An Evaluation of the Xu-Randall Cloud Fraction Parameterization Using ASTEX Data

S. M. Lazarus and S. K. Krueger
University of Utah
Salt Lake City, Utah

A. S. Frisch
National Oceanic and Atmospheric Administration
Environmental Technology Laboratory
Boulder, Colorado

Introduction

A dearth of detailed cloud observations has encouraged large-scale modelers to utilize methods that employ cloud resolving models (CRMs) to evaluate the utility of cloud parameterizations. However, cloud radars are now making detailed observations of clouds. In this paper, we use such observations to evaluate a parameterization based on CRM results. Herein we examine a particular cloud parameterization developed by Xu and Randall (1996). Unlike cloud parameterizations involving probability distribution functions (PDFs), which require knowledge of the higher order moments of the subgrid variables, the Xu and Randall (1996) technique depends only upon the large-scale relative humidity (RH), the saturation water vapor mixing ratio, and cloud and ice water mixing ratios. "Large-scale" refers to space and time scales resolved by a large-scale model, such as a global numerical weather prediction (NWP) model or a global climate model. A large-scale quantity typically represents a spatial average over a 250 km by 250 km area and, under quiescent conditions, a time variation on the order of 3 hours. Herein, we apply the Xu and Randall (1996) stratus cloud parameterization to Atlantic Stratocumulus Transition Experiment (ASTEX) observations of the RH field obtained from sounding data and liquid water content (LWC) profiles derived from a combination of the liquid water path (LWP) measured by a Microwave Radiometer (MWR), and reflectivity Z from a millimeter wavelength cloud radar. The parameterized cloud fraction is then compared with observed cloud fraction profiles determined from cloud radar measurements.

Data

Observations

Radiosonde data were collected approximately every 3 h during the ASTEX on the island of Porto Santo. Although the RH is measured directly by the sonde's hygristors, the data files obtained from the Level II archive (Schubert et al. 1992) report dew point temperature. RH, an input to Xu and Randall (1996), is obtained from the dew point and temperature data.

A vertically pointing 34.6-GHz Doppler radar, collocated with the sonde launch site, measured reflectivity and the radial velocities of detectable particles at 1-min. intervals and in range gate bins of 37.5 m. In addition, LWP data were obtained from a MWR with continuous sampling at 1 min intervals.

Retrieval

The LWC q_1 profiles were derived from measurements of reflectivity and LWP assuming a lognormal drop distribution (Frisch et al. 1995). Equations for q_1 and Z, which are proportional to the third and sixth moments of the drop size, respectively, can be combined to yield

$$q_l \approx 0.39\rho_w Z^{1/2} N^{1/2} \tag{1}$$

where ρ_w is the density of water, and N is the total number of drops per unit volume. To obtain Eq. (1), the logarithmic spread σ_x was set to 0.25 and assumed constant with height. Eq. (1) can be integrated with respect to height to obtain a relationship for the LWP. N (also assumed to be constant with height) can then be determined by constraining the LWP to be that measured by the MWR. Once N is obtained, Eq. (1) is then used to calculate the LWC profiles.

Parameterized Cloud Fraction

The Xu and Randall (1996) cloud fraction parameterization depends upon the large-scale liquid water mixing ratio ($\overline{q}_1$), relative humidity $\overline{RH}$, and saturation water vapor mixing ratio q_{vs}

$$\overline{\sigma} = \begin{cases} \overline{RH}^p \left[1 - \exp\left(\dfrac{-\alpha_0 q_1}{\left[\left(1 - \overline{RH} \right) q_{vs} \right]^{\gamma}} \right) \right], & \text{if } \overline{RH} < 1 \\ 1, & \text{if } \overline{RH} \geq 1 \end{cases} \tag{2}$$

where the parameters γ, α_0, and p can be empirically determined from the data (Xu and Randall 1996). Here they are taken to be the same as Xu and Randall (1996); namely, 0.49, 100, and 0.25, respectively. We take the simplest possible approach and assume that RH measured by each radiosonde ascent accurately represents $\overline{RH}$ at that time.

We use four different methods to calculate the Xu and Randall (1996) cloud fraction $\overline{\sigma}$, namely:

- Method A: We use the retrieved q_l profiles at their nominal time resolution (1 min.) as input to Xu and Randall (1996). The 1-min. cloud fraction estimates are then averaged over a 40-min. window (± 20 min. of sounding launch time).

- Method B: We use a 40-min. window (± 20 min. of sounding launch time) to obtain $\overline{q}_1$, which is then input into Xu and Randall (1996).

- Method C: We calculate $\overline{RH}$ and $\overline{q}_1$ determined from the entire ASTEX period, which are then input to Xu and Randall (1996).

- Method D: Same as Method B, however the sonde RH profiles are adjusted so that 5% is added if the observed RH ≤ 0.95 or set equal to 1.0 otherwise.

Observed Cloud Fraction

We assume that the observed $\overline{\sigma}$ can be approximated by the cloud occurrence frequency (COF) in each radar range gate during the same 40-min. period used to retrieve $\overline{q}_1$. Although this extends beyond the period in which a sonde resides in the boundary layer, tests where the averaging period were doubled and halved indicated little sensitivity.

Because the COF depends on how the local cloud fraction (i.e., the instantaneous value in each range gate) σ is determined or defined, we use two methods to determine σ:

- Method I: If a range gate contains a “detectable echo” (i.e., if dBz > -50), then $\sigma = 1$; otherwise, $\sigma = 0$. This method is applied to each individual radar measurement (20 per min.).

- Method II: If $q_l/q_{vs} > 0.01$, then $\sigma = 1$; otherwise, $\sigma = q_l/q_{vs}$. This method is applied to each radar retrieval (1 per min.).

Upwards of 800 reflectivity measurements (the radar resolution is 3 s) may be used to calculate the observed cloud fraction profiles.

Because there are periods where the observed cloud fraction is available but the parameterized is not (for the most part these periods are confined to drizzle episodes where the retrieval assumptions do not hold and thus LWC profiles are not calculated), observed cloud fraction estimates are limited to the same periods that LWC retrievals are available.

Results

Figure 1 illustrates the mean cloud fraction profiles (i.e., averaged over the entire ASTEX period) for the four parameterized methods and two observed methods. Note the differences in the observed cloud fraction between Methods I and II (the dark blue and green curves, respectively). Using Method I will likely introduce biases in the estimated observed cloud fraction—depending on the radar sensitivity and the reflectivity threshold used to delineate a cloud. Xu and Randall (1996) used Method II to determine the observed σ in each grid volume of a cloud system model in order to develop their cloud fraction parameterization. When testing the Xu and Randall (1996) parameterization, the same definition of cloud (i.e., Method II) should be used.

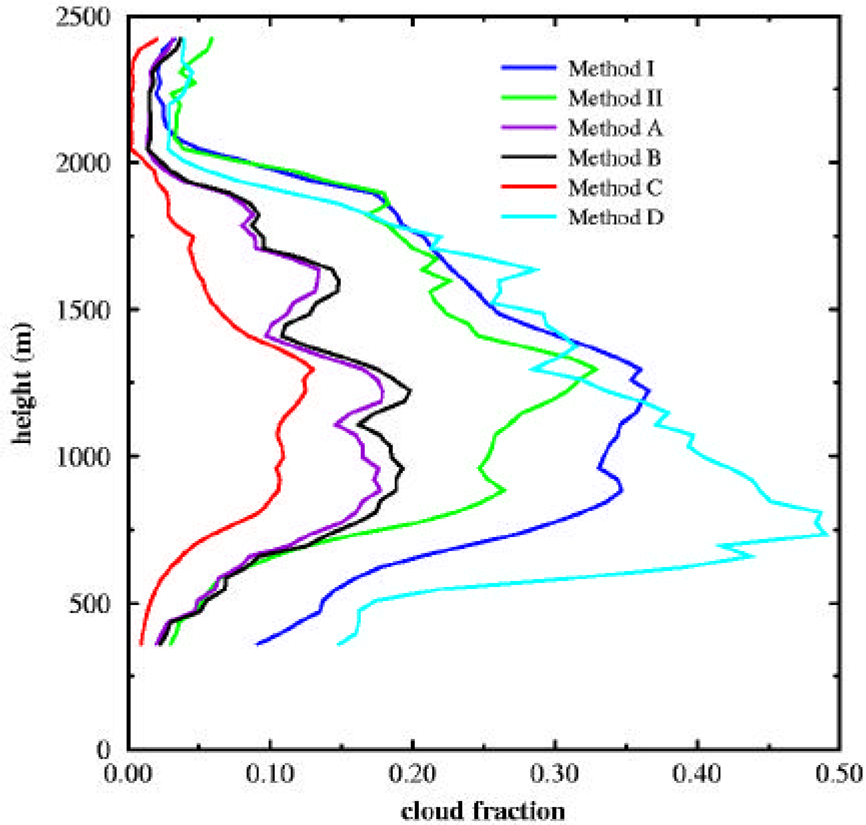

Figure 1. Mean ASTEX cloud fraction from (a) Xu and Randall (1996) 40-min. average using 1-min. LWC profiles (black curve), (b) Xu and Randall (1996) using average LWC profiles (violet curve), (c) Xu and Randall (1996) mean ASTEX sounding (red curve), (d) observed Method I (dark blue curve), (e) observed Method II (green curve), and (f) Xu and Randall (1996) using adjusted RH profiles where if RH ≥ 0.95, the RH is set to 1, otherwise 5% is added to the RH profiles (cyan curve).

Differences between Methods A and B are slight (on the order of 2%), while Method C produces the lowest estimate of the ASTEX cloud fraction. To better understand these differences, we plot a series of analytic Xu and Randall (1996) cloud fraction profiles as a function of relative humidity (for varying q_l) and as a function of q_l (for varying RH; Figures 2 and 3). For RH values close to that of the mean sounding (Figure 4), the Xu and Randall (1996) cloud fraction parameterization is approximately linear with respect to q_l, thus results where the *instantaneous* cloud fraction (i.e., for each individual 1-min. LWC profile, Method A) is averaged are not likely to vary significantly from cloud fraction computed from average LWC profiles (Method B). For typical values of q_l on the order of 0.05 g kg^{-1} (Figure 5), the topology of the Xu and Randall (1996) surface is concave (i.e., biased towards low cloud fraction). Thus, the parameterized cloud fraction decreases as the spatial averaging scale increases.

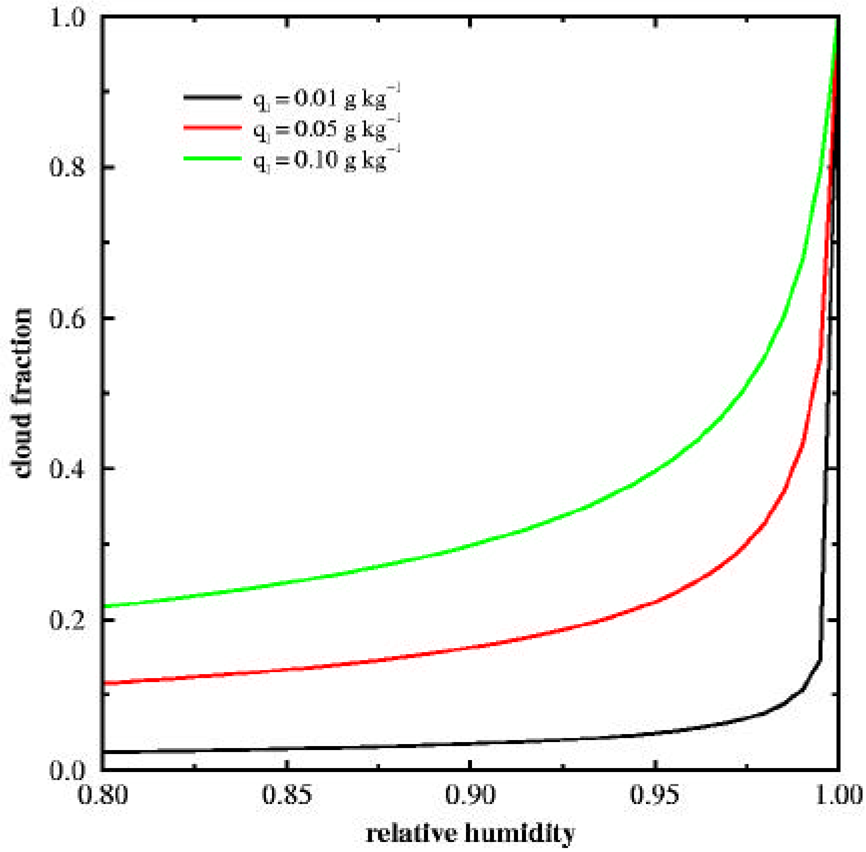

Figure 2. Analytic Xu and Randall (1996) cloud fraction profiles as a function of the relative humidity for (a) $q_1 = 0.01$ g kg^{-1} (black curve), (b) $q_1 = 0.05$ g kg^{-1} (red curve), and (c) $q_1 = 0.10$ g kg^{-1} (green curve).

The steep slope for the Xu and Randall (1996) cloud fraction for large RH suggests that estimates of $\overline{\sigma}$ will be sensitive to small adjustments in the radiosonde's relative humidity. On some flights, visual observations (within cloud) noted that the sonde did not show RH above 95%. This low bias in the sonde RH appears to be one factor contributing to our results, which show that estimates of $\overline{\sigma}$ are significantly smaller, on average, than the average observed cloud fraction determined via Method I or Method II. Adjusting the sonde RH upwards by as much as 5% (Method D) illustrates the sensitivity as the Xu and Randall (1996) cloud fraction is nearly twice that of Methods A and B.

Due to inherent limitations/problems associated with observations, we have begun to apply Xu and Randall (1996) to a CRM simulated data set of a stratus-to-cumulus transition (Krueger et al. 1995). To emulate the observations, we sample (at 2.5-min. intervals) profiles of cloud water, RH, and saturation mixing ratio in a column above a single model grid point. We produce four estimates of CRM cloud fraction including:

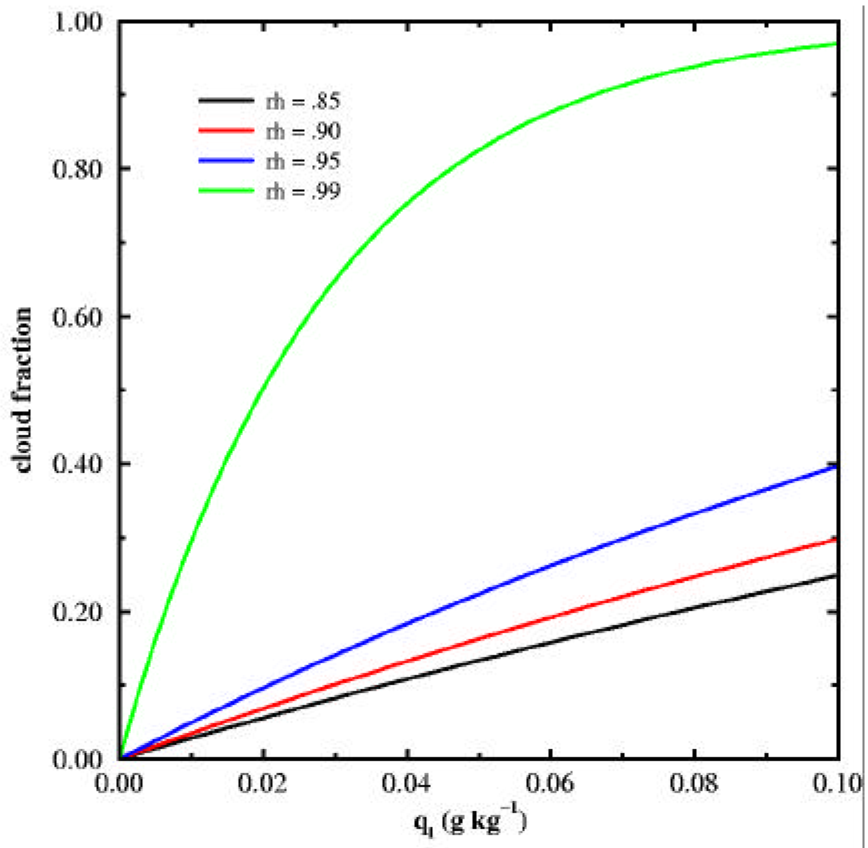

Figure 3. Analytic Xu and Randall (1996) cloud fraction profiles as a function of the liquid water content for (a) $\overline{RH}$ = 0.85 (black curve), (b) $\overline{RH}$ = 0.90 (red curve), (c) $\overline{RH}$ = 0.95 (blue curve), and (d) $\overline{RH}$ = 0.999 (green curve).

- Method A_{CRM}: This method is similar to Method A above for the observations. Using the model's q_l and RH profiles at a given point as inputs to Xu and Randall (1996), we compute the cloud fraction at 2.5-min. intervals and then average over the 3-day simulation.

- Method B_{CRM}: 3-day average CRM subgrid scale cloud fraction at a single model point.

- Method C_{CRM}: This method is similar to Method C above. We calculate $\overline{RH}$ and $\overline{q}_1$ for the entire simulation and use these as inputs to Xu and Randall (1996).

- Method II_{CRM}: As in Method II above, if $q_l/q_{vs} > 0.01$, then $\sigma = 1$; otherwise, $\sigma = q_l/q_{vs}$.

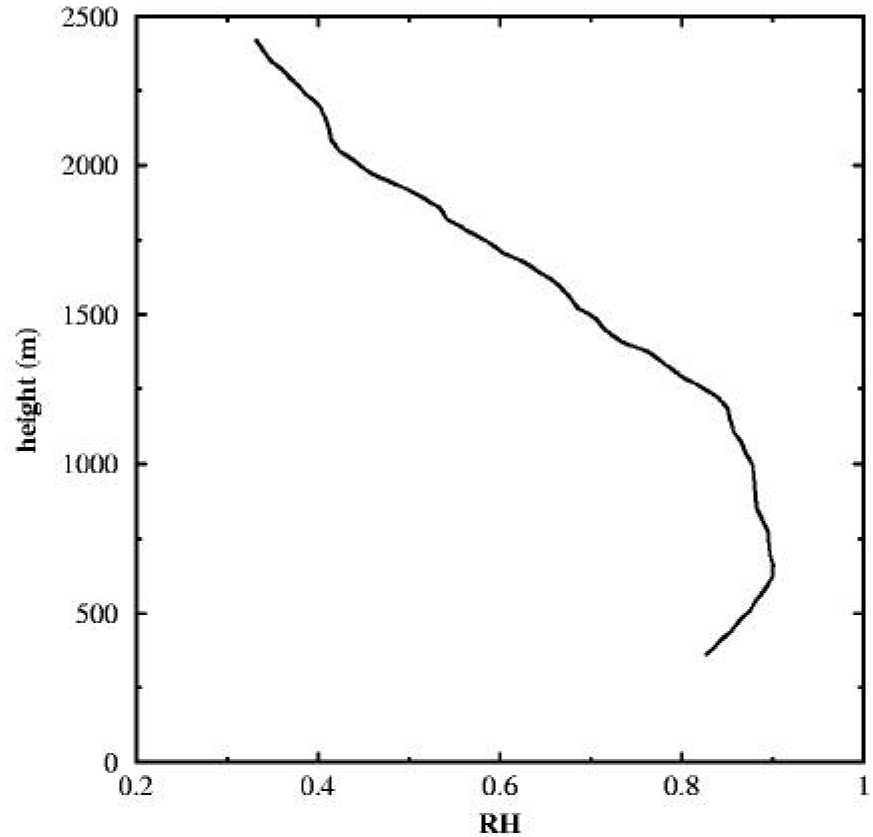

Figure 4. Mean ASTEX observed RH profile versus height.

Estimates of parameterized $\overline{\sigma}$ using a mean sounding taken over the 3-day simulation are not all that different than a 3-day average of the instantaneous cloud fraction (compare blue and green curves in Figure 6). Also, note that these two estimates of $\overline{\sigma}$ agree well with both the CRM's subgrid estimate (Method B_{CRM}) and Method II_{CRM} described above.

Conclusions

We present a study whereby we compare observed and parameterized cloud fractions. Data obtained from the ASTEX are used as input to the parameterization as well as to determine the observed cloud fraction. Results indicate that, using the free parameters as determined by Xu and Randall (1996) from CRM simulations of the Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE), the parameterization tends to under-predict cloud fraction. Sensitivities in both the observed and parameterized cloud fractions were observed. We examine the horizontal scale dependency of the parameterization by using the average of all the soundings as input into the cloud fraction parameterization. For the values of $\overline{q}_1$ and $\overline{RH}$ typical of the ASTEX, our results indicate that the relationship between $\overline{q}_1$ and $\overline{\sigma}$ is approximately linear while that between the RH and $\overline{\sigma}$ is concave—supporting what is observed, namely reduced parameterized cloud fractions as the temporal averaging

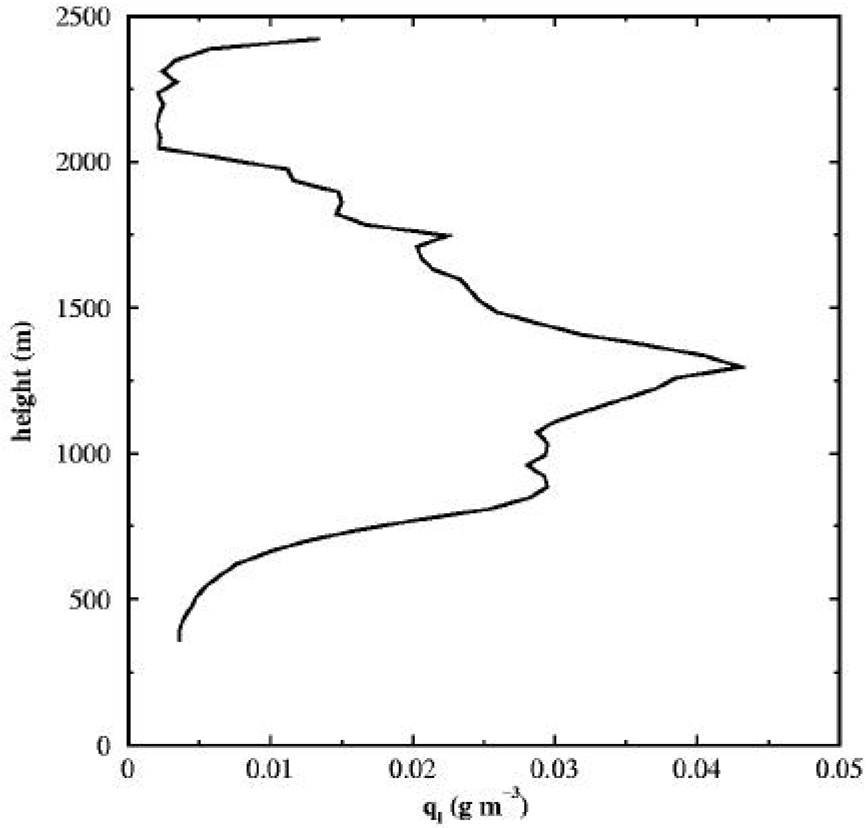

Figure 5. Mean ASTEX retrieved LWC profile versus height.

increases. Weaker signals were observed with respect to q_l as noted by small differences between average instantaneous cloud fraction estimates and $\overline{\sigma}$ estimates from average LWC profiles. Low bias in the sonde RH has been shown to be a potential contributor to the small parameterized $\overline{\sigma}$ with respect to that observed. Differences in observed cloud fraction estimates depend essentially on how one delineates cloud as well as radar sensitivity. Preliminary results obtained from CRM data indicate reduced (compared to observations) scale sensitivity and only slight differences between model subgrid and parameterized cloud fractions. The latter is somewhat expected as the Xu and Randall (1996) parameterization was essentially developed using the CRM in question.

Acknowledgments

This research was supported by the Environmental Science Division, U.S. Department of Energy (DOE), under Grant DE-FG03-94ER61769.

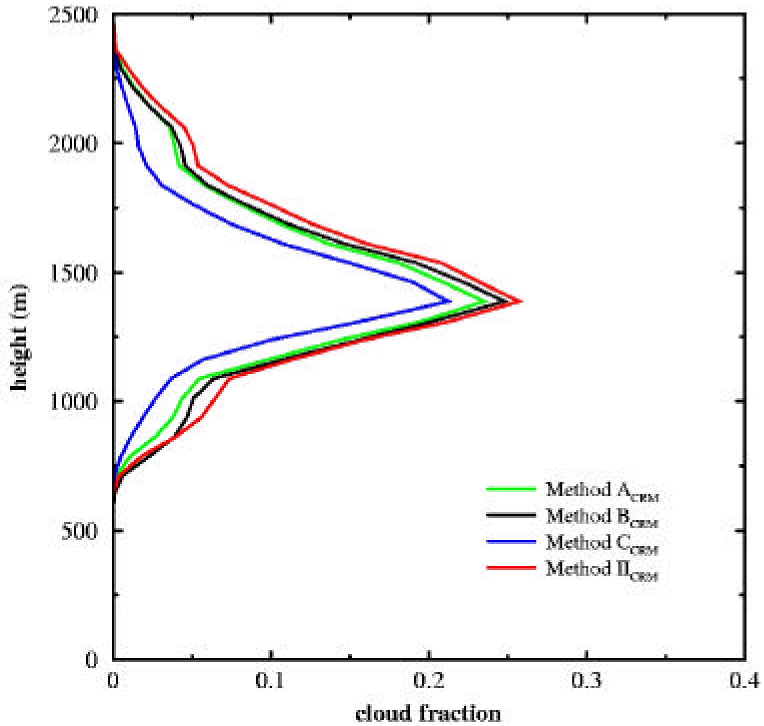

Figure 6. Mean cloud fraction from (a) Xu and Randall (1996), using CRM q_1 and RH profiles at 2.5-min. intervals (blue curve), (b) CRM subgrid-scale parameterized cloud fraction averaged over the 3-day simulation (red curve), (c) Xu and Randall (1996) where the inputs are 3-day average profiles of $\overline{RH}$, $\overline{q}_1$, and q_{vs} (black curve), and (d) Method II in text using CRM q_1 and RH profiles at 2.5-min. intervals (green curve).

References

Frisch, A. S., C. W. Fairfall, and J. B. Snider, 1995: Measurement of stratus cloud and drizzle parameters in ASTEX with a K_α-band Doppler radar and a microwave radiometer. *J. Atmos. Sci.*, **52**, 2788-2799.

Krueger, S. K., G. T. McLean, and Q. Fu, 1995: Numerical simulation of the stratus-to-cumulus transition in the subtropical marine boundary layer. Part I: Boundary-layer structure. *J. Atmos. Sci.*, **52**, 2839-2850.

Schubert, W. H., S. K. Cox, T. B. McKee, D. A. Randall, P. E. Ciesielski, J. D. Kliest, and E. L. Stevens, 1992: Analysis of sounding data from Porto Santo Island during ASTEX. Colorado State University, Department of Atmospheric Science, Report No. 512.

Xu, K.-M., and D. A. Randall, 1996: A semiempirical cloudiness parameterization for use in climate models. *J. Atmos. Sci.*, **53**, 3084-3102.