

Developing a Radar Signal Simulator for the Community Radiative Transfer Model

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Abstract—Active radar instruments provide vertically resolved clouds and precipitation measurements that cannot be provided by the passive instruments. These active measurements are not conventionally assimilated into the data assimilation systems because of the lack of fast forward radiative transfer models and also difficulties in the error modelling of the measurements. This paper describes the development, evaluation, and sensitivity analysis for a forward radar model implemented in the Community Radiative Transfer Model (CRTM). The scattering properties required by the forward model are provided by the hydrometeor lookup tables that were generated using the discrete dipole approximation. The model is able to calculate both the reflectivity and the attenuated reflectivity for any given radar instrument at any given zenith angles as long as CRTM instrument specific coefficients are available. The evaluation using CloudSat measurements shows a very good agreement between the simulations and measurements as long as the input profiles of hydrometeors are consistent with the measured reflectivity profiles. Major sources contributing to the differences between the measured and simulated reflectivities are input hydrometeor profiles, scattering lookup tables, lack of melting layer in the forward model, CRTM scattering solvers, and attenuation calculations. In addition to the forward model, both Tangent Linear and Adjoint of the model are also implemented and tested within CRTM. These components may be required by some data assimilation systems for the assimilation of radar measurements.

Index Terms—radar, radiative transfer, CRTM, data assimilation, microwave.

I. INTRODUCTION

ACTIVE radar and passive microwave instruments are capable of providing valuable measurements of cloud and precipitation even over convective regions. However, microwave instruments only measure the path integrated radiances emitted by the earth system, while radar instruments provide vertically resolved measurements of hydrometeors [1]. Although, observations from passive microwave instruments are routinely assimilated in the Numerical Weather Prediction (NWP) models [2]–[9], the assimilation of radar measurements is very limited [1], [10]–[14]. Over the past decade the parameterization of clouds and precipitation in the

NWP models has been reasonably improved which facilitates assimilating valuable cloud and precipitation information provided by active instruments such as CloudSat Cloud Profiling Radar (CPR), Global Precipitation Measurement (GPM) Dual-frequency Precipitation Radar (DPR), and future European Earth Clouds, Aerosols and Radiation Explorer (EarthCARE) mission [15]. Previous studies show that assimilating these observations into the NWP models can improve both the analyses and the forecasts [1], [16], [17]. Additionally, assimilation of ground based radar measurements can largely improve the representation of storms and convections in the storm scale models [18].

One of the major limiting factors for the assimilation of radar measurements is the lack of a reliable fast radiative transfer model that can help to directly assimilate these observations into the models without intermediate steps. Several radiative transfer (RT) models have been developed that not only are specific to a data assimilation system but also simplify the forward calculations by making assumptions in calculating required backscattering coefficients [12], [18]–[20]. The Community Radiative Transfer Model (CRTM) is widely used to assimilate passive satellite radiances but it lacks the capability for performing RT calculations for the active sensors.

This paper describes the implementation of a forward model for active radars into CRTM which takes advantage of current atmospheric and cloud modules in CRTM. This work benefits from a recently developed CRTM lookup table that utilizes the DDA technique with non-spherical shapes for various particles, as reported in [21]. CRTM includes not only the forward model but also the Tangent Linear and Adjoint models, which have also been developed and evaluated (see Appendix A). These additional components may be necessary in the NWP systems to assimilate radar observations. This active module not only can be used for the assimilation of radar measurements into NWP models, but also it can be used for the modeling of active sensors and also retrieving cloud and precipitation products from active radar measurements.

II. SATELLITE AND ATMOSPHERIC DATA

Although ground-based radars are commonly used, particularly for measuring precipitation and extreme weather, there are only a very limited number of spaceborne radars, including CloudSat CPR and GPM DPR. However, radar instruments are becoming more common onboard new or planned missions, including CPR onboard the European Earth Clouds, Aerosols and Radiation Explorer (EarthCARE) [15],

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as well as Ka/Ku/W Doppler Radars planned for the NASA Atmosphere Observing System (AOS) [22].

Cloudsat was launched in 2006 in a sun-synchronous orbit with an altitude of roughly 700 km to study the role of clouds in the climate system. CloudSat is equipped with Cloud Profiling Radar (CPR) with one channel operating at 94.05 GHz and a bandwidth of 0.3125 MHz that provides radar reflectivities at a vertical resolution of 500 meters. Since backscattering of clouds in microwave frequencies is very small, CPR is designed to maximize the power transmitted which affects the power received by the antenna as well. CPR also has a very high sensitivity to measure the power backscattered by hydrometeors and received by the antenna. The CPR measurements are averaged onboard along-track at an interval of 0.16 s which yields a footprint of 1.4 km by 1.7 km. These measurements are further averaged in ground processing systems to yield an along-track resolution of 3.5 km [23]. We used the radar reflectivity from the CloudSat level 2B-GEOPROF-R05 [24]. Level 2B ensures that there is significant radar echo from hydrometeors rather than noise or clutter.

After evaluating several atmospheric and cloud products, including ECMWF ERA5 reanalysis [25] and the forecasts from the NWP models, we selected the retrieved profiles from the CloudSat CPR and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) for evaluating the forward model. The NWP model simulations or reanalyses are not able to provide the hydrometeor profiles with good accuracy in either temporal or spatial domain. To generate the necessary input water content profiles for CRTM, we merged the water content profiles obtained from various retrievals corresponding to ice, snow, rain, and liquid hydrometeors.

We employed cloud liquid, rain, and cloud ice water content profiles from the release 05 level 2B-CWC-RVOD dataset. These parameters are retrieved from CloudSat radar reflectivity and Aqua MODIS cloud optical depth using the algorithm documented in [26]. The inputs to this algorithm are radar reflectivity from CloudSat [24] and cloud optical depth from MODIS instrument onboard Aqua [27]. Hereafter, we may simply refer to cloud liquid water content and cloud ice water content as liquid and ice water content, respectively. The snow water content was obtained from the Level 2C Snow Profiles (*2C-SNOW-PROFILE*) documented in [28]. The snow water content was retrieved using an optimal estimation technique and because of the ground clutter, the base of the snow layer may be truncated above the surface [28]. While graupel was not explicitly available in the retrievals, it is likely to be encompassed to a significant extent within the ice water content. The incorporation of graupel within the ice water content is expected to have a limited influence on the radiative transfer simulations. This is due to the similar scattering characteristics exhibited by both ice and graupel in the microwave region, as long as comparable shapes are employed for computing scattering effects for these hydrometeor types. The RT simulations have disregarded the scattering signal of hail due to the absence of hail water content information in the retrievals.

The ERA-Interim atmospheric profiles of temperature, water

vapor, and pressure [29] were interpolated to the CloudSat geolocation and used as input for CRTM. These atmospheric profiles have been utilized for comparison with satellite observations and in-situ profiles [30] and are deemed accurate enough for calculating gas attenuation.

III. CRTM

CRTM is a community model developed by the Joint Center for Satellite Data Assimilation (JCSDA). CRTM is a fast model that includes the capability for simulating observations from passive microwave, infrared, and visible instruments in both clear and cloudy conditions. CRTM absorption and scattering coefficients are provided through lookup tables. The absorption coefficients are specifically developed for each instrument, however the scattering lookup tables for hydrometeors are tabulated as a function of mass, frequency, and temperature. Therefore, a single set of hydrometeor lookup tables is used for all the instruments operating within a specific spectral range. Since both radars and microwave instruments operate in the microwave frequency, the same hydrometeor lookup tables are used for both instrument types. The DDA lookup tables recently implemented within CRTM supports any microwave or radar instruments operating in the range of 10 GHz to 200 GHz [21].

CRTM includes two advanced scattering solvers that are capable of accounting for multiple scattering effects: the Advanced Doubling-Adding Method (ADA) [31] and the Successive-Order-of-Interaction (SOI) method [32]. However, it is important to note that multiple scattering is only employed when computing the attenuation. Therefore, the calculations for backscattering are solely based on single scattering. The ADA is the default scattering solver in CRTM and used in this study as well. CRTM requires atmospheric profiles such as temperature, water vapor, and pressure as well as profiles of hydrometeor water contents including snow water content, hail water content, graupel water content, cloud ice water content, cloud liquid water content, and rain water content to perform full radiative transfer calculations for both microwave and radars. CRTM can also operate with the water content profiles from a single hydrometeor type (e.g., only snow water content) but that means that the scattering and attenuation impacts from the other hydrometeors are eliminated.

IV. THE RADAR EQUATION

The electromagnetic signals transmitted by the radars as short pulses travel through the attenuating atmosphere until collide with atmospheric particles such as hydrometeors. A portion of the transmitted signal may be scattered back by liquid or frozen hydrometeors towards the radar and reach the receiving antenna after travelling through the same path. This backscattered signal received by the radar is normally measured by the same antenna that had transmitted the signal. Therefore, the same antenna includes a transmitter to emit the EM pulses, a switch to alternate between transmitting and receiving modes, and a receiver to measure the returned signal. The distance between the target and the antenna is determined

using the time taken for the signal to travel through the same range twice at the speed of light.

The power received by the radar antenna not only depends on the scattering properties of the target hydrometeors and atmospheric attenuation but also highly depends on the transmitted power. However, given that the same antenna is used to transmit and receive the power, the backscattered signal can be detached from the transmitted power and also the instrument characteristics by taking the ratio of measured to the transmitted signal which is also known as reflectivity. The radar equation which is independent of the instrument characteristics and only depends on the scattering properties of the target hydrometeors and also the path attenuation can be formalized as follows:

$$\begin{aligned} R &= \frac{10^{18} \lambda^4}{\pi^5 |k_w|^2} \beta_b \\ R_a &= \frac{10^{18} \lambda^4}{\pi^5 |k_w|^2} \Gamma \beta_b \end{aligned} \quad (1)$$

where λ is wavelength (in m), β_s is volume backscattering coefficient, and k_w is the dielectric factor. The unit for the reflectivity (R) and attenuated reflectivity (R_a) is in $\text{m}^6 \text{m}^{-3}$ ($\text{m}^4 \text{m}^2 \text{m}^{-4} \text{m}^1$) and 10^{18} is used to convert the unit to $\text{mm}^6 \text{m}^{-3}$. These are in turn converted to dBZ or decibels relative to a reference reflectivity of $R_r = 1 \text{ mm}^6 \text{m}^{-3}$ as follows:

$$\begin{aligned} R_e &= 10 \log_{10} (R) \\ R_{ea} &= 10 \log_{10} (R_a) \end{aligned} \quad (2)$$

The volume backscattering coefficient β_s is calculated using the number density of particles per unit diameter of particle, $n(D)$:

$$\beta_b = \int_0^\infty \sigma_b(D) n(D) dD \quad \text{m}^2 \text{m}^{-4} \text{m}^1 \Rightarrow \text{m}^{-1} \quad (3)$$

where D is maximum dimension or the diameter of a sphere enclosing the particle in meters. CRTM requires the mass backscattering coefficient which is calculated as:

$$k_b = \frac{\int \sigma_b(D) n(D) dD}{\int m(D) n(D) dD} = \frac{\int \sigma_b(D) n(D) dD}{\int \rho(D) V(D) n(D) dD} \quad (4)$$

where k_b has a unit of $\text{m}^2 \text{kg}^{-1}$ ($[\text{m}^2 \text{m}^{-4} \text{m}^1] / [\text{kg} \text{m}^{-4} \text{m}^1]$), m is the mass of particles (in kg), V is the volume and can be calculated as $V = (\pi D^3)/6$, and density ρ varies with the particle size such that $\rho = m(D)/V(D)$. The volume backscattering coefficient (β_b) required in Equation 1 is then calculated using mass backscattering coefficient (k_b) and cloud water density or mass concentration (ρ_h in $\text{kg} \text{m}^{-3}$) as $\beta_b = \rho_h k_b$. CRTM provides layer integrated cloud water content (ψ_h) in $\text{kg} \text{m}^{-2}$ that can be converted to cloud water density using $\rho_h = \psi_h / d_x$ where d_x is slant-path layer thickness in meters or $d_z / \cos(\theta)$ where d_z is the layer vertical thickness and θ is the zenith angle.

$$\beta_b = \rho_h k_b = \frac{\psi_h k_b}{d_x} \quad (5)$$

The backscattering cross section (σ_b , in m^2) can be calculated as follows:

$$\sigma_b = 4\pi Z_{11}(\theta_s = 180) \quad (6)$$

where Z_{11} is the first element of the phase function and θ_s is the scattering angle where 180° indicates the backscattering.

The dielectric factor (k_w) is calculated using the complex permittivity of the liquid water ($\epsilon_w = \epsilon' + i\epsilon''$) (or refractive index of liquid water $\eta_w = \sqrt{\epsilon_w}$) at any given frequency and a temperature of 273 K as follows:

$$k_w = \left| \frac{\epsilon_w - 1}{\epsilon_w + 2} \right| = \left| \frac{\eta_w^2 - 1}{\eta_w^2 + 2} \right| \quad (7)$$

We used the permittivity models developed by [33] for the permittivity of liquid water to be consistent with the permittivity model that had been used to develop the cloud optical properties using the DDA technique [34].

In addition to the reflectivity, the two-way path integrated attenuation is also required to compute the attenuation of the signal by the Earth's atmosphere from the range r to the satellite (r_{sat}):

$$\Gamma(r) = \exp \left(-2 \int_{r'}^{r_{sat}} \kappa_e(r) dr \right) = \exp \left(-2 \sum_{i=r}^{r_{sat}} \tau(i) \right) \quad (8)$$

where $\Gamma(r)$ is the transmittance from range r to the satellite ($r_{sat} = 0$), κ_e is the extinction coefficient and accounts for absorption from both gasses and hydrometeors (κ_a) and scattering from hydrometeors (κ_s) so that $\kappa_e = \kappa_a + \kappa_s$, r is the distance (range) from a given volume to the antenna and is calculated using $dr = dh / \cos(\theta)$ with h being the altitude and θ is the zenith angle, and τ is the layer optical depth.

V. RESULTS

A. Hydrometeors Lookup Tables

Previous CRTM lookup tables generated using the Mie theory not only include spherical shapes for all frozen hydrometeors but also lack the backscattering coefficients that are required by active radars for calculating the reflectivities. The phase function is also only provided in terms of the Legendre Polynomials in the CRTM hydrometeor lookup tables. Therefore, computing the backscattering coefficient from the current lookup tables requires first calculating the phase function from the Legendre terms [20], [35] then solving the phase function for a scattering angle of 180 degrees to calculate the backscattering coefficient. Computational speed is one of the requirements for the NWP data assimilation, therefore in a recent effort to generate the lookup tables using the discrete dipole technique, the backscattering coefficients were also included in the hydrometeors lookup tables [21], [34].

Figure 1 shows the scattering properties computed using the DDA theory for single particles and a few typical habits. Figure 1 shows the scattering information for three nominal frequencies, 14 GHz (DPR Ku band), 36 GHz (DPR Ka band), and 94 GHz (CPR W band). The extinction equals scattering and absorption so that a small difference between the absorption and extinction for *LiquidSphere* shows little scattering by liquid hydrometeors. The absorption for liquid sphere is noticeably larger than the absorption for all other habits especially for lower frequencies which indicates a large

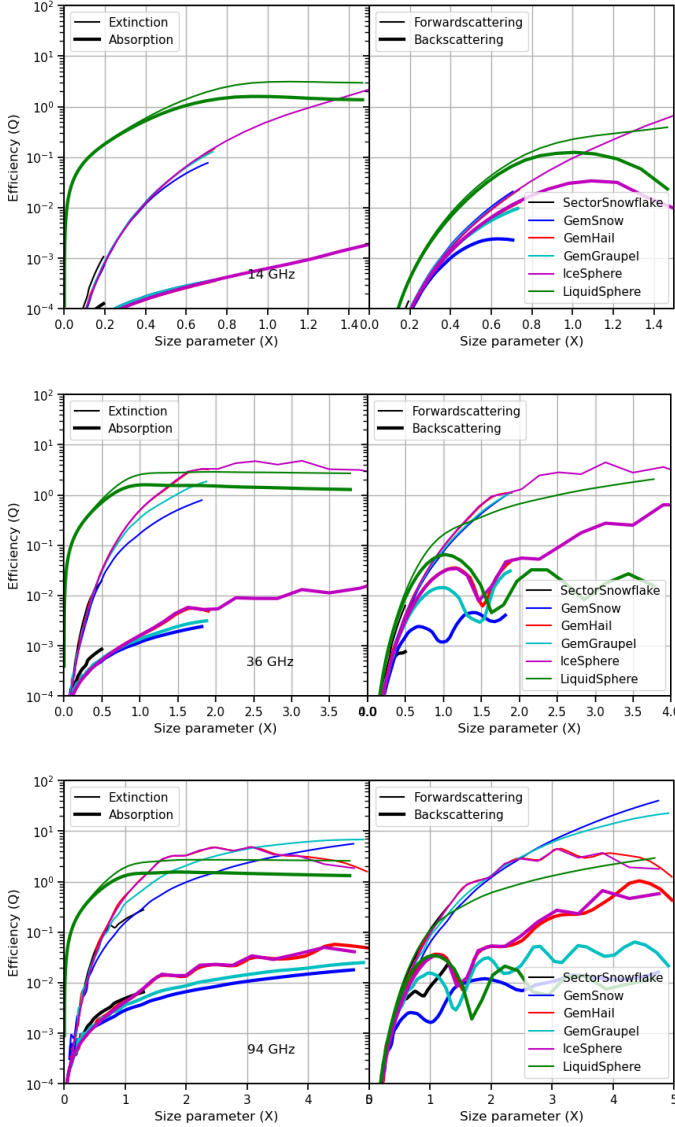


Fig. 1. The scattering coefficients generated using the DDA technique for several habits and different frequencies.

attenuation for the radar signals. The scattering and backscattering generally increase from lower to higher frequencies for frozen hydrometeors.

Figure 2 shows the bulk scattering properties included in the CRTM lookup tables for a water content of 5 g kg^{-1} . In the new DDA lookup tables generated for CRTM, the water content (in kg m^{-3}) is used for interpolation over the mass. The details of calculating the bulk scattering properties for CRTM are provided in [21]. The backscattering for all the habits and frequencies almost linearly changes with water content in a logarithmic scale. The single scattering albedo (ω_{bulk}) shows the ratio of scattering to extinction coefficients. Both single scattering albedo (ω_{bulk}) and asymmetry parameter (g_{bulk}) are also included in Figure 2. The single scattering albedo approaches almost one for frozen hydrometeors where water contents is greater than 10^{-5} g m^{-3} . It is less than 0.2 for *LiquidSphere* which approaches even zero for lower frequencies. These show large scattering for frozen hydrometeors and

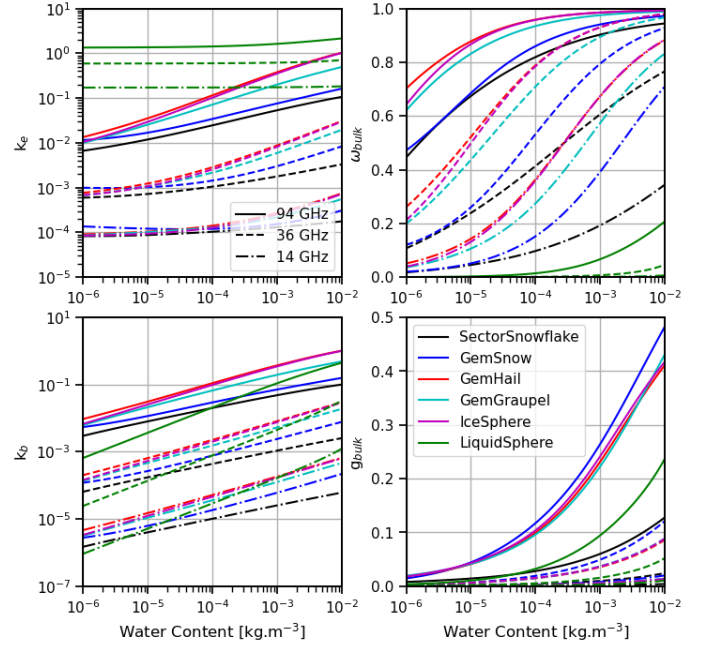


Fig. 2. The CRTM bulk scattering parameters including extinction coefficient (k_e), backscattering coefficient (k_b) and single scattering albedo (ω_{bulk}) and asymmetry parameter (g_{bulk})

little scattering for *LiquidSphere*. The asymmetry parameter is overall larger for frozen hydrometeors and especially higher frequencies showing that spherical particles may be enough for simulating the scattering properties of hydrometeors at lower frequencies but using non-spherical habits for higher frequencies is essential.

The phase function, formulated using Legendre Polynomials, is also included in CRTM hydrometeor lookup tables, however it is only used in the computations within the scattering solver. The phase functions for some nominal habits are shown for three different frequencies (14 GHz, 36 GHz, and 94 GHz) in Figure 3 for a water content of 5 g kg^{-1} . Phase functions are essential in understanding the scattering behaviour of different habits. Overall, the phase function approaches the Rayleigh phase function for lower frequencies where the particle sizes are small compared with the wavelength. At the higher frequencies, the forward scattering is much more dominant than backscattering.

B. Observed vs. Simulated Reflectivities

The RT simulated reflectivities largely depend on the hydrometeor input profiles, known as cloud water content in CRTM, used to perform the RT simulations. The NWP models are not able to simulate the clouds with sufficient accuracy for the evaluation of the active sensor forward model, thus the first-guess provided by the model or the analysis from the data assimilation systems is not a reliable source of input profiles to evaluate the biases in the developed forward model. After investigating several datasets for providing the input profiles for comparison with the CloudSat measurements, we decided to use the profiles directly retrieved from the measurements of CloudSat CPR, Aqua MODIS, and auxiliary data. Although

CPR measured reflectivities for Hurricane Bill. The simulations were performed using an ensemble of hydrometeors including snow, ice, liquid, and rain. As shown in Figure 5, the simulations and observations are generally in good agreement, with the largest differences occurring over the convective regions. The reflectivities are in fact attenuated reflectivities with the attenuation from both hydrometeors and gasses being considered. The forward model implemented in the CRTM does not yet consider the melting layer, therefore there is a noticeable difference below the 273 K temperature zone where the melting of falling snow particles occur. The falling frozen particles normally aggregate and create larger particles when falling towards the lower part of the troposphere which causes higher reflectivities. These large aggregates start melting from outside when passing through the warmer zones of the atmosphere with temperatures above the melting point. These large particles appear as large water droplets and since the water reflectivity is much larger than that of ice, these melting particles cause a large increase in radar reflectivities. The density of large aggregates increases when completely melted which causes smaller and denser particles with a higher falling velocity. This causes not only smaller particles

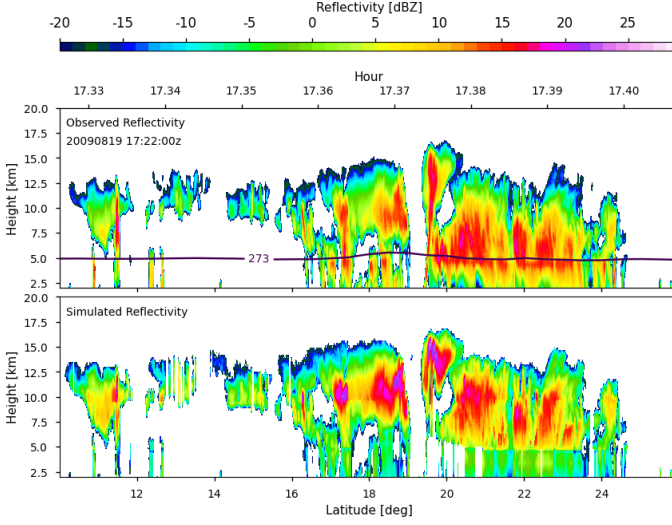


Fig. 5. CRTM simulated vs. CloudSat CPR measured reflectivities for Hurricane Bill on August 19, 2009, at 17:22:00 UTC.

but also decreases the number density which leads to lower reflectivities. The melting layer not only affects the reflectivity directly but also causes a large attenuation for both radar and passive microwave signals.

Various factors contribute to the disparities between simulated and measured reflectivities, but the predominant source of error is likely the bias in the input profiles of hydrometeor water content, particularly the omission of hail water content. Other sources of error include biases in CloudSat CPR reflectivities, single scattering properties used to generate the scattering lookup tables, scattering computations within CRTM such as error in scattering solver or interpolation of scattering properties, particle size distributions used to generate the bulk scattering properties, and bias in atmospheric state variables such as temperature and water vapor.

Figure 6 shows another example of observed versus simulated reflectivities for Typhoon Nida. The upper panels illustrate the CloudSat observed reflectivities contrasted with the CRTM simulated reflectivities. Once more, there is a large qualitative similarity between the measurements and simulations. In Figure 6, the lower panel illustrates the related attenuation, which can reach up to 10 dBZ in areas experiencing intense convection or precipitation. While backscatter radars are usually configured to be less sensitive to atmospheric elements like water vapor, attenuation from hydrometeors can still be considerably high, causing a significant impact on the reflectivities over convective clouds.

Density plots were created to examine the frequency of occurrences of reflectivity as a function of layer temperature and reflectivity. Figure 7 shows the density plots for both Hurricane Bill and Typhoon Nida. The density plots from both cyclones show a good consistency between the measured and simulated reflectivity. The largest deviation occurs in the layer below 270 K where the effect from melting layer increases the occurrence of higher reflectivities in observations than in the simulations.

It should be noted that when utilizing the CRTM lookup ta-

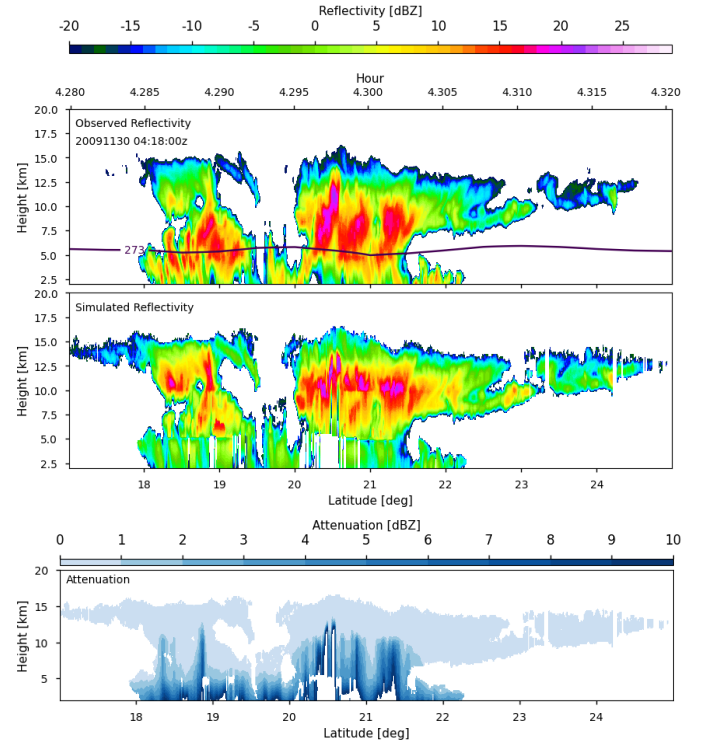


Fig. 6. CRTM simulations performed for the CloudSat CPR over Typhoon Nida on November 30, 2009, at 04:18:00 UTC. The upper panel displays a comparison of observed and simulated reflectivity, while the lower panel shows the computed attenuation resulting from both atmospheric constituents and hydrometeors.

bles created via the DDA technique [21], *IceSphere* should be employed for hydrometeor type to calculate the backscattering signal originating from cloud ice water content. As explained in Moradi et al. [21], when the hydrometeor type is specified as either *ICE_CLOUD* or *WATER_CLOUD*, CRTM does not perform interpolation of scattering properties with respect to the mass of hydrometeors (water content in the DDA scattering lookup tables). Instead, CRTM uses the scattering properties from the lowest water content bin of hydrometeor lookup tables to perform radiative transfer calculations. As illustrated in Figure 2, such hydrometeors are too small to produce any significant backscattering at nominal radar frequencies, leading to the absence of backscattering from *ICE_CLOUD* and *WATER_CLOUD*. Therefore, to ensure proper computation of the scattering signal from cloud ice and liquid water content, it is recommended to use *IceSphere* and *LiquidSphere* to specify the hydrometeor type for cloud ice and liquid water content, respectively.

Figure 8 shows how the choice of the cloud type for cloud ice water content affects the computed reflectivities. The top panel shows the reflectivities when the cloud ice water content is completely assigned to *IceSphere*, while the second panel depicts the same simulations with the cloud ice water content wholly assigned to graupel. The third panel from the top in Figure 8 shows the differences between reflectivities in the top two panels (*IceSphere* minus graupel), which can be up to 4 dBZ. As mentioned earlier, the graupel water

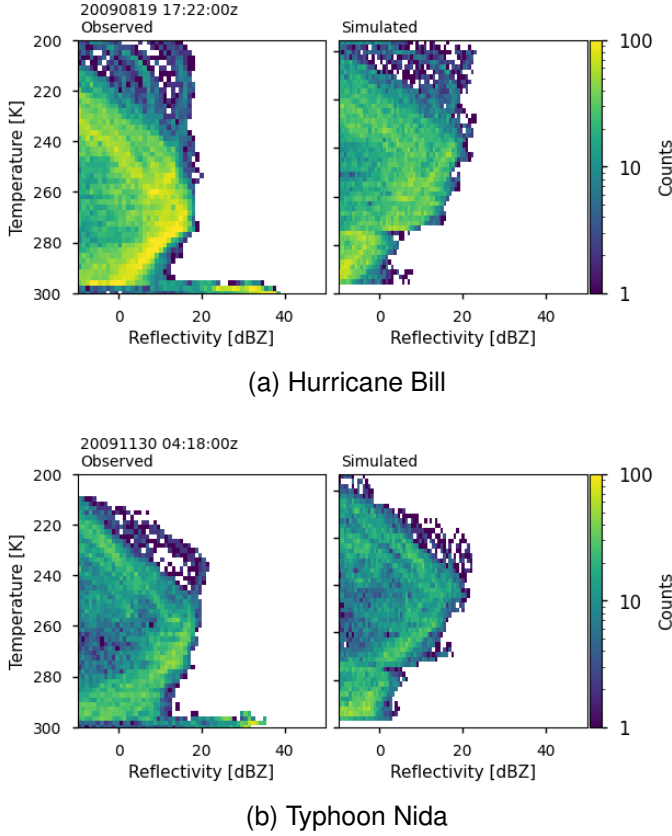


Fig. 7. Density plots for the frequency of occurrences of reflectivity as a function of layer temperature and reflectivity for Hurricane Bill (top) and Typhoon Nida (bottom). The left panels display the density plots for the observed reflectivities and the right panels show the histogram for the CRTM simulated reflectivities.

content was implicitly incorporated in the radiative transfer computations primarily through ice water content. Figure 8 demonstrates the maximum impact that arises due to the absence of distinction between ice and graupel. Although the impact may be relatively small, the choice of ice crystal habit used to compute the scattering from cloud ice water content impacts not only the reflectivity above the melting layer but also the computed attenuation, which can consequently affect the reflectivity all the way down to the surface.

C. Sensitivity of Radar Measurements to Hydrometeors

Figure 9 shows the contribution of different hydrometeors to simulated radar reflectivities for Typhoon Nida. This figure illustrates the reflectivities simulated by using a single type of hydrometeor as input while ignoring all other hydrometeors. For instance, reflectivities in Figure 9(a) were simulated using snow water content only and the water content values for all other hydrometeors (ice, liquid, and rain) were set to zero. In addition to the simulated reflectivities, Figure 9 also includes the corresponding hydrometeor water content values that were used as input to CRTM. As expected, the frozen hydrometeors mostly occur above the melting zone, while rain and liquid clouds mostly exist below the melting layer. The effect of rain water content on simulated reflectivities is generally small; however, in regions where the rain water content exceeds 1

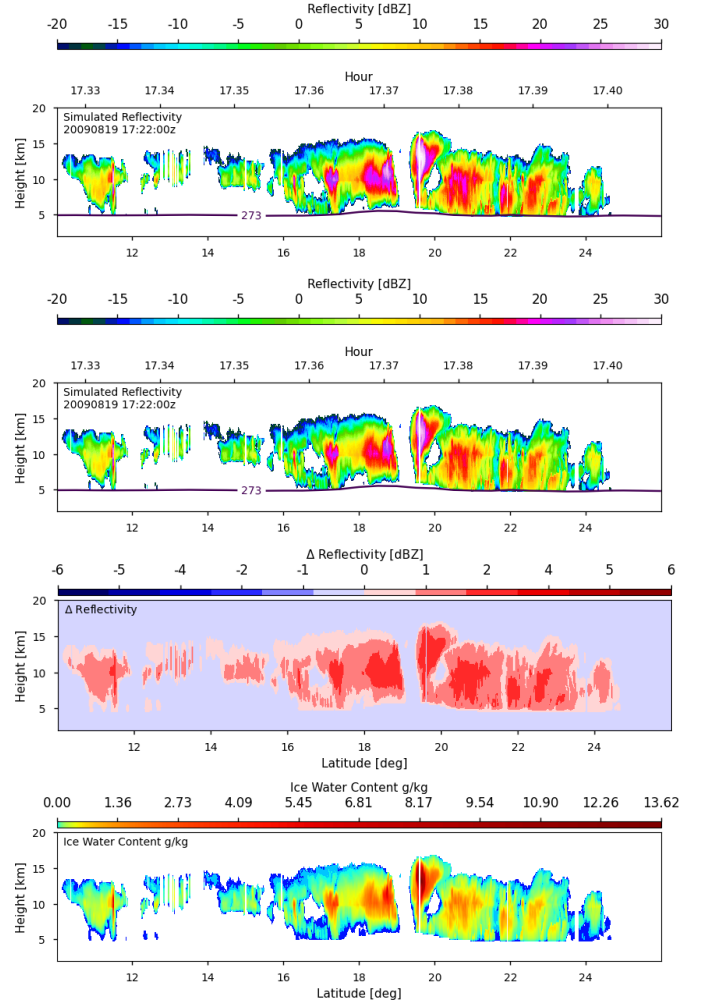


Fig. 8. The difference in simulated non-attenuated reflectivity when ice water content is assigned to either cloud ice or graupel for Hurricane Bill on August 19, 2009, at 17:22:00 UTC. The top panel displays the simulated reflectivities when the ice water content is entirely assigned to *IceSphere*, while the second panel from top shows the reflectivities when the ice water content is entirely assigned to graupel. The third panel from the top displays the difference between the top two panels (*IceSphere* minus graupel). The bottom panel shows the corresponding ice water content values used as input to CRTM.

gkg^{-1} , the impact can be as high as 10 dBZ. Such regions occur on both the north and south sides of the cyclone. In the frontal region (north side) of the cyclone, as shown in Figure 4, the snow water content can reach up to 9 gkg^{-1} . Snow has a significant impact on CPR reflectivities, with simulated reflectivities from the snow water content reaching up to 20 dBZ in regions with high snow water content values. The ice water content is more widely observed through the north frontal side of the cyclone. Reflectivities due to ice particles can reach up to 30 dBZ in convective regions.

As previously discussed, CRTM does not generate any backscattering when the hydrometeor type is specified as *WATER_CLOUD* or *ICE_CLOUD*. However, as illustrated in Figure 9(f), cloud ice particles produce a significant backscattering signal, particularly above 90 GHz in the microwave frequencies. Hence, it is vital to utilize *IceSphere* instead of *ICE_CLOUD* to accurately calculate the scattering signal

from cloud ice water content, as demonstrated in Figure 9(b). Additionally, though the reflectivities generated from liquid clouds are not as prominent as those from ice clouds, they still exhibit reflectivity values ranging from -40 dBZ to -10 dBZ for the given tropical cyclone, as seen in Figure 9(d). Therefore, it becomes crucial to use *LiquidSphere* to prescribe the cloud liquid water content while simulating radar reflectivity using CRTM.

All simulations conducted thus far utilized the sector snowflake to compute the scattering signal from the snow water content. There are various shapes available in the DDA database that can be employed to calculate the scattering signal for different water content values [21]. Figure 10 illustrates the impact of the hydrometeor shape used to determine the scattering and backscattering signal for the snow water content. In this figure, the top panel displays the difference in simulated non-attenuated reflectivities using the sector snowflake and eight column aggregate for Typhoon Nida. The middle panel illustrates the effect of these shapes on calculated attenuation. The bottom panel shows the effect of the shapes on simulated attenuated reflectivity. The bottom panel, in fact, demonstrates the combined effect of both backscattering and attenuation from the two different shapes. Generally, the sector snowflake generates less scattering than the eight column aggregate, leading to lower non-attenuated reflectivity when used to compute the backscattering signal for snow water content in comparison to the eight column aggregate. However, the computed attenuation is also lower for the sector snowflake than the eight column aggregate. This, in turn, compensates for the lower backscattering effect, especially below the snowing layer, resulting in higher attenuated reflectivity when performing simulations using the sector snowflake compared to the eight column aggregate.

VI. CONCLUSIONS

Unlike passive instruments which provide vertically integrated observations, active instruments provide vertically resolved measurements of atmospheric hydrometeors. Despite the importance of the active measurements, observations from active instruments have not been used by data assimilation communities because of the lack of forward radiative transfer models as well as difficulties in modelling the observation error. CRTM is widely used in the United States for the assimilation of passive microwave and infrared observations but did not have the capability to simulate the observations for active instruments. However, it includes many capacities such as modules to compute the atmospheric absorption by gases and hydrometeors as well as scattering by hydrometeors that can be used in the radar forward module. In addition, it is highly preferred by data assimilation communities to use the same radiative transfer model for the assimilation of all satellite observations instead of implementing different RT models for different observation types.

We have therefore implemented a simulator for active radar instruments into CRTM that takes advantage of many current CRTM modules from reading input atmospheric and cloud profiles, lookup tables for both absorption and scattering,

computing atmospheric absorption and emission, computing cloud scattering properties, and also calculating Jacobians. The module does not require any input other than what currently being used for all-sky microwave observations. The active module not only computes the radar reflectivities but also is capable of computing Jacobians when needed. The forward simulator however lacks capability to simulate the melting layer impact.

The radar simulator was evaluated using the measurements from CloudSat as well as a subset of profiles of temperature, water vapor, and pressure from ERA-Interim collocated with the retrievals from instruments onboard A-Trian satellites including CloudSat CPR and Aqua MODIS. Although the simulated reflectivities largely agree with the measurements, the differences can be large especially when the input profiles do not match the reflectivity measurements. In addition to the input profiles likely being the largest source of the difference between measurement and simulations, other sources of error are uncertainty in the scattering database, particle size distribution used to generate the bulk scattering properties, ignoring the impact of multiple scattering on the backscattering computations, as well as temperature and water vapor profiles used to compute the attenuation of the atmosphere.

Multiple scattering is a complex phenomenon in radar observations that can significantly impact the accuracy of radar reflectivity simulations [36]–[38]. In the presence of multiple scattering, radar signals interact with multiple particles within a cloud, resulting in intricate and often non-linear effects on the observed radar returns. Multiple scattering influences both backscattering and attenuation from hydrometeors [39]. Quantifying the impact of multiple scattering on radar reflectivity simulations is a complex endeavor, contingent on multiple factors like cloud type, cloud water content, particle size distribution, and radar frequency [36], [39]. At lower frequencies such as 13 GHz (Ku band), the effect of multiple scattering never surpasses a few dBz, even in extreme scenarios. However, this effect escalates with frequency, reaching up to tens of dBz in intense conditions, as observed at 35 GHz (Ka band). Even in moderate rain rates, multiple scattering can affect reflectivities at 94 GHz (W band) [39]. For an in-depth exploration of the impact of multiple scattering on radar reflectivity simulations, readers are referred to Battaglia et al. [39].

In this study, hydrometeor profiles used as input for radiative transfer simulations were retrieved from CloudSat reflectivities, enabling a direct comparison between simulations and measurements at both spatial and vertical resolutions. However, in data assimilation systems, the input profiles are typically provided by NWP models with a grid size much larger than the radar footprint. Sub-grid variability in atmospheric properties can significantly impact radiative transfer simulations, especially when this variability is larger than the grid size. As a result, it is important to either account for sub-grid variability in the radiative transfer simulations, e.g., [40], [41], or to use superobing techniques to generate observations that are representative of the model grid [42].

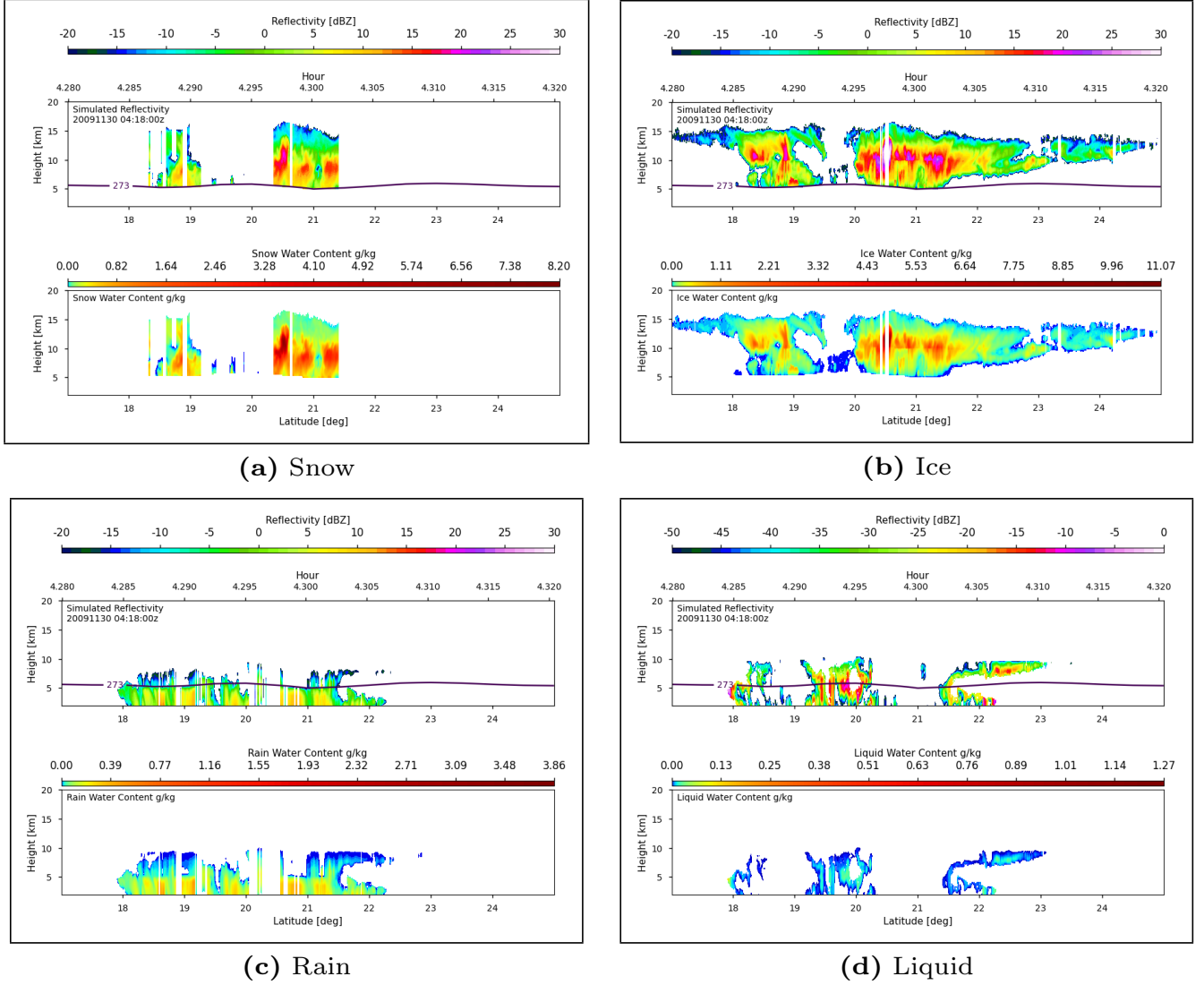


Fig. 9. Simulated non-attenuated radar reflectivity due to individual clouds for Typhoon Nida on November 30, 2009, at 04:18:00 UTC. In each panel, the top depict shows the simulated reflectivities and the bottom depict shows the corresponding hydrometeor water contents. Note that the colorbar scale for the panel for the liquid clouds differs from the scales used in other panels.

APPENDIX A TANGENT LINEAR AND ADJOINT

In addition to the forward model, some data assimilation systems also require tangent linear (TL) and adjoint (AD) of the radiative transfer models. This section describes the derivation of both TL and AD for the active radar simulator. The ultimate outputs of the active radar module are reflectivity (R_e , in dBZ) and attenuated reflectivity (R_{ea} , in dBZ) which are in turn, as shown in Equation 2, calculated from corresponding reflectivity (R in $\text{mm}^6 \text{m}^{-3}$) and attenuated reflectivity (R_a in $\text{mm}^6 \text{m}^{-3}$). In order to simplify the mathematical expressions in Equation 1, we define P_1 as $P_1 = (10^{18} \lambda^4) / (\pi^5 |k_w|^2 d_x)$ and considering $\beta_b = (\psi k_b) / d_x$ then R and R_a can be expressed as:

$$R = \frac{10^{18} \lambda^4}{\pi^5 |k_w|^2} \beta_b = \frac{10^{18} \lambda^4}{\pi^5 |k_w|^2} \frac{\kappa_b}{d_x} = P_1 \kappa_b \quad (9)$$

$$R_a = P_1 \Gamma \kappa_b$$

As shown in Equation 5, the backscattering coefficients are related to each other as follows:

$$\kappa_b = \beta_b d_x = \psi k_b \quad (10)$$

where β_b is volume backscattering coefficient, ψ is water content, κ_b is the mass backscattering coefficient scaled by water content, and Γ is two-way path integrated transmittance from the satellite to the given layer. Note that d_x is the slant path and equal to $d_z / \cos(\theta)$.

The code for the tangent linear and adjoint is developed in a reverse order compared with the code for the forward model, therefore we start from Equation 10 and proceed to Equation 2. We use ∂x and ∂x^* to refer to tangent linear and adjoint, respectively. It is easier to separate different components of the reflectivity and compute the adjoint and tangent linear separately for each component which avoids dealing with very large matrices. Therefore, we explain how

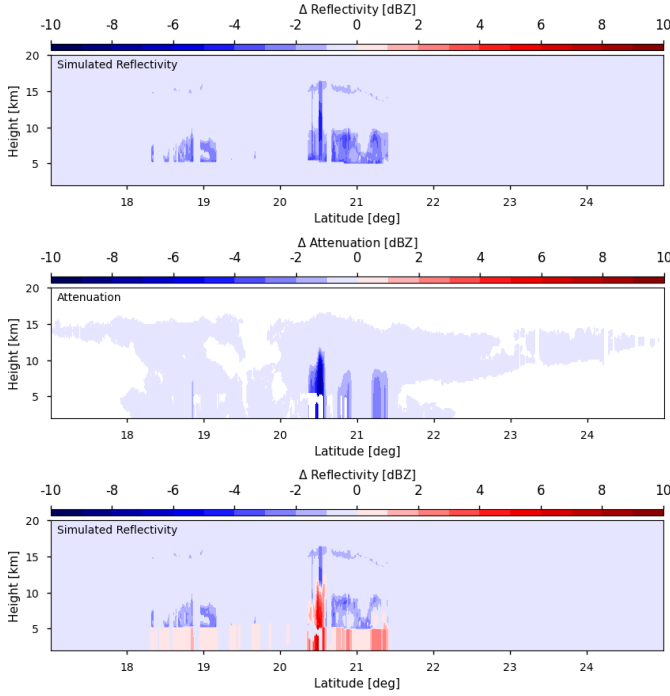


Fig. 10. The impact of the hydrometeor shape used to prescribe snow water content in RT calculations for Typhoon Nida on November 30, 2009, at 04:18:00 UTC. The top panel shows the difference between non-attenuated reflectivities simulated using sector snowflake and eight-column aggregate. The middle panel shows the difference between computed attenuation using the two shapes. The lower panel shows the difference in attenuated reflectivities using the two shapes, which is the combined impact from the top and middle panels.

to separately derive the AD and TL for the backscattering coefficient, transmittance, and reflectivity.

A. Backscattering coefficient

The tangent linear expression of Equation 10 can be defined as follows:

$$\begin{aligned} \psi &= \psi & \implies \partial\psi &= \partial\psi \\ k_b &= k_b & \implies \partial k_b &= \partial k_b \\ \kappa_b &= \psi k_b & \implies \partial \kappa_b &= \psi \partial k_b + k_b \partial \psi \end{aligned} \quad (11)$$

This system of linear equations can be expressed in a matrix form as follows:

$$\begin{bmatrix} \partial\psi \\ \partial k_b \\ \partial \kappa_b \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ k_b & \psi & 0 \end{bmatrix} \begin{bmatrix} \partial\psi \\ \partial k_b \\ \partial \kappa_b \end{bmatrix} \quad (12)$$

The AD matrix can be derived by transposing the TL matrix and switching the TL operator (∂) to the AD operator (∂^*):

$$\begin{bmatrix} \partial\psi^* \\ \partial k_b^* \\ \partial \kappa_b^* \end{bmatrix} = \begin{bmatrix} 1 & 0 & k_b \\ 0 & 1 & \psi \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \partial\psi^* \\ \partial k_b^* \\ \partial \kappa_b^* \end{bmatrix} \quad (13)$$

This will yield the following system of equations for the adjoint of backscattering that can be used for developing the corresponding AD code:

$$\begin{aligned} \partial\psi^* &= \partial\psi^* + k_b \partial \kappa_b^* \\ \partial k_b^* &= \partial k_b^* + \psi \partial \kappa_b^* \\ \partial \kappa_b^* &= 0 \end{aligned} \quad (14)$$

B. Transmittance

The transmittance is computed based on the optical depth that itself is integrated from the top of the atmosphere (or instrument location) to the target volume of the air or layer in a given profile. Since CRTM profiles are sorted from top to bottom thus we start from TOA (index 1) to the given layer n . Since we calculate the reflectivity for all layers, this process needs to be repeated for all the layers in a given profile. Given the general rule of derivation that $\partial e^u / \partial x = u' e^u$, thus for the transmittance at layer k (Γ_k), $u' = -2\partial\tau_1 - 2\partial\tau_2 \cdots - 2\partial\tau_k$, and then $\partial\Gamma_k$ can be expressed as follows:

$$\partial\Gamma_k = \exp\left(-2\sum_{i=1}^k \tau_i\right) \left[-2\sum_{i=1}^k \partial\tau_i\right] = -2\Gamma_k \sum_{i=1}^k \partial\tau_i \quad (15)$$

Therefore the adjoint of the transmittance can be expressed as a system of linear equations as follows:

$$\begin{aligned} \tau_1 &= \tau_1 & \implies \partial\tau_1 &= \partial\tau_1 \\ \tau_2 &= \tau_2 & \implies \partial\tau_2 &= \partial\tau_2 \\ &\vdots & & \vdots \\ \tau_k &= \tau_k & \implies \partial\tau_k &= \partial\tau_k \\ \Gamma_k &= \exp\left(-2\sum_{i=1}^k \tau_i\right) & \implies \partial\Gamma_k &= -2\Gamma_k (\partial\tau_1 + \partial\tau_2 \cdots + \partial\tau_k) \end{aligned} \quad (16)$$

The tangent linear matrix can again be constructed from these equations as follows:

$$\begin{bmatrix} \partial\tau_1 \\ \partial\tau_2 \\ \vdots \\ \partial\tau_k \\ \partial\Gamma_k \end{bmatrix} = \begin{bmatrix} 1 & 0 & \cdots & 0 & 0 \\ 0 & 1 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 1 & 0 \\ -2\Gamma_k & -2\Gamma_k & \cdots & -2\Gamma_k & 0 \end{bmatrix} \begin{bmatrix} \partial\tau_1 \\ \partial\tau_2 \\ \vdots \\ \partial\tau_k \\ \partial\Gamma_k \end{bmatrix} \quad (17)$$

The adjoint of transmittance can be computed by transposing the tangent linear matrix and converting the TL operators to the AD operators:

$$\begin{bmatrix} \partial\tau_1^* \\ \partial\tau_2^* \\ \vdots \\ \partial\tau_k^* \\ \partial\Gamma_k^* \end{bmatrix} = \begin{bmatrix} 1 & 0 & \cdots & 0 & -2\Gamma_k \\ 0 & 1 & \cdots & 0 & -2\Gamma_k \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 1 & -2\Gamma_k \\ 0 & 0 & \cdots & 0 & 0 \end{bmatrix} \begin{bmatrix} \partial\tau_1^* \\ \partial\tau_2^* \\ \vdots \\ \partial\tau_k^* \\ \partial\Gamma_k^* \end{bmatrix} \quad (18)$$

This AD matrix can be expanded into its components for the purpose of code development as follows:

$$\begin{aligned} \partial\tau_1^* &= \partial\tau_1^* - 2\Gamma_k \partial\Gamma_k^* \\ \partial\tau_2^* &= \partial\tau_2^* - 2\Gamma_k \partial\Gamma_k^* \\ &\vdots \\ \partial\tau_k^* &= \partial\tau_k^* - 2\Gamma_k \partial\Gamma_k^* \\ \partial\Gamma_k^* &= 0 \end{aligned} \quad (19)$$

Iter	R (dBZ)	R _{pert} -R	R_TL	WC _{pert}	Ratio	-	R	R _{pert} -R	R_TL	WC _{pert}	Ratio
1	28.425	1.76091259056	2.17147240952	2.50000000000	0.18906978378	1	28.425	-3.08129300945	-2.17147240952	-2.50000000000	-0.41898787014
2	28.425	0.96910013008	1.08573620476	1.25000000000	0.10742579474	2	28.425	-1.24938736608	-1.08573620476	-1.25000000000	-0.15072828981
3	28.425	0.51152522447	0.54286810238	0.62500000000	0.05773571475	3	28.425	-0.57991946978	-0.54286810238	-0.62500000000	-0.068225114100
4	28.425	0.26328938722	0.27143405119	0.31250000000	0.0300605094	4	28.425	-0.28028723600	-0.27143405119	-0.31250000000	-0.03261633820
5	28.425	0.13363961558	0.13571702559	0.15625000000	0.01530692266	5	28.425	-0.13788284486	-0.13571702559	-0.15625000000	-0.01595834607
6	28.425	0.06733382659	0.06785851280	0.07812500000	0.00773206170	6	28.425	-0.06839424530	-0.06785851280	-0.07812500000	-0.00789484596
7	28.425	0.0339740651	0.03392925640	0.03906250000	0.00388602342	7	28.425	-0.03406248692	-0.03392925640	-0.03906250000	-0.00392671501
8	28.425	0.01693158019	0.01696462820	0.01953125000	0.00194805359	8	28.425	-0.01699784878	-0.01696462820	-0.01953125000	-0.00195822621
9	28.425	0.00847404136	0.00848231410	0.00976562500	0.00097529279	9	28.425	-0.00849060841	-0.00848231410	-0.00976562500	-0.00097783593
10	28.425	0.00423908752	0.00424115705	0.00488281250	0.00048796359	10	28.425	-0.00424322928	-0.00424115705	-0.00488281250	-0.00048859937
11	28.425	0.00212006097	0.00212057852	0.00244140625	0.00024406118	11	28.425	-0.00212109641	-0.00212057852	-0.00244140625	-0.00024422013
12	28.425	0.00106015985	0.00106028926	0.00122070312	0.00012205045	12	28.425	-0.00106041871	-0.00106028926	-0.00122070312	-0.00012209019
13	28.425	0.00053011228	0.00053014463	0.00061035156	0.00006103019	13	28.425	-0.00053017699	-0.00053014463	-0.00061035156	-0.00006104012
14	28.425	0.00026506423	0.00026507232	0.00030517578	0.00003051634	14	28.425	-0.00026508041	-0.00026507232	-0.00030517578	-0.00003051882
15	28.425	0.00013253414	0.00013253616	0.00015257899	0.00001525849	15	28.425	-0.00013253818	-0.00013253616	-0.00015258789	-0.00001525909
16	28.425	0.00006626757	0.00006626808	0.00007629395	0.00000762931	16	28.425	-0.00006626858	-0.00006626808	-0.00007629395	-0.00000762946
17	28.425	0.00003313391	0.00003313404	0.00003814697	0.00000381466	17	28.425	-0.00003313404	-0.00003313404	-0.00003814697	-0.00000381476
18	28.425	0.00001656699	0.00001656702	0.00001907349	0.00000190717	18	28.425	-0.00001656705	-0.00001656702	-0.00001907349	-0.00000190738
19	28.425	0.00000828350	0.00000828351	0.00000953674	0.00000095332	19	28.425	-0.00000828352	-0.00000828351	-0.00000953674	-0.00000095395
20	28.425	0.00000414175	0.00000414175	0.00000476837	0.00000047768	20	28.425	-0.00000414176	-0.00000414175	-0.00000476837	-0.00000047617

TABLE I

TL/FWD TEST FOR THE ACTIVE SENSOR MODULE. THE PERTURBATION IS BOTH ADDED AND SUBTRACTED FROM THE ORIGINAL WATER CONTENT AND THE RATIO SHOULD APPROACH ZERO IN BOTH CASES.

TL	AD	TL-AD /TL
-4.3998822007	-4.3998822007	0.0000000000
-5.1525209385	-5.1525209385	-0.0000000000
-5.9051596763	-5.9051596763	-0.0000000000
-6.6577984141	-6.6577984141	-0.0000000000
-7.4104371519	-7.4104371519	0.0000000000
-8.1630758897	-8.1630758897	-0.0000000000
-8.9157146274	-8.9157146274	-0.0000000000
-9.6683533652	-9.6683533652	0.0000000000
-10.4209921030	-10.4209921030	0.0000000000
-11.1736308408	-11.1736308408	-0.0000000000
-11.9262695786	-11.9262695786	-0.0000000000
-12.6789083164	-12.6789083164	-0.0000000000
-13.4315470542	-13.4315470542	-0.0000000000
-14.1841857920	-14.1841857920	-0.0000000000
-14.9368245297	-14.9368245297	-0.0000000000

TABLE II

AD/TL TEST FOR ACTIVE SENSOR MODULE FOR SEVERAL LAYERS WITH HYDROMETEOR WATER CONTENT GREATER THAN ZERO.

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