Prognostic Cloud Water in the Los Alamos General Circulation Model

J. E. Kristjánsson and C-Y.J. Kao
Earth and Environmental Sciences Division
Los Alamos National Laboratory
Los Alamos, NM 87545

Most of today's general circulation models (GCMs) have a greatly simplified treatment of condensation and clouds. Recent observational studies of the earth's radiation budget have suggested cloud-related feedback mechanisms to be of tremendous importance for the issue of global change. Thus, an urgent need for improvements in the treatment of clouds in GCMs has arisen, especially as the clouds relate to radiation. In this paper, we investigate the effects of introducing prognostic cloud water into the Los Alamos GCM. The cloud water field, produced by both stratiform and convective condensation, is subject to 3-dimensional advection and vertical diffusion. The cloud water enters the radiation calculations through the longwave emissivity calculations.

Results from several sensitivity simulations show that realistic cloud water and precipitation fields can be obtained with the applied method. Comparisons with observations show that the most realistic results are obtained when more sophisticated schemes for moist convection are introduced at the same time. The model's cold bias is reduced and the zonal winds become stronger because of more realistic tropical convection.

Introduction

The last decade has seen an increasing demand for better and more reliable models for the general circulation of the atmosphere. As the models have improved, their results have been used as a basis for political documents (IPCC 1990). The models still have many unresolved problems. Perhaps the most notable ones concern the coupling between the atmosphere and ocean and the treatment of clouds. In this paper, we shall address some aspects of the latter problem.

For a long while, cloud treatment was extremely simple in most GCMs, see, e.g., Manabe et al. (1965). The condensation schemes simply dumped out as rain all condensing moisture, meaning that no mass was left in the water/ice phase. The radiation scheme would then assume a certain cloud distribution, which in the earliest models was based on climatology, but was later replaced by some interactive information, e.g., condensation rates. This is still the situation in many of today's models, and there is an urgent need to develop more realistic couplings between condensation and radiation. These couplings are a key feature of the atmosphere's response to changes in external forcings, as emphasized by, e.g., Kiehl and Ramanathan (1990).

One step that can be taken to improve the cloud treatment and its coupling to radiation is to carry cloud water/ice as a prognostic variable in the model. First proposed by Sundqvist (1978), the approach has been subsequently adopted by a few GCM groups, e.g., Roeckner (1988), Le Treut and Li (1988). But none of these studies have clearly identified the significance of using prognostic cloud water. Furthermore, the cloud water has been computed for stratiform condensation only. In the present model, convection also produces cloud water, which is put together with its stratiform counterpart and subjected to both advection and vertical diffusion.

Since it is well known that both short- and longwave radiative transfer are strongly dependent on liquid (or ice) water path, the cloud water variable enables an improved interaction with radiation. It is perhaps less obvious that the cloud water needs to be prognostic, rather than diagnostic. However, as discussed by Randall (1989), the prognostic feature is expected to be particularly important in areas of deep convection. There, cloud ice, in the form of cirrus clouds formed by the deep convection, can be subject to advection over long distances by upper-tropospheric winds, since ice particles have a long lifetime in these environments.

In this paper, the effects of introducing the prognostic cloud water treatment of Sundqvist (1988) in the Los Alamos GCM will be investigated. Results from several annual-cycle sensitivity simulations will be described. The purpose of the simulations was to clarify details concerning the cloud treatment.

The Los Alamos GCM and its Cloud Treatment

The GCM at Los Alamos National Laboratory (LAGCM) is a modified version of the National Center for Atmospheric Research's (NCAR) Community Climate Model (CCMO) described by Pitcher et al. (1983). The modifications, described in detail by Malone et al. (1986) and Kao et al. (1990) are

- The vertical resolution has been expanded from 9 to 20 levels.
- The advection of moisture has been improved substantially by introducing a fourth-order accurate finite-element scheme in the horizontal and an FCT method in the vertical.
- The vertical diffusion parameterization has been improved by introducing stability-dependent fluxes of heat and moisture between the planetary boundary layer (PBL) and the free atmosphere.
- The model now has prognostic equations for temperature in 6 soil-layers instead of a diagnostic equation.
- There are now prognostic equations for soil moisture based on the model's hydrological cycle, instead of constant soil-moisture conditions.
- Two changes have been made to the condensation scheme, as a consequence of the enhanced vertical resolution in the model. First, the stratiform condensation now requires 100% relative humidity in the grid box, compared to 80% earlier. Second, the maximum cloud cover allowed in a stratiform grid box has been changed from 95% to 80%.

Obvious weaknesses that remain are lack of vegetation and lack of snow cover. Also, the coarse horizontal resolution (R15 spectral truncation) prohibits an accurate positioning of the cyclone tracks.

In the control version of the LAGCM, the cloud treatment is of the greatly simplified type described in the previous section. Convection is treated by the moist-adiabatic adjustment (MAA) scheme of Manabe et al. (1965). Krishnamurti et al. (1980) have shown this scheme to yield unrealistic distributions of precipitation. In both the convective and stratiform treatment, all the condensed moisture is immediately released as precipitation, which falls to the ground in one time-step. In reality, of course, condensation produces clouds, which subsequently may or may not precipitate, depending on their water content, temperature, vertical motions, etc. Furthermore, a portion of the precipitation evaporates on the way down, moistening the air column. In addition, the presence of the ice phase may complicate the picture, e.g., by causing cooling at the level where precipitation changes from frozen to liquid form. All these modifications to the simplified original picture are taken into account in the alternative condensation treatment introduced in this paper.

The starting point for the new condensation treatment is the scheme of Sundqvist (1988), hereafter termed S88. Cloud water is introduced as a prognostic variable for both stratiform and convective clouds. The cloud water is subject to both 3-dimensional advection and vertical diffusion. As explained by S88, the treatment can be applied to any convection scheme. Because of the inherent weaknesses with the existing convection scheme, we have in this paper applied this cloud treatment to the more sophisticated Kuo (1974) and Arakawa-Schubert (A-S) (1974) schemes, as well as to the MAA scheme. In all three cases the stratiform condensation will be treated in the same way, given by S88. This means that stratiform condensation takes place as long as the relative humidity is above a "threshold value," in this case, 85%. For humidities between 85% and 100%, an assumption is made on the partitioning of moisture between the cloudy and cloudfree parts of the grid box.

A fairly detailed parameterization of cloud microphysics is applied to all clouds. Precipitation release is enhanced in those grid points where coalescence is expected to occur, as well as in mixed ice-water clouds (Bergeron-Findeisen effect). A novelty here compared with S88 is the inclusion of the latent heat of freezing and melting. When condensation occurs at temperatures below 273 K, a portion of the condensed water is assured to freeze. This is determined by a function, P_{fr}, which increases linearly from zero to unity as the temperature goes from 273 to 233 K. For temperatures below 233 K, P_{fr} is equal to 1, meaning that spontaneous freezing is expected to occur. Melting is assumed to occur as frozen or mixed precipitation falls through the 275 K isotherm on its way down. The degree of melting is computed based on the average temperature of the cloud from which the precipitation is falling.

An important advantage of treating cloud water content explicitly is that it can be used in the radiation calculations. Shortwave albedo and absorption as well as longwave emissivity are known to depend strongly on the liquid water path, which is obtained as the vertical integral of the cloud water mixing ratio.

No changes have been made to the model's cloud cover parameterization. The cloud cover is determined as a function of the condensation rate at the actual time-step. There is some empirical "hard-coding", e.g., a low stratiform cloud will always extend over three model-levels. Also, no clouds are allowed to form above a specific level, which varies with latitude.

Experimental Setup

So far, four 1-year-cycle simulations using seasonally varying boundary conditions have been conducted, as well as several shorter-term sensitivity experiments. The purpose of the simulations has been to study the performance of the prognostic cloud water scheme, as well as to seek ways to improve the overall treatment of condensation and clouds in the model. In all cases, results were compared with the basic version of the LAGCM, which is termed CONTROL.

The following items were specially investigated:

Sensitivity to cloud water treatment. This was done by comparing runs with prognostic cloud water and diagnostic cloud water (hence no transport of cloud water). These runs will be termed PROG and DIAG, respectively. Both were conducted using the SUNKUO condensation treatment.

Sensitivity to coupling between condensation and radiation. So far, only the effect of cloud water content on longwave radiation has been investigated. We compared experiments assuming that all clouds are black (BLACK), and conducted two experiments with cloud water dependent emissivities. In the first case, the vertical integral of cloud water through all model levels was taken as a measure of the optical depth (TOTAL); in the other case, the integral was taken only over one model layer at a time (LAYER). All three runs were performed using the SUNKUO condensation treatment.

Sensitivity to choice of convection scheme. Runs applying the MAA scheme, the Kuo scheme and the A-S scheme for convection were compared. In all cases, the runs were combined with the prognostic cloud water treatment of S88, as explained in the previous section. The runs are termed, respectively SUNMAA, SUNKUO, and SUNAS.

Results

Comparisons between PROG and DIAG reveal certain changes in precipitation patterns. These changes are not unexpected, since in DIAG all the cloud water produced in a given time step is dumped out as precipitation. The most important difference between the two runs is stronger condensational heating in PROG, especially in the tropics, which has less cirrus than in DIAG. Further investigations are required to fully explain these results, but they seem to suggest that the transport of cloud water may be an important feature in enhancing tropical convection.

When all clouds are treated as "black," cirrus clouds tend to emit unrealistically large amounts of heat, thereby cooling the upper troposphere. Here, BLACK turned out to have more cirrus than LAYER; furthermore the tropical convection was stronger, yielding larger cloud water contents (Table 1). The LAYER run, on the other hand, exhibited a very strong surface inversion at high latitudes, resulting in unrealistically low surface temperature, as well as persistent fog in these areas. This result appears to stem from an insufficient "thermal shielding effect" of the clouds. Precipitation in LAYER is grossly underestimated, possibly because of reduced cloud-top cooling. These results suggest that with 20 vertical levels, it is not

Table 1. Global averages for selected quantities as given by the different experiments and observations: Cloud cover, vertically integrated cloud water content, precipitation rate, planetary albedo.

Experiment	Cloud cover (%)	Cloud Water (kg/[m*m])	Precipitation (mm/day)	Albedo (%)
CONTROL	60.2		2.11	29.1
SUNMAA	75.2	0.164	2.73	34.8
SUNKUO	52.5	0.056	2.34	26.0
SUNAS	65.2	0.083	2.47	29.9
PROG/TOTAL	52.5	0.056	2.34	26.0
DIAG	63.9	0.000	2.28	27.3
BLACK	50.9	0.064	2.68	26.0
LAYER	59.5	0.053	1.38	26.2
Observed	62[a]	0.072[b]	2.67[c]	31.7[c]

(a) Hurrell and Campbell 1992.
(b) Njoku and Swanson 1983.
(c) Piexoto and Oort 1992.

appropriate to compute the liquid water path for the emissivity calculations "layer by layer."

The model has been run one full annual cycle with the different convection schemes. We then compared the results for January of the following year (1980). Some comparisons will be made to ECMWF analyses of the Januaries 1979-1986, as well as to the papers referenced in Table 1.

Temperature

Both SUNKUO and SUNAS significantly reduce the model's cold bias (a well-known feature of this model) in the mid- and upper tropical troposphere and the cold bias in the winter hemisphere (NH).

Zonal Winds

In all cases there are significant errors. The maximum westerlies in the northern hemisphere (winter) troposphere are shifted poleward compared with observations. The easterlies in the tropical tropopause are too strong. SUNKUO and SUNAS have a larger northern hemispheric (NH) jet maximum than CONTROL, quite close to the observed. The jet in the southern hemisphere (SH) is stronger than observed in both SUNKUO and SUNAS, weaker than observed in CONTROL.

Meridional Winds

In both CONTROL and SUNMAA, the southerly wind maximum associated with the Hadley cell is displaced 5 to

10° poleward (in NH) and is about twice as large as the observed maximum. SUNKUO and SUNAS, on the other hand, give results quite similar to observations.

Cloud Cover

In CONTROL, SUNMAA, and SUNAS, the bulk of the cloudiness is between 750 and 950 hPa at all latitudes. At mid-latitudes, SUNMAA has more cloudiness here than does CONTROL because the threshold value in the Sundqvist scheme is lower than in CONTROL. SUNKUO does not exhibit the "excessive" low-level cloudiness, but exhibits more high clouds in the tropics, as well as at high latitudes. The zonally and vertically averaged cloud cover is clearly excessive in the SUNMAA run (Table 1) and too low in SUNKUO. Consequently, the global planetary albedo is too large in SUNMAA, too low in SUNKUO.

Cloud Water Mixing Ratio

In SUNKUO, SUNMAA, and SUNAS (Figure 1), the vertically integrated cloud water content has maxima in the tropics and in connection with the cyclone tracks in both hemispheres. The zonally averaged values are mainly between 0.1 and 0.01 kg m^{-2} in SUNAS and SUNKUO, which is in good agreement with Njoku and Swanson (1983) (Table 1), whose SMMR-microwave-analysis only applies over ocean areas between 60°N and 60°S. In SUNMAA, on the other hand, the values are generally two to three times larger. This seems to indicate that the "excessive low cloudiness" mentioned above is associated with dense clouds. It has to be kept in mind that, because of the large uncertainty in measurements of cloud water content, the values given by Njoku and Swanson (1983) can only be regarded as an order of magnitude guidance.

Precipitation

As seen in Table 1, globally averaged precipitation is larger in the runs with prognostic cloud water than in CONTROL. It is also closer to the observed. In all cases, the precipitation is largest in the tropics, with a secondary maximum in the mid-latitude storm tracks.

Discussion

The MAA scheme does not produce sufficiently deep convection. Another point to note is that when this scheme was used, the number of convective grid columns over the globe was only half of what it is when the Kuo scheme is used. This reduction is probably caused by the abrupt release of the conditional instability in this scheme, rendering a more stable atmosphere than after a corresponding time-step with the Kuo scheme. This stable atmosphere can then undergo stratiform condensation in the next time-step. Hence, one reason for the excessive low cloudiness in the SUNMAA run may be that there is too much stratiform cloud formation. The microphysical parameterization is slightly different for stratiform and convective clouds (S88), respectively, such that the former have longer lifetimes than the latter. This contributes to larger cloud water contents when convective clouds are "replaced" by stratiform clouds.

The excessive cloud coverage in SUNMAA is tied to the model's cloud cover parameterization. The formulation is quite empirical and may not be valid once significant changes are made to other parts of the cloud treatment, as is done in this paper.

Summary and Conclusions

A sophisticated condensation and cloud package has been incorporated in the LAGCM. The most important features of this package, which is based on the work of Sundqvist (1978, 1988), are prognostic cloud water; sophisticated microphysics, including freezing and melting; and subgrid scale condensation parameterization for stratiform condensation. The package has been coupled to improve convection schemes that also carry cloud water. The cloud water field is subject to transport by both advection and diffusion. Furthermore, clouds are no longer assumed to be "black" emitters in the infrared. Rather, in agreement with observations, their emissivities are assumed to depend on the cloud water content.

The effects of these improvements have been studied by comparing results from sensitivity experiments with the GCM. The main findings so far are

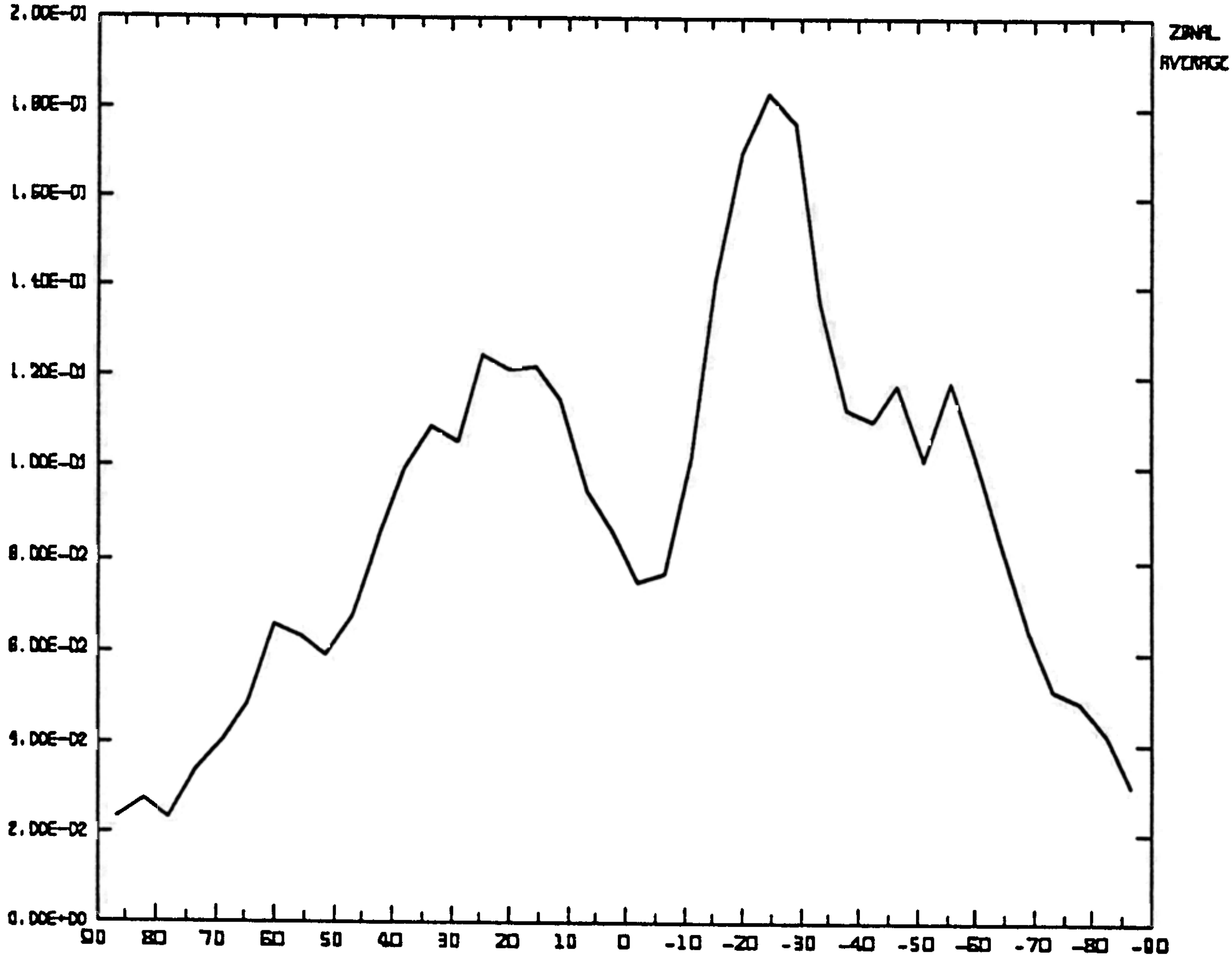

Figure 1. Vertically integrated zonally averaged cloud water content versus latitude in run SUNAS. Positive latitudes refer to NH, negative to SH. Units are kg m^{-2}.

The biggest advantage of using prognostic cloud water rather than diagnostic cloud water is that it can be transported by the winds. Hence, a more correct time evolution of the clouds is obtained.

The results are quite sensitive to the change in the cloud emissivity. When all clouds are black, there is an excessive cooling of the upper troposphere. When the emissivity is calculated layer by layer, excessive cooling at the ground is found because of an underestimated "shielding" from the clouds.

- All the runs with different convective schemes yield cloud water fields that have many realistic features. However, the integrated cloud water content in the SUNMAA run seems to be overestimated because of very persistent low clouds associated with this scheme.
- The A-S scheme and the Kuo scheme render more realistic latent heating distributions in the tropics, with more deep convection than the MAA scheme. This, together with reduced cloud cover, substantially reduces the model's cold bias and gives stronger zonal winds, which correspond better to observations.

Future Plans

The following items will be investigated further during the next few months:

- The shortwave albedo will be made dependent on the cloud water content, see e.g., Taylor and Ghan (1992). This will presumably enhance the model's sensitivity to the cloud water treatment.
- The model's cloud forcing and climate sensitivity will be investigated to find out how these important parameters change as the cloud treatment is modified.
- Improvements will be sought to the model's cloud cover parameterization, which is fairly "hard-coded" at the present time.
- Ten-year simulations will be carried out to obtain more confidence in the results. More extensive comparisons will be made to available observations.

Acknowledgments

The authors would like to thank David Langley for assistance regarding computer graphics and model runs. We have benefitted from numerous discussions with Prof. Hilding Sundqvist, Stockholm University, and Dr. Phillip Rasch, National Center for Atmospheric Research.

References

Arakawa, A., and W. H. Schubert. 1974. Interaction of a cumulus cloud ensemble with the large-scale environment, Part I. *J. Atmos. Sci.* **31**:674-701.

Hurrell, J. W., and G. G. Campbell. 1992. *Monthly mean global satellite data sets available in CCM history tape format.* NCAR Technical Note 371+STR, pp. 33-34.

International Panel on Climate Change (IPCC). 1990. *Climate change. The IPCC scientific assessment. Report prepared for Intergovernmental Panel on Climate Change by Working group I.* WMO/UNEP, Cambridge University Press.

Kao, C.-Y.J., G. A. Glatzmaier, R. C. Malone, and R. P. Turco. 1990. Global three-dimensional simulations of ozone depletion under postwar conditions. *J. Geophys. Res.* **95D**:22495-22512.

Kiehl, J. T., and V. Ramanathan. 1990. Comparison of cloud forcing derived from the Earth Radiation Budget Experiment with that simulated by the NCAR Community Climate Model. *J. Geophys. Res.* **95D**:11679-11698.

Krishnamurti, T. N., Y. Ramanathan, H.-L. Pan, R. J. Pasch, and J. Molinari. 1980. Cumulus parameterization and rainfall rates I. *Mon. Wea. Rev.* **108**:465-472.

Kuo, H. L. 1974. Further studies of the parameterization of the influence of cumulus convection on large-scale flow. *J. Atmos. Sci.* **31**:1232-1240.

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

Malone, R. C., L. H. Auer, G. A. Glatzmaier, M. C. Wood, and O. B. Toon. 1986. Nuclear winter: Three-dimensional simulations including interactive transport, scavenging, and solar heating of smoke. *J. Geophys. Res.* **91D**:1039-1053.

Manabe, S., J. Smagorinsky, and R. F. Strickler. 1965. Simulated climatology of a general circulation model with a hydrological cycle. *Mon. Wea. Rev.* **93**:769-797.

Njoku, E. G., and L. Swanson. 1983. Global measurements of sea surface temperature, wind speed and atmospheric water content from satellite microwave radiometry. *Mon. Wea. Rev.* **111**:1977-1987.

Peixoto, J. P., and A. H. Oort. 1992. *Physics of climate.* American Institute of Physics, New York.

Pitcher, E. J., R. C. Malone, V. Ramanathan, M. L. Blackmon, K. Puri, and W. Bourke. 1983. January and July simulations with a spectral general circulation model. *J. Atmos. Sci.* **40**:580-604.

Randall, D. A. 1989. Cloud parameterization for climate modelling: status and prospects. *Atmos. Res.* **23**:245-361.

Roeckner, E. 1988. Cloud-radiation feedbacks in a climate model. *Atmos. Res.* **21**:293-303.

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

Sundqvist, H. 1988. Physically-based modelling and simulation of climate and climatic change, ed. M. Schlesinger, pp. 433-461. Reidel Publishing, Dordrecht, Holland.

Taylor, K. E., and S. J. Ghan. 1992. An analysis of cloud liquid water feedback and global climate sensitivity in a general circulation model. *J. Clim.* **5**:907-919.