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IMPACT OF CLOUD MICROPHYSICS ON THE CSU GCM ATMOSPHERIC MOISTURE BUDGET

Laura D. Fowler* and David A. Randall
Department of Atmospheric Science
Colorado State University
Fort Collins, CO 80523. USA.

1. INTRODUCTION

Our ability to quantify the role of clouds-hydrologic cycle-climate interactions in studying Global Climate Change strongly relies upon our ability to reproduce the chief characteristics of today's climate. One current challenge in the development of atmospheric General Circulation Models (GCMs) deals with the parameterization of the sources and sinks of the atmospheric moisture budget components and their impact upon the time and space variability of cloudiness.

A cloud microphysics package which encompasses five prognostic variables for the mass of water vapor, cloud water, cloud ice, rain, and snow has been newly implemented in the Colorado State University General Circulation Model (CSU GCM). Convection interacts with the large-scale environment through the detrainment of cloud liquid and ice at the top of convective cumulus towers. Our objectives are to (1) yield an improved global distribution of the predicted water vapor, cloud liquid and ice amounts, and (2) link the fractional cloud cover and optical properties of the model-generated clouds to the predicted liquid/ice water amounts.

In this article, we present the very first global maps of the instantaneous distributions of the cloud liquid/ice water contents produced by the CSU GCM.

2. THE CLOUD MODEL

The model structure is completely described in Smith and Randall (1992). It is largely based upon the bulk cloud microphysics equations used in Lin *et al.* (1983), and Rutledge and Hobbs (1983). Five prognostic variables for the mass of water vapor, cloud water, cloud ice, rain, and snow are taken into account. Cloud liquid and ice water amounts are predicted to form

through large-scale condensation and sublimation processes plus detrainment at the top of convective cumulus towers. It is assumed that the terminal fall velocity of cloud liquid/ice particles may be neglected compared with the velocity of air, rain, and snow. Rain and snow are assumed to have non-negligible fall velocities. Interactions between water vapor, cloud water, cloud ice, rain, and snow are best described in Fig. 1:

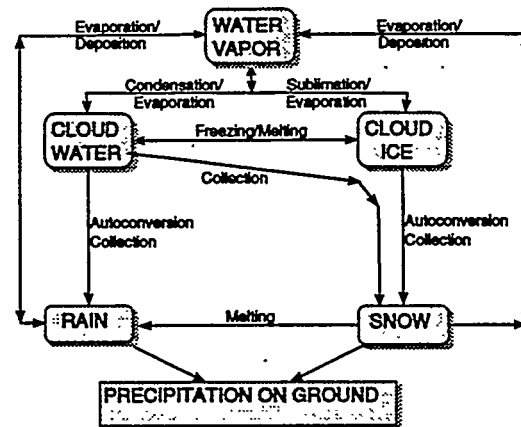


Figure 1: Schematic diagram of cloud microphysics processes.

Water vapor as a source: Water vapor is a source of both cloud liquid and cloud ice water through instantaneous processes. Cloud liquid water is predicted to form by condensation of vapor when the temperature (T) is equal or greater than 0°C and the air is supersaturated with respect to water. Similarly, cloud ice is predicted to form by sublimation of vapor when $T < 0^{\circ}\text{C}$ and the air is supersaturated with respect to ice.

Cloud liquid as a source: Cloud liquid is a source of vapor by evaporation of cloud droplets when the air is sub-saturated with respect to water. It may be a source of cloud ice by instantaneous

* Maiden name: Dr. Laura D. Smith

freezing if evaporation cooling yields T to become less than 0°C , and some cloud water is still available after saturation with respect to ice is reached. Cloud water is a source of rain through two different mechanisms: (1) autoconversion of cloud droplets to form rain drops; and (2) collection of cloud droplets by rain drops falling through the free atmosphere. Finally, cloud water may also be a source of snow by riming ($T < 0^{\circ}\text{C}$) or rain ($T \geq 0^{\circ}\text{C}$) by collection of snow falling through warm layers.

Cloud ice as a source: As for cloud liquid water, cloud ice water is a source of water vapor by evaporation of cloud ice crystals when when the air is sub-saturated with respect to ice. Otherwise, cloud ice is a source of snow through two different mechanisms: (1) conversion of ice crystals to form snow; and (2) collection of ice crystals by snow falling through the free atmosphere. Instantaneous melting of cloud ice to form cloud water occurs if T is equal or greater than 0°C .

Rain as a source: Rain may only be a source of water vapor by evaporation of rain drops while falling through subsaturated layers.

Snow as a source: As for rain, snow may be a source of water vapor by evaporation while falling through sub-saturated layers for which $T < 0^{\circ}\text{C}$. Also, snow may be a source of rain by melting if it falls through layers for which $T \geq 0^{\circ}$.

3. RESULTS

The 17-level CSU GCM is used to test the various cloud microphysics processes and their interactions with the cumulus convection scheme. Smith and Randall (1992) describe the temporal behavior of the rates of production/removal of the cloud liquid/ice water, rain, and snow contents using the one-dimensional version of the CSU GCM. The GCM employs a "modified- σ " vertical coordinate system so that the planetary boundary layer depth is the thickness of the lowest model layer. The core of the model physics, in terms of the long and short wave parameterizations, and prediction scheme of the cloud fraction and cloud optical properties, is that of the UCLA/GLA GCM discussed in Harshvardhan *et al.* (1989) and Randall *et al.* (1989). Two major modifications to the routinely used version of the model code are: (1) the inclusion of a new cumulus convection parameterization based upon the theory of Arakawa and Schubert (1974), but allowing for a more consistent coupling between cumulus convection and associated stratiform anvils through the detrainment of cloud liquid and ice water (Randall and Pan, 1992); and (2) the re-

placement of the large-scale condensation scheme with the cloud microphysics package described above. It is important to note that, in the present model version, there exists no coupling between the cloud liquid (ice) water computed by the cloud model and the prediction scheme of the cloud fraction and optical properties.

The model is run for three hours starting from the initial conditions of January 1st obtained with an earlier run. The model physics is computed every hour while the model dynamics is run using a time-step of 6 minutes. At present, the cloud microphysical package which is embedded in the model dynamic package is called every minute.

Figures 2 and 3 show global maps of the instantaneous distribution of the vertically-integrated cloud liquid and ice water contents after two hours of model simulation. Shaded areas correspond to values of the cloud liquid and ice water paths greater than 0.5 and 1.0 kg m^{-2} , respectively. The cloud ice content of the atmosphere is significantly larger than the cloud liquid content. The cloud ice content is maximum over the Intertropical Convergence Zone over the Pacific Ocean, the Southern Hemisphere Oceans, and the Northern Hemisphere cyclogenetic areas over the Pacific and Atlantic Oceans. The cloud liquid water content is the largest over some areas of the Southern Pacific Ocean, and along the western coast of South America and eastern coast of China. Although these results are very preliminary in terms of the actual magnitude of the cloud liquid and ice water amounts, they indicate that the model reproduces successfully the geographical distribution of both moisture variables. Also the actual partition between the cloud liquid and ice water amounts needs to be further investigated.

4. SUMMARY

In this article, we present the first maps of the global distribution of the cloud liquid and ice water contents of the atmosphere. It is shown that the cloud microphysics package produces realistic distributions of both moisture variables. We are presently adapting the present model so that long-term simulations with the CSU GCM may be made. In the near future, we plan to couple the cloud liquid and ice water contents prognosed by the cloud microphysics package with the cloud fraction and cloud optical properties.

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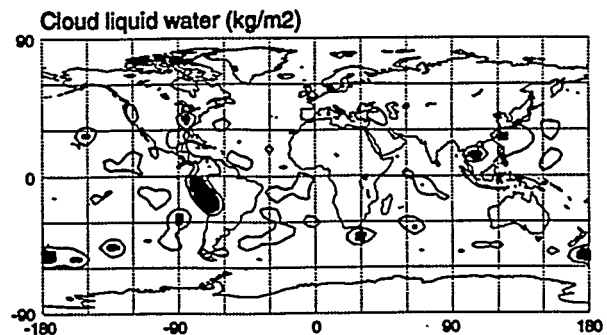


Figure 2: Map of the vertically-integrated cloud liquid water content, contour interval every 0.25 kg m^{-2} . Areas above 0.5 kg m^{-2} are shaded.

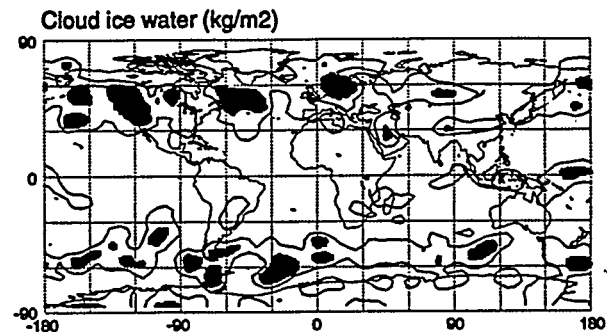


Figure 3: Map of the vertically-integrated cloud ice water content, contour interval every 0.5 kg m^{-2} . Areas above 1.0 kg m^{-2} are shaded.

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Department of
Atmospheric Science
Fort Collins, Colorado 80523
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