud amount and/or a change in the optical properties of the clouds. If this change were such that the longwave trapping by the clouds intensified while solar reflection remained fixed, the net effect would be a tendency to further warm the oceans, i.e. a positive cloud feedback. On the other hand, if the cloud amount and or cloud optical properties changed in such a way as to cool the ocean, a negative cloud feedback would be said to occur.

The above example illustrates that the concept of feedback involves an "external perturbation" of some kind. The overall response of the system to such a perturbation is determined in part by the responses of "internal" parameters or processes. These external and internal processes are illustrated in Fig. 1. It is the responses of these internal parameters that constitute the feedbacks in the system. See Schlesinger (1989) for a more detailed discussion.

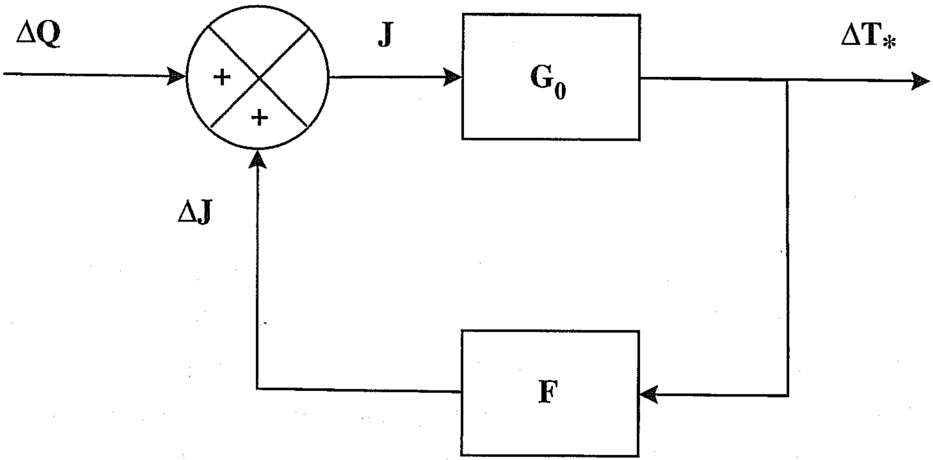


Figure 1. Diagram illustrating the concept of feedback, after Schlesinger (1989). ΔQ and $\Delta T_* = G_0\,J$ are the forcing and surface-temperature response of the climate system, respectively, with G_0 the gain of the system in the absence of feedback and $J = \Delta Q + \Delta J$, with $\Delta J = F\,\Delta T_*$. The feedback of the system is $f = G_0\,F$.

We usually think of external perturbations in terms of increasing greenhouse gas concentrations, as discussed above, or perhaps in terms of changes in the solar luminosity, or atmospheric injections of dust and gas through volcanic eruptions. There is another type of external perturbation that is much more commonly encountered at ECMWF and other modeling centers, however: Changes to the formulation of a model. These changes are the most external of perturbations! They are often implemented to produce desired improvement in the model's performance, but they may also be introduced in numerical experiments designed to investigate the sensitivity of the model (or of the real atmosphere) to a particular physical process.

As an example, we might perform a pair of runs in one of which a parameterization, a numerical method, or even the spatial resolution of the model is altered. We might then compare the differences in the results obtained in the two runs, perhaps focusing on medium-range forecast skill. Among the many approaches that might be taken to analyze and interpret the differences, one possibility would be to investigate the role of the GCM's cloudiness parameterization.

If the change to the model directly involved the cloudiness parameterization, then this change would itself be the "external perturbation." On the other hand, if the change to the model did not directly involve the cloudiness parameterization, then the cloudiness would properly be considered as an "internal parameter," as discussed above, and changes in cloudiness would produce "cloud feedbacks."

At an operational weather forecasting center like ECMWF, changes in model formulation are constantly being developed and tested. Any such change that does not directly involve the cloudiness parametrization itself provokes a cloud feedback, in the sense defined above.

In this paper, we discuss cloud feedbacks as responses to changes in model formulation, and give four specific examples of cloud feedbacks that can significantly affect the simulated general circulations of the atmosphere and ocean.

2. THREE CLOUD FEEDBACKS INVOLVING DEEP CONVECTIVE SYSTEMS

The anvils and cirrus clouds associated with deep convection in the tropics can powerfully affect the general circulation of the atmosphere. In the present climate state the net radiative effect of these clouds on the Earth's radiation budget is near zero (Ramanathan et al., 1989), because solar cooling and longwave warming nearly cancel, the solar cooling acts mainly at the Earth's surface, while the longwave warming acts mainly on the atmosphere (Harshvardhan et al., 1989). Current observations do not allow us to determine the effects of clouds on the radiative heating of the atmosphere, but GCM results indicate that clouds radiatively warm the atmosphere in the tropics and cool in middle and high latitudes (Harshvardhan et al., 1989), thus reinforcing the warming due to latent heat release, and "demanding" an additional poleward transfer of energy by the atmosphere. There is no reason to believe that the observed near-cancelation of shortwave and longwave cloud forcing by deep convective systems would also occur in altered climate regimes.

If we combine the net radiative energy flux at the top of the atmosphere with the net radiative energy flux at the Earth's surface, we obtain the net atmospheric radiative cooling (ARC). The ARC is the net effect of the emission (both upward and downward) by the atmosphere of infrared radiation, the absorption by the atmosphere of radiation emitted by the Earth's surface, and the absorption by the atmosphere of solar radiation.

There are at least two cloud feedbacks that link the hydrological cycle and the ARC. The first, discussed by Slingo and Slingo (1988) and Randall et al. (1989), is a positive feedback between the horizontal gradients of radiative warming/cooling associated with the localized high clouds produced by deep convection, and the large-scale rising motion associated with the convection (Fig. 2) The basic mechanism, as summarized in the figure, is as follows. In convectively active regions, longwave radiation is trapped by anvils and cirrus produced by convective detrainment, and so the longwave radiative cooling of the atmospheric column is reduced, and may even be transformed into a heating. Thinking now of the horizontal distribution of radiative heating/cooling, we see that the convectively active column is radiatively warmed relative to the surrounding, convectively inactive regions. This radiative warming reinforces the latent heating, as already mentioned. The combination of these two heatings, together with the radiative cooling in the surrounding radiatively inactive regions, favors mean or large-scale rising motion in the convectively active column. In reality, of course, we expect to find large-scale rising motion in convectively active columns anyway, so the point is that the pattern of cloud-induced radiative heating favors *stronger* rising motion.

This stronger rising motion favors increased moisture convergence, for two reasons. First, the rising air must converge at low levels, where moisture is abundant. Second, the stronger rising motion implies or entails a stronger Hadley/Walker circulation, which means stronger low-level winds and more surface evaporation.

Increased moisture convergence and large-scale rising motion favor more vigorous convection, which then tends to increase the upper tropospheric clouds that are responsible for the radiative warming of the convective column. In this way, the feedback loop is closed, and we see that the feedback is positive. In a nutshell, the high clouds have radiatively induced (or enhanced) a circulation that favors the production of more high clouds.

Since horizontal gradients of radiative heating and large-scale dynamics and convection are all important here, we call this the *Radiative-Dynamical-Convective (RDC) feedback.*

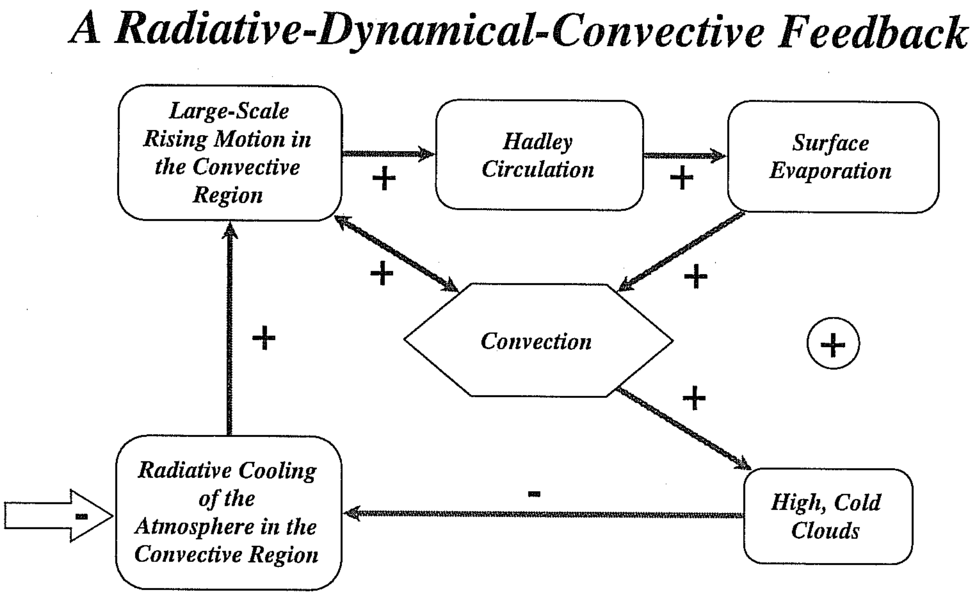


Figure 2. The Radiative-Dynamical-Convective Feedback. An external perturbation leads to a reduction in the rate of radiative cooling in a convective region of the atmosphere. The reduced cooling promotes rising motion in the convective region, and a stronger Hadley/Walker circulation. The stronger circulation leads to more vigorous surface evaporation. At the same time, the stronger rising motion and the increased evaporation lead to more vigorous convection. The convection produces more high, cold clouds, thus further reducing the radiative cooling rate, and so reinforcing the external perturbation. This is, therefore, a positive feedback.

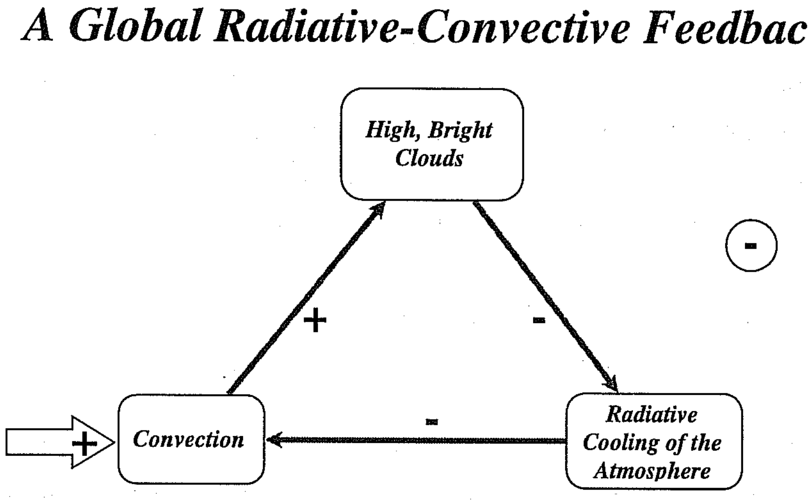
The RDC feedback was originally discussed by Slingo and Slingo (1988) who used version 1 of NCAR's Community Climate Model (CCM1). They performed a numerical experiment in which the longwave atmospheric cloud radiative forcing (longwave ACRF) was omitted. A comparison with the control run showed that the longwave ACRF acted to increase the water vapor content of the tropical atmosphere. In addition, the precipitation rate and rising motion both intensified in the climatological centers of precipitation. Because Slingo and Slingo (1988) performed their experiments with a full general circulation model, including all of the complexities of the real atmosphere and land surface, their results are complicated and somewhat difficult to interpret.

Similar but more readily interpretable results were obtained by Randall et al. (1989) using a very different GCM, run in a simplified "Seaworld" mode in which the lower boundary is a global ocean, with fixed, zonally uniform sea surface temperatures (SSTs) varying with latitude in the same way as the observed July zonally averaged temperature of the Earth's surface. The motivation for using a global ocean is two-fold:

- The response reported by Slingo and Slingo (1988) was most apparent over the tropical oceans, and did not show up clearly over land in the tropics or elsewhere.
- Clouds cast shadows on the land. Because the land-surface responds quickly to the reduced insolation, the clouds shadows can reduce the surface evaporation and sensible heat flux, thus tending to reduce the intensity of convection and retarding stratiform cloud formation. This is an interesting negative feedback which has not been quantified at present and deserves some attention in the future. At any rate, by considering a Seaworld with fixed sea surface temperatures, Randall et al. (1989) eliminated this negative feedback, allowing them to focus on positive feedbacks that might be at work over the oceans.

There is a second, negative feedback involving radiation and convection. It can be understood as follows. To a first approximation, the ARC is balanced by latent heat release (e.g., Peixoto and Oort, 1992). A possible interpretation of this simple balance requirement is that the globally averaged precipitation rate is determined by radiative processes! Although there is some merit to this idea, a major complication is that the hydrological and dynamical processes that directly control the precipitation rate can very strongly influence the ARC. For example, the distribution of water vapor in the atmosphere strongly affects the ARC, as does the high cloud amount.The coupling between the ARC and latent heat release leads to a very simple feedback: stronger convection leads to more high cloud, which reduces the ARC, which reduces the precipitation rate and the level of convective activity (Fig. 3). Since this control loop involves the global ARC and the global intensity of convective activity, we call it the *Global Radiative-Convective (GRC) feedback.* Fowler and Randall (1994) discussed an example of the GRC feedback encountered during the testing of a cloud microphysics parameterization.

Fig. 4 schematically shows what is known as the Thermostat hypothesis (Ramanathan and Collins, 1991). Suppose that a positive SST perturbation leads to an increase in surface evaporation and moisture convergence (Lindzen and Nigam, 1987). The increased moisture supply induces more convection, which leads to the formation of more high bright clouds, which reflect more solar energy back to space. The resulting reduction in the solar radiation absorbed the sea surface thus acts to damp the postulated positive SST perturbation. The term "thermostat" naturally suggests itself; the thermostat is attached to an air conditioner rather than a furnace.



A Global Radiative-Convective Feedback

Figure 3. The Global Radiative-Convective Feedback. An external perturbation leads to more vigorous convection, which produces more high, cold clouds. This reduces the rate at which the atmosphere cools radiatively. Weaker radiative cooling "demands" less latent heating, so on a global average the convective activity must diminish, thus counteracting the effects of the external perturbation. This is, therefore, a negative feedback.

To support their idea, Ramanathan and Collins presented observational evidence that SST fluctuations associated with El Niño are accompanied by changes in the solar cloud radiative forcing that would tend to damp the SST fluctuations regionally. Where the ocean warms, the solar radiation reaching the sea surface diminishes, and where the ocean cools, the increased solar radiation tends to warm it. Ramanathan and Collins argued that convection and high bright clouds increase when the SST increases to about 300 K. They suggested that the increased solar cloud forcing associated with deep convection acts to prevent temperatures much higher than this.

Although Ramanathan and Collins explicitly discussed only regional effects, their paper has been widely interpreted as suggesting that the global surface temperature of the Earth is limited in this way.

The Thermostat hypothesis has been very controversial. It has been criticized by Wallace (1992), Hartmann and Michelsen (1993) and Lau et al. (1994) for failure to recognize the importance of regional effects associated with large-scale dynamics, and also for underemphasizing the tendency of surface evaporation to cool the oceans. Fu et al. (1992) argued on the basis of satellite data that the strong regional cloud radiative forcing anomalies associated with El Niño average to near zero over the tropics as a whole. The discussion continues in the literature and at conferences. The existence of local negative shortwave cloud radiative forcing anomalies in response to local positive SST anomalies is apparent, but the importance of such shortwave cloud radiative forcing anomalies relative to other processes, and also their importance for the globally averaged surface temperature, are still being disputed. We can already say with certainty, however, that the Thermostat Hypothesis has stimulated a lot of valuable thinking.

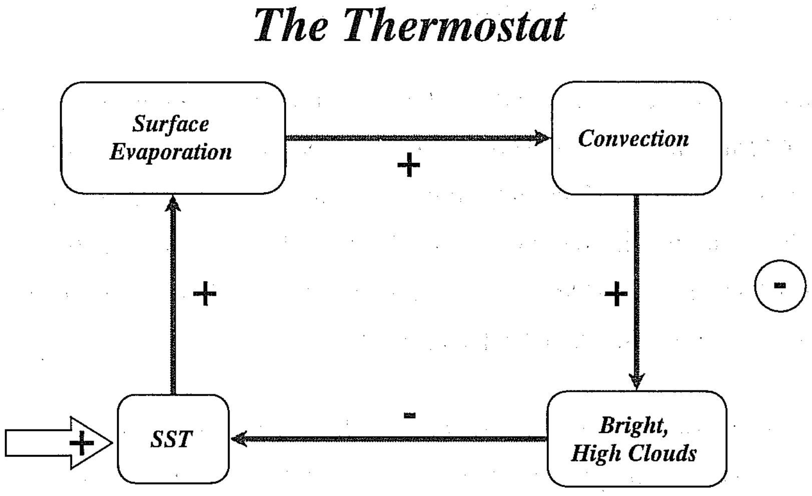


Figure 4. The Thermostat feedback. An external perturbation leads to an increase in the sea surface temperature, either locally or globally. This promotes stronger evaporation and moisture convergence, which then lead to more vigorous convection. The convection generates high, bright clouds, which reduce the insolation of the ocean, thus counteracting the external perturbation. This is, therefore, a negative feedback.

3. LOW-CLOUD LOCK-IN

Deep convective cloud systems are not the only clouds that can affect the general circulation. The marine stratocumulus clouds that commonly occur on the eastern sides of the subtropical oceans (e.g. Hanson, 1991) are also quite important, and are completely missed by many existing atmospheric general circulation models. Similar clouds occur in the Arctic in summer (e.g. Herman and Goody, 1976), as well as over the mid-latitude oceans (Klein and Hartmann, 1994). These low clouds are important because they strongly reflect solar radiation away from the ocean (e.g. Randall et al., 1984; Slingo, 1990). Recent studies have suggested that marine stratocumulus clouds must be simulated successfully in order to obtain realistic SST distributions in coupled ocean-atmosphere models (Robertson et al., 1994). From a forecasting perspective, low-level cloudiness is important as a forecast product in itself.

Marine stratocumulus clouds are interesting in part because they actually "like" subsidence; they are formed when a subsidence inversion associated with a subtropical high pressure cell confines moisture evaporated from the ocean within a thin, cool marine layer. The coolness of the marine layer is due in part to the coolness of the water below. The upper portion of the marine layer becomes saturated in part because of the moisture trapping associated with the inversion or, we may say, associated with the cold water. As emphasized by Lilly (1968), cloud-top radiative cooling also tends to lower the temperature of the cloudy air, thus helping to keep the relative humidity high. This low-level radiative cooling favors the large-scale sinking motion, which reinforces the subsidence inversion.

A key point is that the ocean itself is cooled by the bright cloud layer, which drastically reduces the surface insolation. We thus have the following situation: The existence of cold water favors the formation of low stratiform cloud. The existence of low stratiform cloud helps to keep the water cold. Obviously, this process can only be simulated by a model that has variable SSTs.

Low clouds are believed to be favored by strong capping temperature inversions (e.g. Lilly, 1968; Randall, 1980; Klein and Hartmann, 1994). At the same time, the radiative cooling associated with the clouds helps to maintain such inversions, as does the turbulent entrainment associated with the moist convective turbulence, which is driven in part by radiative destabilization. In short, the clouds tend to produce strong temperature inversions which are favorable for the continued existence of the clouds. Note that this process can work in a model that employs prescribed, non-interactive SSTs.

Summarizing, we can say that *low-level stratiform clouds promote conditions favorable for their own continued existence*. We refer to this phenomenon as "Low-Cloud Lock-In." It is illustrated in Fig. 5, and obviously it can be interpreted as a positive feedback: under suitable conditions, an external perturbation which tends to reduce the SST favors a change in cloudiness which further reduces the SST.

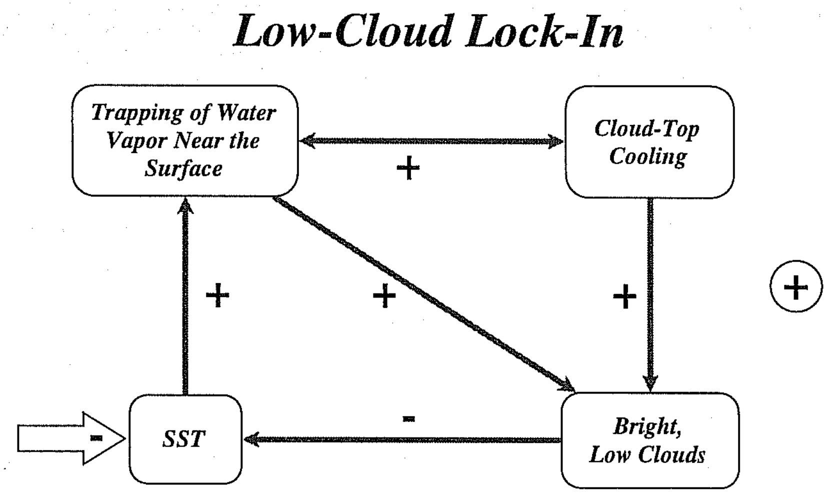


Figure 5. Low-Cloud Lock-In. An external perturbation leads to a reduction in the sea surface temperature. This favors the creation of a low-level inversion, thus trapping water vapor near the surface. Radiative cooling is concentrated near the top of the moist layer. Both the moisture trapping itself and the radiative cooling that it promotes lead to an increase in low-level relative humidity, favoring the production of low-level clouds. These clouds reduce the insolation of the sea surface, favoring a further reduction in the sea surface temperature. This is, therefore, a positive feedback.

Low-Cloud Lock-In is a real process of finite strength. A model that exaggerates the strength of Low-Cloud Lock-In may have a tendency to produce excessive low-level cloudiness. The coupled ocean-atmosphere general circulations models which are now proliferating in both climate and seasonal forecasting centers may be particularly susceptible to Low-Cloud Lock-In, because they have the potential to produce negative SST anomalies in response to increases in low-level cloudiness.

4. CONCLUSIONS

We have described four distinct cloud feedback processes, some positive and some negative, that can affect the response of the atmospheric general circulation to external perturbations, and which can affect the response of the *simulated* atmospheric general circulation to changes in model formulation. Certainly there are more, as yet unrecognized cloud feedbacks in nature. One of the points that we wish to make here is that "cloud feedback" is not a monolithic phenomenon.

A second point is that the strengths of the cloud feedbacks must be *quantified*; we have argued and cited studies showing that the cloud feedbacks are capable of altering the general circulation quite significantly. These feedbacks do not occur in isolation, however; they coexist not only with each other, but with many other powerful processes that can affect weather and climate. Idealized numerical experiments with GCMs can be designed to focus on particular feedbacks in relative isolation (as in the Seaworld study of Randall et al., 1989), and so are particularly well suited to investigating the strengths of such feedbacks.

5. ACKNOWLEDGEMENTS

Graeme Stephens has strongly influenced my ideas on this subject. This research was sponsored by the National Science Foundation under grant ATM-8907414 and by NASA under grant NAG-1653. I am grateful to ECMWF for supporting my participation in this Seminar.

6. REFERENCES

Arakawa, A., 1975: Modeling clouds and cloud processes for use in climate models. In *The Physical Basis of Climate and Climate Modelling.* GARP Publications Series No. 16, 181-197, ICSU/WMO, Geneva.

Fowler, L. D., and D. A. Randall, 1994: A global radiative convective feedback. *Geophys. Res. Let.*, in press.

Fowler, L. D., D. A. Randall, and S. A. Rutledge, 1994: Liquid and ice cloud microphysics in the CSU General Circulation Model. Part 1: Model description and results of a baseline simulation. Submitted to the *Journal of Climate.*

Fu, R., A. D. Del Genio, W. B. Rossow, and W. T. Liu, 1992: Cirrus-cloud thermostat for tropical sea surface temperatures tested using satellite data. *Nature*, **358**, 394-397.

Hanson, H. P., 1991: Marine stratocumulus climatologies. *Internat. J. of Climatol.*, **11**, 147-164.

Harshvardhan, D. A. Randall, T. G. Corsetti, and D. A. Dazlich, 1989: Earth radiation budget and cloudiness simulations with a general circulation model. *J. Atmos. Sci.*, **46**, 1922-1942.

Hartmann, D. L., and M. L. Michelsen, 1993: Large-scale effects on the regulation of tropical sea surface temperature. *J. Climate*, **6**, 2049-2062.

Herman, G., and R. Goody, 1976: Formation and persistence of summertime arctic stratus clouds. *J. Atmos. Sci.*, **33**, 1537-1553.

Klein, S. A., and D. L. Hartmann, 1993: The seasonal cycle of low stratiform clouds. *J. Climate*, **6**, 1587-1606.

Le Treut, H., and Z.-X. Li, 1988: Using Meteosat data to validate a prognostic cloud generation scheme. *Atmos. Res.,* **21,** 273-292.

Lilly, D. K., 1968: Models of cloud-topped mixed layers under a strong inversion. *Quart. J. Roy. Meteor. Soc.,* **94**, 292-309.

Peixoto, J. P., and A. H. Oort, 1992: *Physics of Climate.* Amer. Inst. Physics, New York, 520 pp.

Ramanathan, V., 1981: The role of ocean-atmosphere interactions in the CO_2 climate problem. *J. Atmos. Sci.,* **38**, 918-930.

Ramanathan, V., R. D. Cess, E. F. Harrison, P. Minnis, B. R. Barkstrom, E. Ahmad, and D. Hartmann, 1989: Cloud-radiative forcing and climate: Results from the Earth Radiation Budget Experiment. *Science,* **243**, 57-63.

Ramanathan, V., and W. Collins, 1991: Thermodynamic regulation of ocean warming by cirrus clouds deduced from observations of the 1987 El Niño. *Nature,* 351, 27-32.

Randall, D. A., 1980: Conditional instability of the first kind, upside-down. *J. Atmos. Sci.,* **37**, 125-130.

Randall, D. A., J. Coakley, C. Fairall, R. Kropfli, and D. Lenschow, 1984: Outlook for research on marine subtropical stratocumulus clouds. *Bull. Amer. Meteor. Soc.,* **65**, 1290-1301.

Randall, D. A., Harshvardhan, D. A. Dazlich, and T. G. Corsetti, 1989: Interactions among radiation, convection, and large-scale dynamics in a general circulation model. *J. Atmos. Sci.,* **46**, 1943-1970.

Robertson, A. W., C.-C. Ma, C. R. Mechoso, and M. Ghil, 1994: Simulation of the tropical-Pacific climate with a coupled ocean-atmosphere general circulation model. Part I: The seasonal cycle. *J. Climate* (submitted).

Schlesinger, M. E., 1989: Quantitative Analysis of Feedbacks in Climate Model Simulations in Understanding Climate Change. *Geophysical Monograph 52, IUGG Volume 7*, 177-187

Slingo, A., 1990: Sensitivity of the Earth's radiation budget to changes in low clouds. *Nature,* **343**, 49-51.

Slingo, A., and J. M. Slingo, 1988: The response of a general circulation model to cloud longwave radiative forcing. I: Introduction and initial experiments. *Quart. J. Roy. Meteor. Soc.,* **114**, 1027 - 1062.

Ramanathan, V., and W. Collins, 1991: Thermodynamic regulation of ocean warming by cirrus clouds deduced from observations of the 1987 El Nino. *Nature,* **351**, 27 - 32.

Randall, D. A., Harshvardhan, D. A. Dazlich, and T. G. Corsetti, 1989: Interactions among radiation, convection, and large-scale dynamics in a general circulation model. *J. Atmos. Sci.,* **46**, 1943 - 1970.

Slingo, A., and J.M.~Slingo, 1988: The response of a general circulation model to cloud longwave radiative forcing. I: introduction and initial experiments. *Quart. J. Roy. Meteor. Soc.,* **114**, 1027 - 1062.

Sundqvist, H., 1978: A parameterization scheme for non-convective condensation including prediction of cloud water content. *Quart. J. Roy. Meteor. Soc.,* **104**, 677-690.

Tiedtke, M., 1993: Representation of clouds in large-scale models. *Mon. Wea. Rev.,* **121**, 3040-3061.

Wallace, J. M., 1992: Effect of deep convection on the regulation of tropical sea surface temperature. *Nature,* **357**, 230-231.