A Multipurpose Radar Simulation Package: QuickBeam

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Since launch in April of 2006, *CloudSat* has provided the first near-global view of the three-dimensional structure of clouds from space. *CloudSat*, part of NASA's afternoon A-TRAIN constellation of satellites, flies a 94-GHz cloud radar that takes near-nadir measurements of the vertical structure of both cloud and precipitation systems from a sun-synchronous orbit approximately 705 km above the Earth's surface. Observations of the variability of clouds over the surface of the Earth and through the depth of the atmosphere are creating a continually growing database that is useful for a broad range of meteorological applications, including evaluation of numerical prediction models and development of new and better convective parameterizations.

Meteorological radar systems transmit a pulse of electromagnetic energy and measure the backscattered energy that is returned to the radar dish. The backscatter occurs as a result of interactions with cloud and precipitation particles, as well as intervening atmospheric gases like water vapor and oxygen. The way electromagnetic radiation interacts with these particles is dependent on the frequency of the radiation, and the type, size, orientation, and distribution of the particles. The *CloudSat* cloud profiling radar (CPR) operates at 94 GHz and is therefore especially sensitive to cloud-sized particles. At this frequency, attenuation by water vapor is nonnegligible and attenuation by precipitation can be significant. In contrast, lower-frequency radars, such as those used in the NEXRAD system, operate closer to 3 GHz and are sensitive primarily to precipitation. Measurements of backscattered power are typically converted to the meteorological unit of radar reflectivity, expressed in decibels (d*BZ*). Retrievals of quantities like cloud water content or precipitation rate then typically follow from these reflectivity measurements.

Since *CloudSat* observations provide detailed information on the structure of cloud systems on a global scale, this information is especially valuable for evaluation of climate and weather prediction models. To compare modeled clouds to the new observations being made by *CloudSat*, it is useful to have a tool that converts modeled clouds to the equivalent radar reflectivities measured by the CPR. QuickBeam is a user-friendly radar simulation package that performs this function and is freely available to the meteorological community. Though developed with *CloudSat* in mind, it simulates a wide range of meteorological radar systems, including both spaceborne and ground-based systems, operating at frequencies between L-band and W-band (1 to 110 MHz).

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THE SIMULATOR. *Reflectivity simulations.* To simulate a profile of radar reflectivities with QuickBeam, the user specifies a spectrum of mixing ratios of any number of hydrometeor species, including cloud and precipitation particles, as depicted in Fig. 1. These mixing ratios may be derived from sources such as numerical models or field observations. Each species of hydrometeor can have its own distribution, phase, and mass–diameter relationship. The user matches each of these mixing ratios to one of the built-in distributions, including modified gamma, exponential, power law, lognormal, and monodisperse. The user must also input a profile of temperature and ambient relative humidity or use one of the built-in tropical or midlatitude profiles. This environmental sounding is used to calculate the scattering and absorption by atmospheric gases and thus the gaseous attenuation of the radar beam.

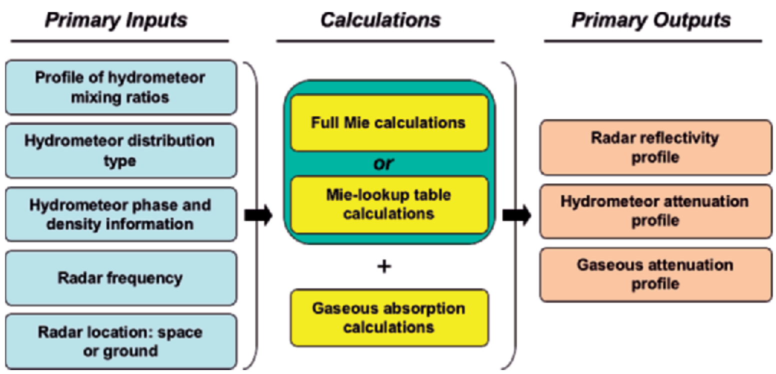

FIG. 1. Flowchart showing the primary simulator inputs, calculations, and outputs.

The simulator operates in two modes, either calculating particle scattering properties through full Mie calculations or using precalculated lookup tables of the relevant scattering properties. Full Mie calculations, while more accurate, are computationally more demanding than using the lookup tables. Reflectivity error realized in using the lookup tables is generally less than 2 dB compared to the full Mie calculations.

At the present time all hydrometeors are treated as spheres with densities that vary with diameter in a way that can be specified by the user. The calculation of ice-particle scattering properties is a universally difficult task for any microwave application, owing in part to uncertainty in the index of refraction of pure ice at low temperatures, the highly variable nature of ice-crystal shapes and densities, and also since ice often exists as a heterogeneous mixture with both air and melted liquid water. As an attempt to represent the dielectric properties of snow more accurately, the user may optionally specify a melted-water content for snowflakes. Such a representation of melting ice particles is useful in the representation of the radar bright band, a region of enhanced reflectivity associated with the presence of the melting layer.

Following the calculation of hydrometeor scattering and absorption properties, the simulator outputs a profile of radar reflectivities, including both unattenuated reflectivity and the reflectivity attenuated by other hydrometeors and gases between the radar and each range gate. When the simulator is applied to cloud-scale model output, these attenuated reflectivities may then be compared directly with observed reflectivities from *CloudSat* or any other radar platform. To apply this simulator to a general circulation model (GCM), where the hydrometeor information is on a coarser scale, subgrid-scale sampling procedures are needed.

Subgrid-scale sampling approach. The resolution of current climate models is of the order of 100 km, so these models are unable to resolve small-scale variability of atmospheric variables, particularly those of cloud fields. However, this subgrid variability and how clouds overlap within the grid box significantly impact the transfer of radiation through the atmospheric vertical column. Therefore, it is necessary to account for the subgrid variability in GCMs when simulating reflectivities for comparison with finer-scale observations.

One approach to accounting for this subgrid-scale variability is that of the Subgrid Cloud Overlap Profile Sampler (SCOPS), developed for the International Satellite Cloud Climatology Project (ISCCP) simulator, but useful for producing subgrid-scale cloud features that may be input into a radar simulator, as well. SCOPS samples the subgrid distribution of clouds within a large-scale GCM grid box using a statistical, pseudo-random sampling algorithm. It provides a subgrid distribution of clouds that is compatible with the grid box mean vertical profiles of cloud amount and the cloud overlap assumptions.

The Cloud Feedback Model Intercomparison Project (CFMIP), a joint effort by several climate modeling centers, is developing a community simulator for both *CloudSat* and the lidar platform CALIPSO. This project aims to provide a joint radar–lidar simulator designed to easily plug into a variety of weather prediction models, including high-resolution, cloud-resolving models as well as climate models. QuickBeam is utilized as the component that simulates the radar reflectivity. As *CloudSat* is sensitive to precipitation as well as clouds, CFMIP also includes an algorithm that provides the subgrid distribution of precipitation compatible with the SCOPS cloud distribution, although this part is currently under development.

APPLICATIONS. To illustrate the capabilities of the simulator, it has been applied to two different global prediction models. One is the Multiscale Modeling Framework (MMF) GCM (also referred to as a superparameterization—see the 2003 *Bulletin* article by Randall et al.) in which most cloud parameterizations are replaced by a three-dimensional cloud-resolving model (CRM) embedded into each grid cell of the GCM on a coarse (approximately 4-km) grid. It is relatively straightforward to take the output of the embedded CRM and couple it to the simulator, thus making it possible to compare the results directly to *CloudSat*.

Such a comparison is illustrated in Fig. 2 for a tropical convective system over the Asian summer monsoon region. The modeled clouds and precipitation were produced by the CSU–MMF model. It should be noted that the CSU–MMF is a climate model and as such does not predict specific weather events. That is, the CSU–MMF was not being used to model the specific convective outbreak observed by *CloudSat* in the upper panel of Fig. 2 (although they do appear somewhat similar). Rather, the model aims at a faithful representation of the collective effects of individual weather events that compose the climate. A better way to compare climate model output to *CloudSat* observations is through the sort of longer-term, broad-region analysis presented in Fig. 3. Defining cloud occurrence as any time reflectivity exceeds a given threshold (–27.5 dB*Z* is used here), modeled cloud fraction can be compared to that observed by *CloudSat*. The figure is striking because it represents some of the first truly global observations of cloud vertical structures. The comparison of model output to observations in this way provides a snapshot of what the model is doing well, and likewise not so well. For example, though one may argue that the large-scale structures in Fig. 3 are for the most part well simulated by CSU–MMF, it is also apparent that the model overestimates the cloud fraction in the northern midlatitudes and underestimates it in the southern subtropics.

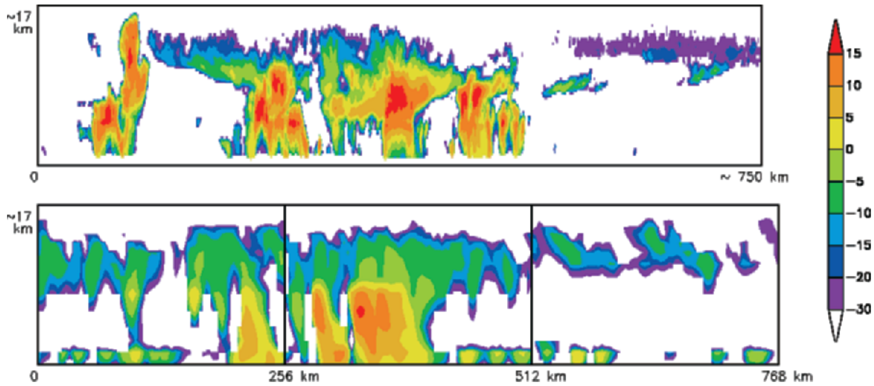

Fig. 2. Examples of the observed vs. simulated tropical convective systems over the Asian summer monsoon region. The upper panel is the radar reflectivity (in dB*Z*) observed by *CloudSat* with a horizontal span of ~750 km and vertical extension of ~17 km. The lower panels are selected MMF-simulated systems in three grid boxes within the same region with similar horizontal and vertical extension.

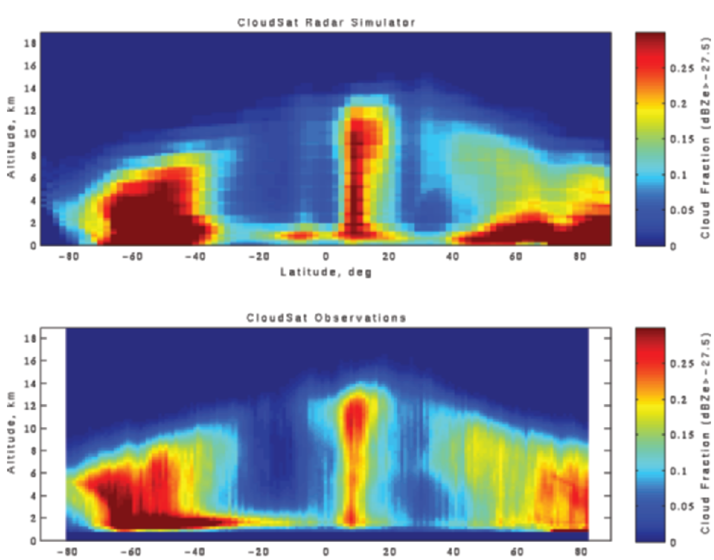

Fig. 3. Monthly zonal profiles of cloud fraction (defined as reflectivity > –27.5 dB*Z*) for July simulated (top panel) from the model and (bottom panel) from observations. Vertical axis is height above mean sea level (km) and horizontal axis is latitude. *CloudSat* is a near-nadir pointing instrument and does not obtain full polar coverage.

A second example of application of the simulator to a GCM is shown in Fig. 4. Here the simulator is applied to the output of the Met Office global forecast model, which has a horizontal resolution of approximately 40 km at midlatitudes. The subgrid sampling approach described above has been applied and the grid box mean radar reflectivity is then obtained by averaging. The figure shows a transect through a midlatitude depression in the North Atlantic on 7 July 2006. The upper panel shows the surface analysis valid at 1800 UTC, with the approximate *CloudSat* track in red, from point A near the Azores to

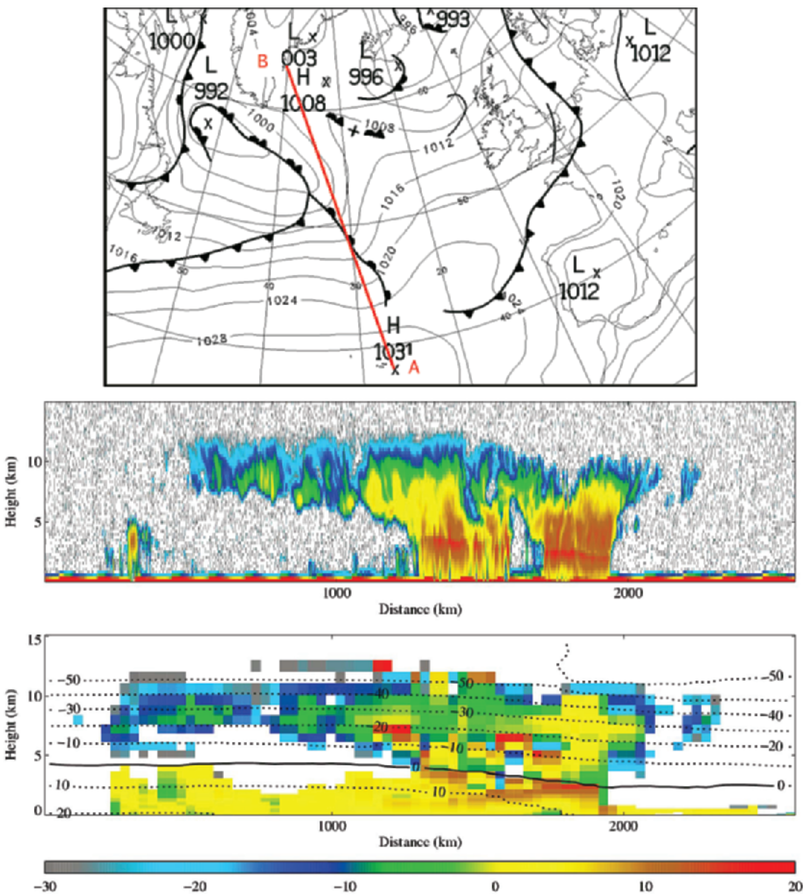

Fig. 4. Example of simulated midlatitude system in the Met Office global forecast model. The upper panel is the North Atlantic analysis chart at 1800 UTC on 7 July 2006. The red line shows the *CloudSat* track, from A to B. The middle panel shows the radar reflectivity (in dBZ) observed by *CloudSat*. The lower panel is the simulated reflectivity from the model outputs. Isotherms (°C) are contoured, the solid line denoting the freezing level.

point B off the southeast coast of Greenland. *CloudSat* passed over a mature midlatitude system that was traveling eastward in the North Atlantic, first crossing the warm front and then the core of the system near the occluded front. The middle panel shows the radar reflectivity from *CloudSat* (dBZ), while the lower panel shows the simulated radar reflectivity. The vertical structure of the frontal system is very well represented by the model, which captures the deepening high clouds approaching the core of the system. The core is dominated by large-scale precipitation, which is also reasonably well represented by the model. However, the model produces too much high-level cloud that extends toward the south (left in the image), beyond the area where it is present in the observations, and also produces low-level drizzling clouds in the warm sector beneath the high cloud, which is not observed by *CloudSat*.

PLANNED UPDATES TO QUICKBEAM. Although spherical ice crystals are convenient because their electromagnetic properties are easily calculated from Mie theory, treating ice crystals as complex combinations of needles, plates, stellars, and aggregates allows for a more realistic simulation of their appearance to radar. Work is currently underway to better account for the various habits of ice crystals that are found in real clouds. One approach is the use of the discrete dipole approximation (DDA) to represent complex ice-crystal habits as an array of interacting dipoles (as discussed in the 1995 *Journal of the Atmospheric Sciences* article by Schneider and Stephens). A lookup table incorporating DDA representations of various ice crystal habits is being developed and should be included in future versions of the simulator.

A methodology is also being developed to account for multiple scattering effects within the radar beam. Initial studies show *CloudSat* radar returns are significantly affected by multiple scattering when rain exceeds about 3 to 5 mm h^{-1}. In these heavier rainfall events, photons may be scattered out of the radar beam and reenter the beam at a later point in time through multiple scattering. This means that the power returned from a given radar pulse volume may include both the backscatter from particles within that volume and also power from earlier pulses that underwent multiple scattering. Efforts are ongoing to parameterize this effect and make simulation of heavier rain at cloud radar frequencies more accurate.

DISTRIBUTION. The source code is written in Fortran 90 and is thus highly portable to a wide variety of platforms. The package and a more technically oriented guide to the simulator can be downloaded from http://cloudsat.atmos.colostate.edu/radar-sim. For more information about the community *CloudSat*/*CALIPSO* simulator, see www.cfmip.net.

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FOR FURTHER READING

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