Overlapping Cloud: What Radars Give and What Models Require

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Introduction

Large-scale models (LSMs) of earth's atmosphere parameterize clouds and radiative transfer for domains measuring thousands of square kilometers. For domains this large, assumptions regarding vertical structure of non-overcast clouds are crucial for radiation budgets. Uni-directional cloud-profiling radars (CPRs) can yield information about the vertical structure of clouds but regardless of whether they are at the surface or on a satellite, they sample clouds very differently than how they are portrayed in LSM radiation codes. Data from two-dimensional (2-D) and three-dimensional (3-D) cloud-resolving models (CRMs) are used to demonstrate how well cloud overlap statistics for large domains are represented by 2-D radar-like cross sections.

Cloud-Resolving Model Data

Data from two CRMs were used. The first data set is from Fu et al.'s (1995) 2-D simulation of a tropical squall-line (GATE-III [Global Atmospheric Research Program Atlantic Tropical Experiment]). The domain measures 512 km x 20 km with 1-km horizontal grid spacing and 35 layers of varying thickness. Snapshots of the domain were saved every 10-model minutes for 10 hours. Five types of water condensates are accounted for in the model. The second data set is from Grabowski et al.'s (1998) 3-D simulation of seven days during GATE-III (September 1 to September 7). Their domain is 400 x 400 x 20 km with a horizontal grid spacing of 2 km. Four water condensates are considered.

The Radiative Importance of Cloud Overlap

Figure 1 shows solar fluxes and heating rates for a sample field from Grabowski et al. (1998) assuming different overlap properties (Barker et al. 1999). The top two plots show broadband solar flux differences between four approximate models and a 3-D Monte Carlo algorithm for the 400-km x 400-km CRM domain shown at the top of the figure (Barker et al. 1999). The independent column approximation (ICA) accounts for horizontal fluctuations (but not horizontal transport), while the others assume plane-parallel, homogeneous (PPH) clouds. Clearly, even when PPH clouds overlap exactly as dictated by the CRM, there are still large flux errors; the random overlap model is obviously completely inappropriate. The lower two plots show 3-D heating rates and corresponding fractional errors as a result of the different overlap assumptions. Aside from the ICA, errors exceeding 30% are not unusual.

These results indicate that assumptions about the overlap of unresolved clouds can be extremely important for solar radiative transfer calculations.

What LSMs Need vs. What CPRs Give

LSMs operate on series of domains while surface-based CPRs give 2-D cross sections of reflectivity as a function of time and height (Figure 2) and satellite-based CPRs cut 2-D swaths across domains (e.g., the line across the image in Figure 1). Thus, a fundamental question is: can one expect biases in basic cloud structural properties, such as profiles of fractional amount and overlap rate due to CPR sampling restrictions?

Define adjacent overlap rate Θ as the fraction C_i of cloudy cells in the i^{th} layer that overlap with cloudy cells in an adjacent layer (with cloud fraction C_{i+1}) normalized by the minimum of the two cloud fractions (Barker et al. 1999). When clouds do not overlap, $\Theta = 0$; for random overlap, $\Theta = \max\{C_i, C_{i+1}\}$; while for maximal overlap, $\Theta = 1$.

Figure 3 shows the expectation E(...) and standard deviation F(...) for profiles of domain-averaged C for all 120 fields in Fu et al.'s (1995) simulation when all condensates and only cloud droplets and small ice crystals are considered. Also shown are E(...) and F(...) for all 512 'surface CPR swaths' sampled, as shown in Figure 2. Note that E(C) for both methods are equal. Somewhat surprisingly, radars sample Θ well but have a tendency to make large errors in C. For example, between 8 km and 10 km, one stands a 33% chance of making more than a 100% error in C. As may be expected, when precipitation is included, Θ increases because of the strong vertical correlation of precipitation (makes clouds appear to be more overlapped than they actually are).

The heavy solid line in Figure 4 shows Θ (liquid clouds) for the entire domain shown in Figure 1. The dashed line represents mean Θ for all 2-D scan and tracking lines across the field. Likewise, the thin solid line is the median of all 2-D swaths and the horizontal bars represent the inter-quartile range. There is a distinct tendency for Θ derived from 2-D cross sections to exceed Θ applicable to the corresponding 3-D field. This is simply because the sampling domain is smaller, which favors maximal

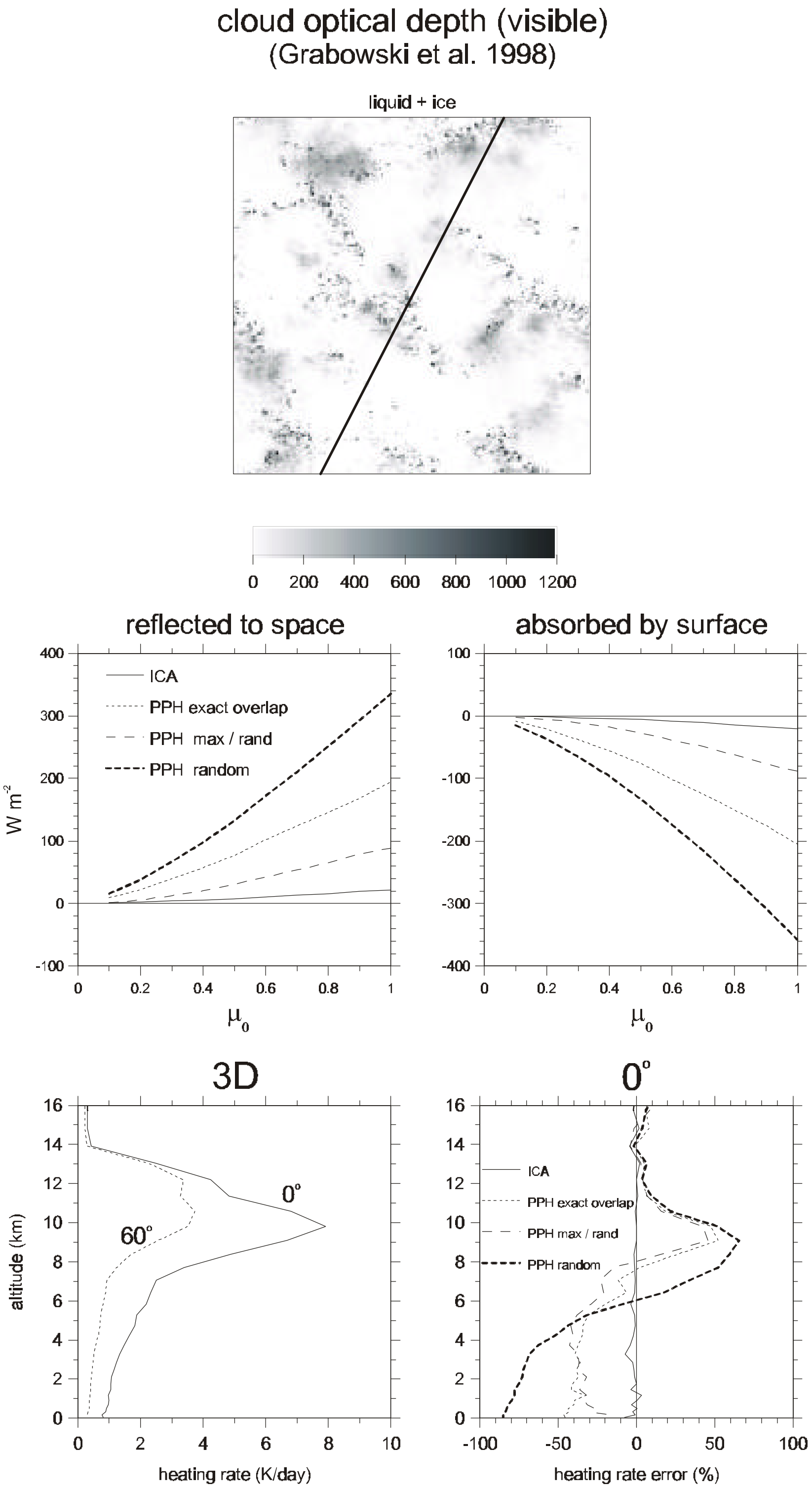

Figure 1. Top plots show flux differences between 3-D Monte Carlo and four models as a function of cosine of solar zenith angle for the field shown above. Lower plots show 3-D heating rates for two solar zenith angles and errors for the four approximate models for overhead sun.

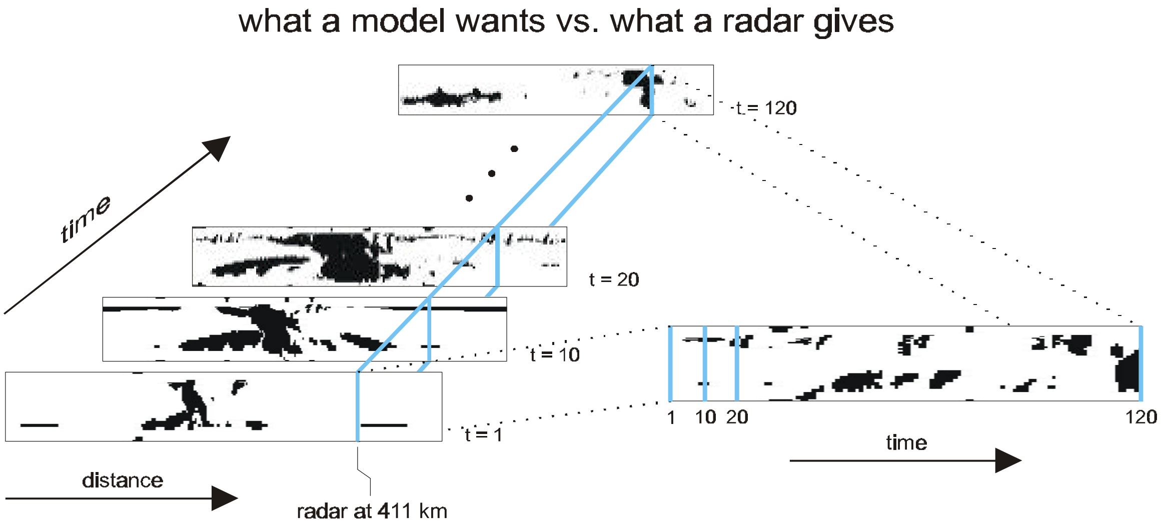

Figure 2. A CPR is fixed and randomly positioned at 411 km along a 512-km domain (Fu et al. 1995). As time passes, the CPR samples 120 profiles that, when strung together, yield the field shown at right. In a dynamic model, the series of domains are used and their time-averaged cloud statistics could differ much from the CPR-sampled cross section.

overlap. While this bias appears to be rather minor, there is nevertheless a fairly large probability that any individual 2-D sample will be a poor representative of the 3-D population (the inter-quartile range is typically ~0.2).

Thus, if one wishes to use 2-D cross sections of radar data to draw inferences about statistics for the 3-D domain from which the 2-D samples were drawn, one can run a significant risk of making a sizable error. This is not desirable when using CPR data to validate LSM cloud schemes. Work on this sampling issue is, however, in progress (e.g., Astin and Di Girolamo 1999).

A second issue related to CPR reflectivity data is the fact that CPRs respond to all condensates (especially precipitation), whereas LSM radiation codes are concerned only with liquid droplets and ice crystals. Figure 5 shows cloud-mask plots for data from Fu et al.'s (1995) simulation. The panels for liquid and liquid + ice are what an LSM's radiation code would require. A CPR, however, would yield something like the panel entitled liquid + ice + precipitation. The three lower panels are from the CPR at the Atmospheric Radiation Measurement's (ARM's) Southern Great Plains (SGP) site (Clothiaux et al. 1999). These panels are typical and resemble those from the CRM using all condensates.

Therefore, the important question is: will there be biases in overlap information due to CPR detection of precipitation? The results shown in Figure 3 for Fu et al.'s data are quantitatively very similar to those for Grabowski et al.'s simulation: eliminating precipitation reduces Θ from ~0.9 to ~0.8. Thus, it appears that for precipitating clouds (and not just those with precipitation reaching the surface), it would be beneficial if cloud liquid droplets and ice crystals could be partitioned from falling precipitation.

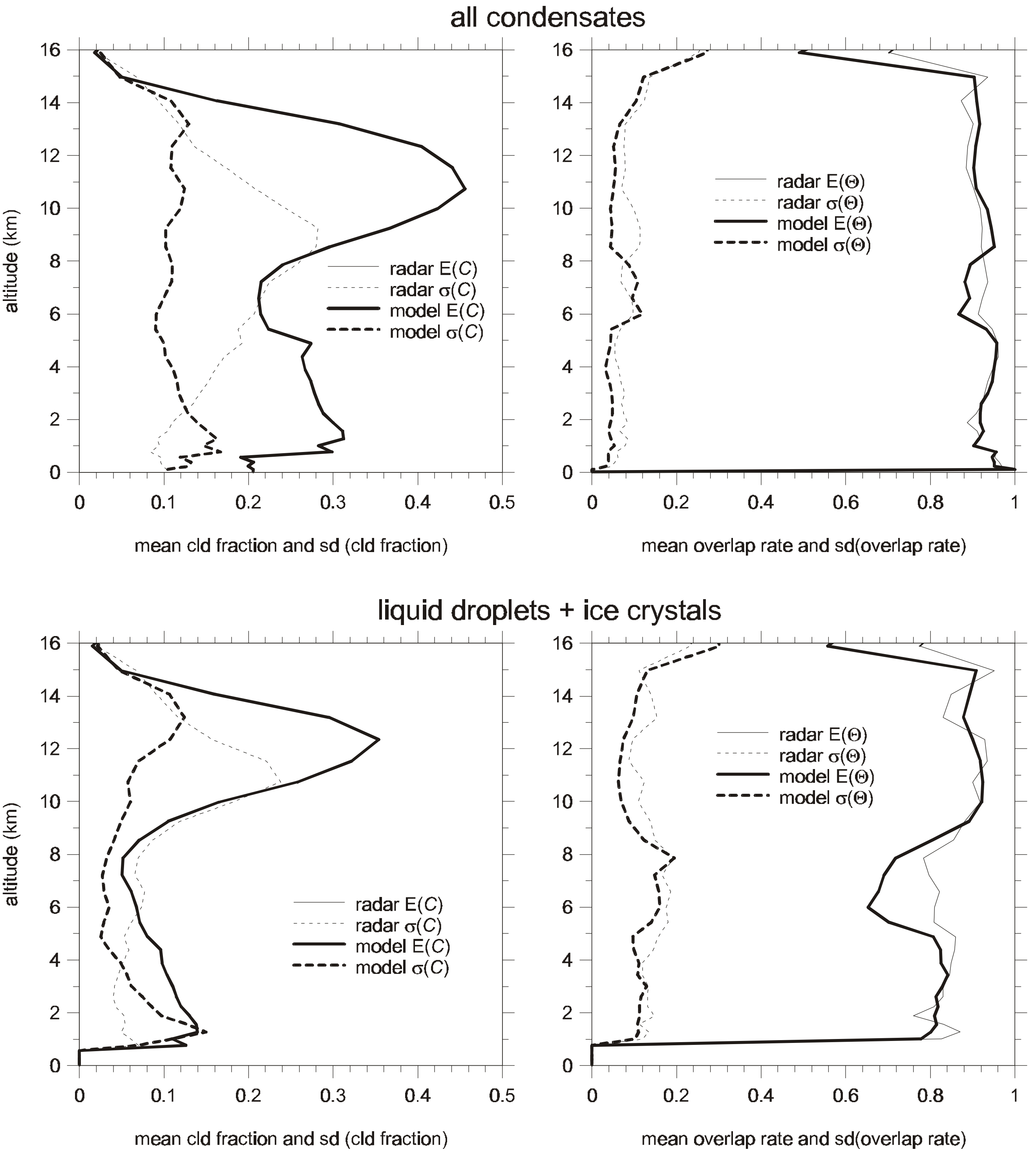

Figure 3. Expectation E(…) and standard deviation F(…) for profiles of cloud fraction C and overlap rate Θ for all 120 fields from Fu et al.'s (1995) simulation. Curves labeled 'model' are based on 120 domain-averaged profiles (i.e., 512 km long) while those labeled 'radar' are based on all 512 profiles in the time domain (i.e., 120 samples long; see Figure 2).

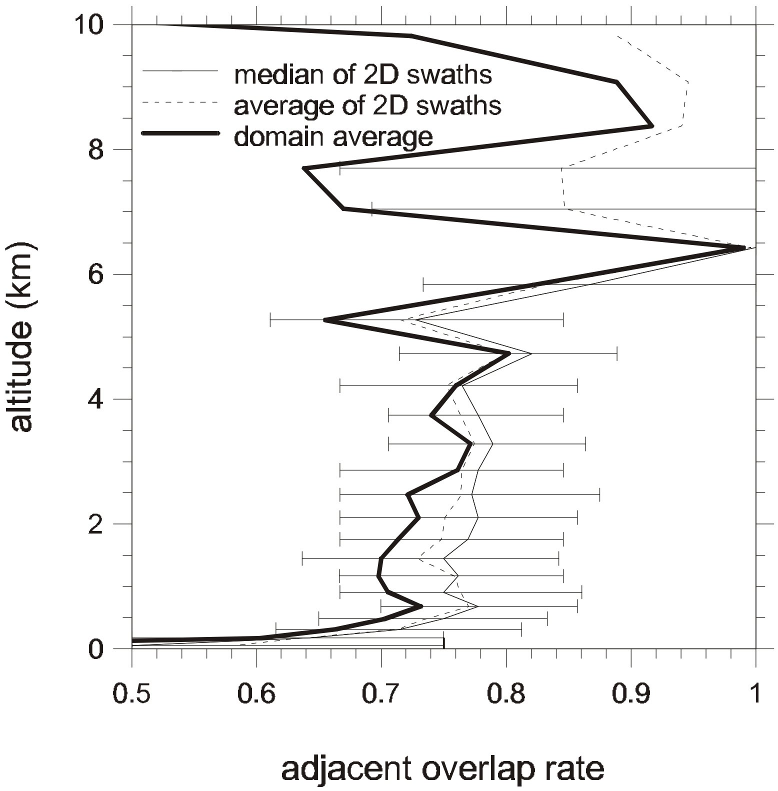

Figure 4. Overlap rates Θ as a function of altitude for the liquid-only phase for the field shown in Figure 1. See text for discussion.

This is because the impact on radiative transfer could be large if the true cloud particles are forced to overlap in accordance on cloud/precipitation overlap rates (which lean too much towards maximal overlap). Again, work is in progress, with Doppler surface CPRs, to separate falling precipitation, which follows maximal overlap closely, from the radiatively important suspended cloud particles, which (based on CRM data) tend to fall between maximal and random overlap.

Concluding Remarks

Radiative transfer computations in large-scale models of earth's atmosphere require realistic parametrizations of unresolved cloud structure. One of the most promising means of aiding development, and validation, of these parametrizations is with data from CPRs; be they fixed at the surface or flying on an aircraft or satellite. With the aid of data from CRMs, it has been shown here that the seemingly tractable questions concerning CPR 2-D sampling and detection of precipitation must be addressed before too much is inferred about cloud structure from CPR data.

Another issue not addressed here, that is likely to be important, especially for the deep convective clouds, involves radar attenuation by hydrometeors, water vapor, and oxygen. A tacit assumption in this study was that radar beams are unattenuated.

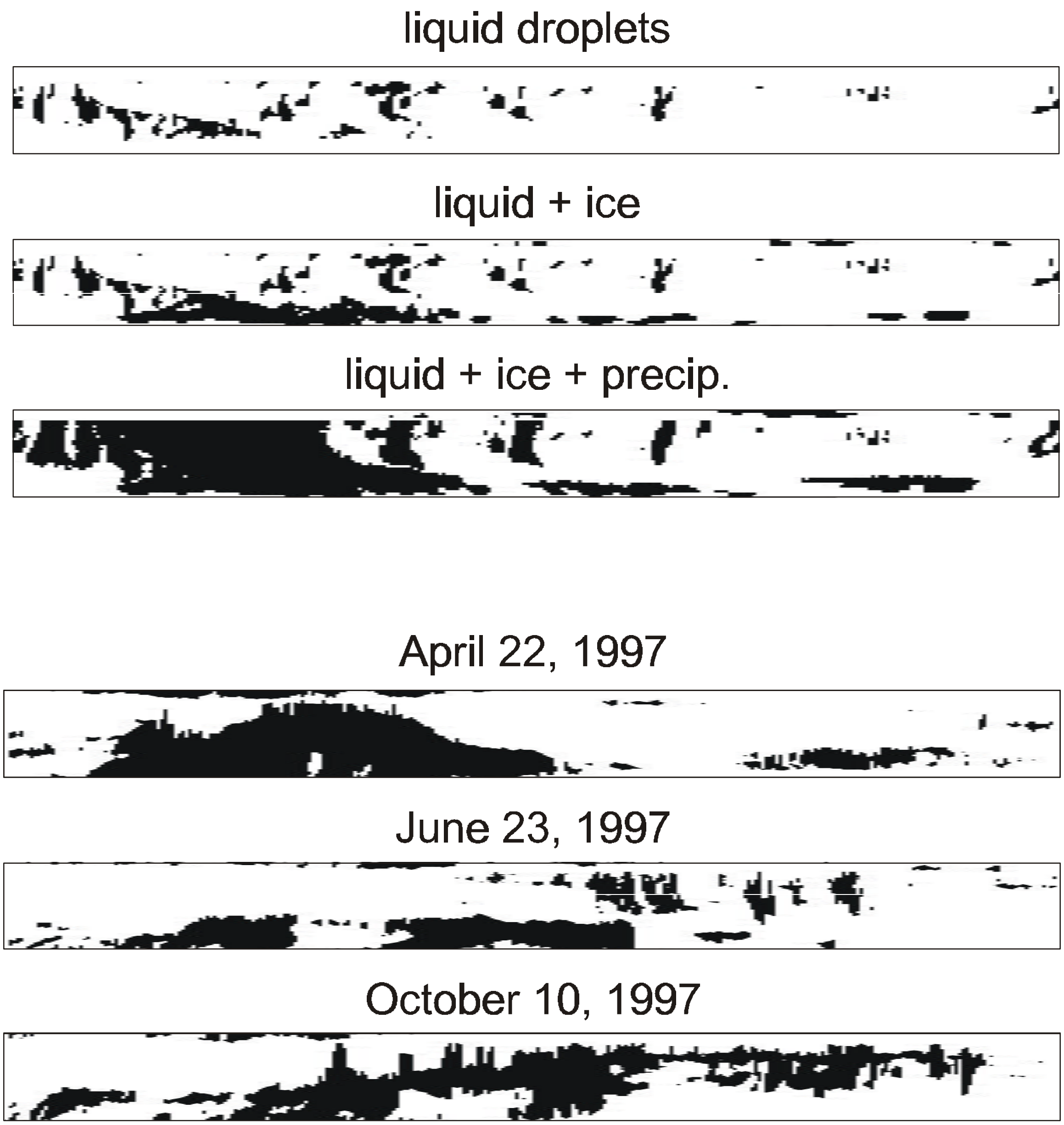

Figure 5. The top three panels show 512-km domain cloud-masks from a simulation conducted by Fu et al. (1995). The lower three panels are day-long cloud-masks derived from the ARM-SGP radar.

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