A New Parameterization Framework for Boundary-Layer Cumuli

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Introduction

Clouds have an important influence on the earth's climate and can contribute to either a net warming or a net cooling of the atmosphere through their effects on the short and longwave energy budgets. On one hand, clouds tend to cool the atmosphere by reflecting sunlight away from the earth, thus reducing the amount of solar radiation that reaches the earth's surface. On the other hand, clouds emit less longwave radiation to space then the earth's surface, leading to a warming of the atmosphere. This longwave effect is greatest for cirrus at very high altitudes. Fair-weather cumuli, the focus of this work, tend to cool the atmosphere. The cumuli increase the earth's albedo during the day, but have only small effects on the longwave energy budget because they are relatively close to the ground and their temperature is approximately the same as the surface temperature. Over land the fair-weather cumuli disappear near sunset so the effect on the longwave energy budget is reduced further. Other effects of the fair-weather cumuli include venting of moisture from the boundary layer, which decreases the likelihood that deep convective clouds will form.

The Parameterization Framework

The Cumulus Potential (CuP) scheme presented by Berg and Stull (2005) consists of two independent modules: one representing boundary-layer turbulence, the other representing clouds (Figure 1). In the boundary-layer module, the CuP scheme examines each parcel in the boundary layer over a heterogeneous surface, and determines if that parcel will rise to its lifting condensation level (z_{LCL}). Those parcels that have a virtual potential temperature ($\theta_{v,p}$) larger than the environmental θ_v will rise, and the warmest parcels should rise the highest. However, if a warm parcel is also dry, it still may not reach its z_{LCL}, so it will remain a clear-air updraft. A less buoyant parcel, but one that is still more buoyant than the environment, might not rise as high, but might be more moist so that it reaches its z_{LCL}. The water vapor in the parcel will condense and the parcel will continue to rise as a cloudy parcel. Once a cloud forms, a cloud model is used to represent both the exchange of mass between the cloud and the environment and to determine the cloud thermodynamic properties. The CuP scheme predicts a range of cloud-top heights by applying the cloud-model to each parcel that becomes a cloud. The parcels will be treated as a separate "cloud" by the parameterization, although they may, in fact be part of the same cloud. Distributions of $\theta_{v,p}$ and water vapor mixing ratio (r) in the boundary layer are parameterized as mixing diagrams as described by Berg and Stull (2004).

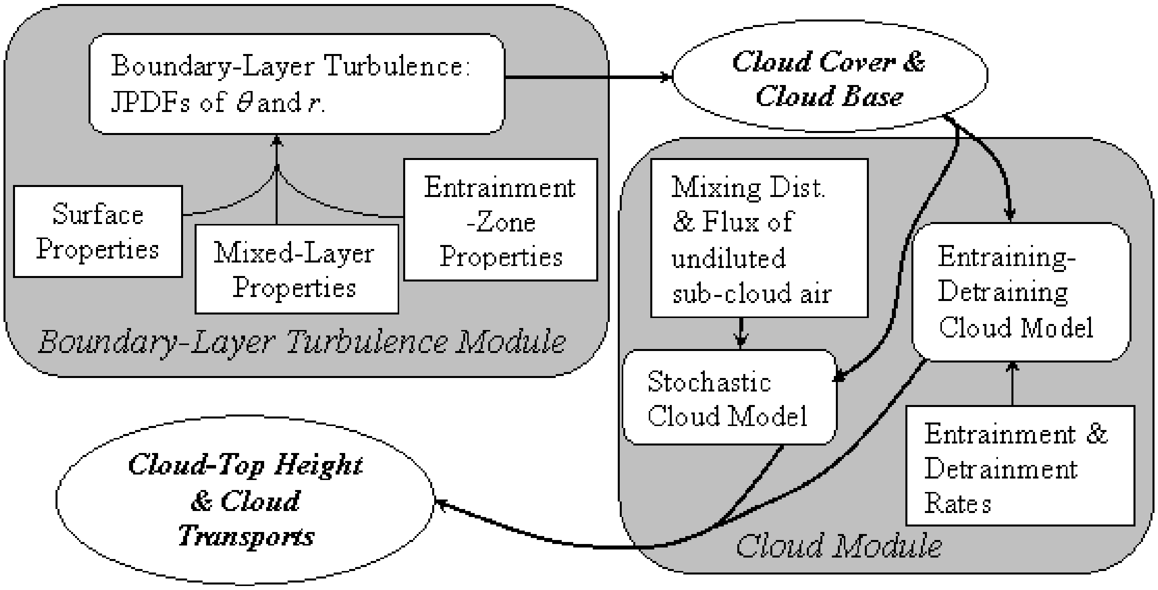

Figure 1. CuP scheme flow diagram. Shading represents the two main modules; one representing boundary-layer turbulence, and the other representing processes in the cloud. Squares indicate input into the two modules. Ovals indicate output from the scheme. Details can be found in the following sections.

Preliminary Evaluation of the Framework

Berg and Stull (2005) made estimates of cloud cover, cloud-base height, and cloud-top height using the CuP scheme and three other schemes: the relative-humidity-based scheme used by Roeckner et al. (1996), the classical statistical scheme suggested by Sommeria and Deardorff (1977), and the boundary-layer scheme suggested by Albrecht (1981) for trade-cumuli. Data for this comparison was obtained from the Boundary-Layer Experiment 1996 (BLX96). BLX96 was conducted between 15 July and 13 August 1996 over regions within the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site (Stokes and Schwartz 1994). The main instrument platform used during BLX96 was the University of Wyoming King Air aircraft. Details of BLX96 were reported by Stull et al. (1997).

The CuP predicted cloud-top heights were superior to predictions made using the three alternate parameterizations during BLX96 (Figure 2A). The level of agreement found for cloud-base height is gratifying; Stull and Eloranta (1985) found that the value of z_{LCL} calculated from surface-layer air accurately predicted the cloud-base height of boundary-layer cumuli as observed using lidar. The CuP predicted mode cloud-top heights were also superior to the predictions made using the three alternate parameterizations (Figure 2B). In most cases, the three alternative parameterizations over predicted the cloud-top height. In addition, the predictions by the schemes of Sommeria and Deardorff and Albrecht seemed to frequently predict a cloud top height of approximately 2.2 km.

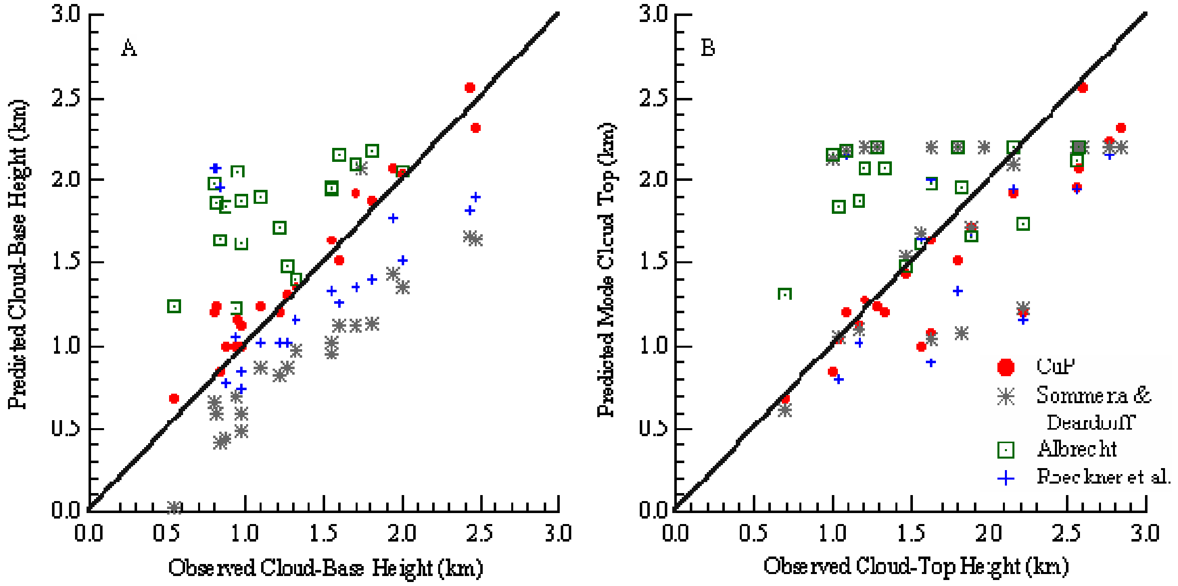

Figure 2A and 2B. A) CuP (circles), Sommeria and Deardorff (asterisks), Albrecht (squares), and Roeckner et al. predicted cloud-base height versus observed cloud-base height. B) CuP (circles), Sommeria and Deardorff (crosses), Albrecht (squares), and Roeckner et al. predicted mode cloud-top height versus observed cloud-top height. The solid line in each figure is the 1:1 line.

The CuP scheme and the three alternate methods can be used to estimate the total cloud cover. Overall, the agreement between the CuP-predicted cloud cover and observations is better than the agreement between the alternate methods and observations, but there is much scatter (Figure 3). The mean absolute error is used to evaluate the performance of each scheme, and is defined as

$$err = \frac{1}{N}\sum\left|\alpha_{cloud,scheme} - \alpha_{cloud,obs}\right| \quad (1)$$

where $\alpha_{cloud,scheme}$ is the cloud cover predicted by the scheme, $\alpha_{cloud,obs}$ is the observed cloud cover, and N is the total number of observations. The CuP scheme had the smallest absolute error by a small margin, while the schemes of Roeckner et al. (1996) and Sommeria and Deardorff (1977) had the largest error by an equally small margin (Table 1). The scheme of Sommeria and Deardorff under-predicts the cloud cover for all but one point, while the scheme of Albrecht under-predicts the cloud cover in all cases. The mean absolute errors found using Eq. (1) (e.g., 0.07 for the CuP scheme) are similar in magnitude to the measurement errors of 0.05 found by Berg and Stull (2002). The scatter in all of the methods indicates the difficulty in predicting small amounts of cloud cover. The CuP scheme, the scheme of Sommeria and Deardorff, and the scheme of Albrecht each had one particularly poor cloud-cover forecast that had a large influence on the statistics shown in Table 1.

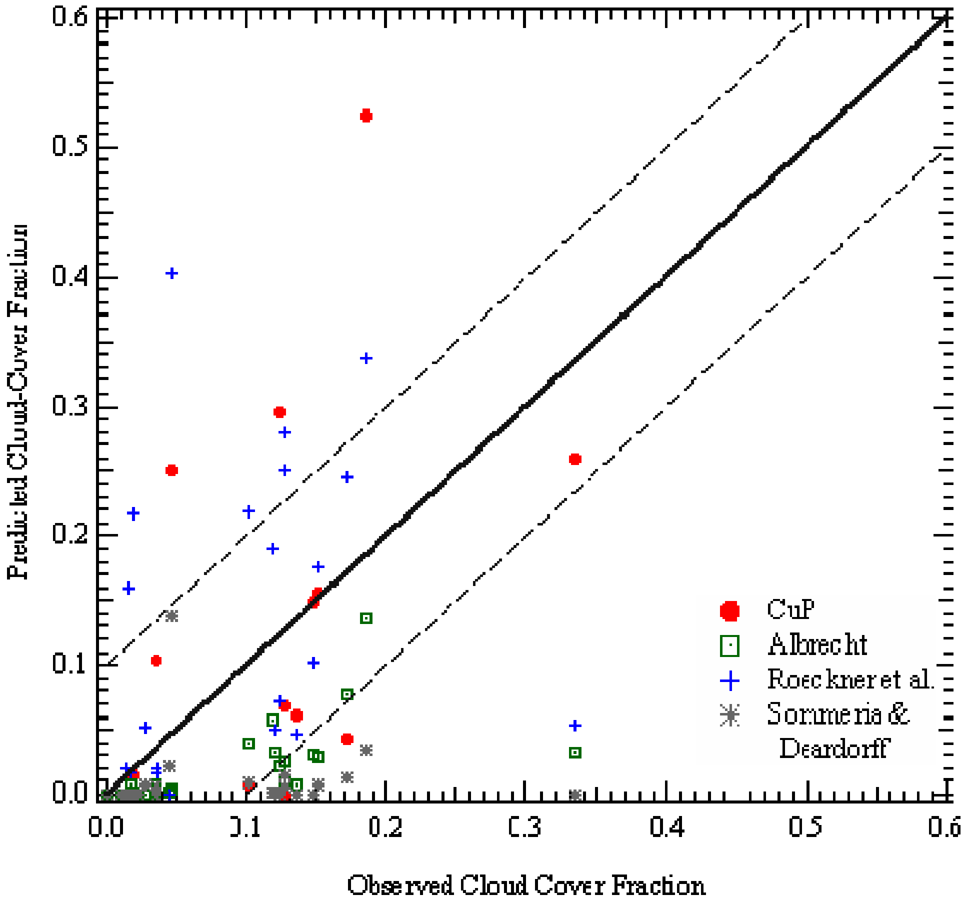

Figure 3. Predicted cloud cover versus observed cloud cover for all BLX96 case study days using the CuP scheme (dots), and the methods of Albrecht (squares), Roeckner et al., (crosses), and Sommeria and Deardorff (asterisks) versus observed cloud-cover fraction. The heavy solid line is the 1:1 line; the dashed lines are ±0.1 from the 1:1 line.

Table 1. Mean absolute error [calculated using Eq. (1)] and mean bias in predicted cloud cover for each method.

Test Statistic	CuP	Albrecht (1981)	Roeckner et al. (1996)	Sommeria and Deardorff (1977)
Mean Absolute Error	0.07	0.08	0.09	0.09
Mean Bias	-0.01	-0.07	0.04	-0.08

In addition to the calculations of absolute error, the bias of each scheme was computed. The methods of Albrecht (1981) and Sommeria and Deardorff (1977) have a bias of approximately -0.07 (Table 1). The method of Roeckner et al. (1996) overestimates the cloud cover, while the CuP scheme shows little bias. Thus, of the four methods used, the CuP scheme has the smallest mean absolute error as well as the smallest bias.

Research Design and Methods

The proposed research seeks to improve the representation of fair-weather cumuli in global climate models (GCMs). This research will address two specific areas of interest described in the ARM Program: developing and testing new cloud submodels for GCMs, and incorporating new cloud submodels into GCMs. A comprehensive strategy, following the suggestions of Jakob (2003), has been developed to implement, test, and evaluate the new version of the CuP scheme. Three different models will be used to conduct this research: a stand-alone model consisting of the CuP parameterization, observed θ_v and r profiles, and surface observations; a regional scale model; and a GCM. The stand-alone model and the regional scale model will be run for specific case studies and compared to a high temporal resolution dataset. In addition to the case studies, the regional scale model will be operated in a quasi-operational mode through the summer months to provide daily forecasts that will be compared to a low temporal resolution dataset. The GCM will be used to make global forecasts that will be compared to a low temporal resolution dataset over a period of years.

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References

Albrecht, BA. 1981. "Parameterization of trade-cumulus cloud amounts." *Journal of Atmospheric Sciences* **38**, 97-105.

Berg, LK, and RB Stull. 2002. "Accuracy of point and line measures of boundary-layer cloud amount." *Journal of Applied Meteor*ology **41**, 640-650.

Berg, LK, and RB Stull. 2004. "Parameterization of joint frequency distributions of potential temperature and water vapor mixing ratio in the daytime convective boundary layer." *Journal of Atmospheric Sciences* **61**, 813-828.

Berg, LK, and RB Stull. In press. "A simple parameterization coupling the convective daytime boundary layer and fair-weather cumuli." *Journal of Atmospheric Sciences.*

Jakob, C. 2003. "An improved strategy for the evaluation of cloud parameterizations in GCMs." *Bulletin of the American Meteorological Society* **84**, 1387-1401.

Roeckner, E, L Bengtsson, M Christoph, M Claussen, L Dumenil, M Esch, M Giorgetta, U Schlese, and U Schulzweida. 1996. "The atmospheric general circulation model echam-4: Model description and simulation of present-day climate." Max-Planck-Institut fur Meteorologie. Technical Report 218.

Sommeria, G, and JW Deardorff. 1977. "Subgrid-scale condensation in models of non-precipitating clouds." *Journal Atmospheric Sciences* **34**, 344-355.

Stokes, GM, and SE Schwartz. 1994. “The Atmospheric Radiation Measurement (ARM) Program: Programmatic background and design of the cloud and radiation test bed.” *Bulletin of the American Meteorological Society* **75**, 1201-1222.

Stull, RB, and E Eloranta. 1985. “A case study of the accuracy of routine, fair-weather cloud-base reports.” *National Weather Digest* **10**, 19-24.

Stull, R, E Santoso, L Berg, and J Hacker. 1997. “Boundary Layer Experiment 1996 (BLX96).” *Bulletin of the American Meteorological Society* **78**, 1149-1158.