Community Radiative Transfer Model (CRTM) For Cloud Radiance Simulation

Quanhua (Mark) Liu[1], Paul van Delst[2], Tong Zhu[3], Fuzhong Weng[1], Sid-Ahmed Boukabara[2]
1 NOAA/NESDIS Center for Satellite Applications and Research, College Park, Maryland
2 Joint Center for Satellite Data Assimilation
3. CIRA, Colorado State University

1. Introduction

The Community Radiative Transfer Model (CRTM), developed at the Joint Center for Satellite Data Assimilation, has been applied to the operational radiance assimilation in supporting of daily weather forecasting, satellite products' generation, instruments' verification, validation and monitoring. The CRTM is a sensor (or channel) based fast radiative transfer model. In the past, the CRTM was more focused on clear-sky radiance assimilation. Vertical profiles of temperature, water vapor, ozone, other trace gases, aerosols, and surface variables and emissivity model play an important role in clear-sky radiance simulations. When applying the CRTM towards all-sky radiance assimilation, the accurate inputs of cloud variables are still very challenging. This poster will discuss cloud radiance simulations in aspects of radiative transfer calculations.

1. Cloud Radiance Calculation

In addition to clear radiance calculations, user inputs of cloud variables, calculations of cloud optical properties, and radiative transfer solution are the most important components in cloud radiance assimilations. The cloud variables are cloud water content , particle size, density, fraction and ambient temperature. The calculations of cloud optical properties depend on cloud dielectric constant, algorithm, and the assumptions of particle shape and size distribution, and the mixture of ice cloud particle habits. The radiative transfer solver is the core engine to computational efficiency. In the CRTM, polarization and 3D radiative effect of clouds haven't been included because of high computational burden. In order to speed up cloud radiance simulations, cloud optical properties are computed offline and stored as a lookup table (LUT). The scattering function is expressed as polynomial series and truncated for 4, 6, 8, and 16 streams. The asymmetry factor is also stored in the LUT for a two-stream approximation. The less number (N) of streams, the faster of radiative transfer calculations. An optimal selection of the number of stream in scattering calculations is developed by Greenwald et al.

2. Cloud Optical Properties

The scattering of electromagnetic wave by atmospheric particles depends on dielectric constant of particles, particle size distributions, particle shapes and orientations. In the CRTM, we deal with spherical particles and non-spherical particles with a random orientation. The assumption is common and can simplify the optical properties to a scalar extinction and scattering coefficients and to 4 phase function elements for spheres and 6 phase function elements for non-spherical particles with a random orientation. Dielectric constant depends on electromagnetic wavelength and may also depend on temperature.

Cloud particle size changes from micrometer to centimeter. The particle size affects emission and scattering of electromagnetic waves from ultraviolet to microwave. In the CRTM, we deal with 6 cloud types: liquid, ice, hail, graupel, and snow corresponding to the densities in gcm^{-3} of 1.0, 0.9, 0.9, 0.4, and 0.1 respectively. Liquid clouds (water and rain) are assumed to be spherical water droplet and follow the size distribution given by Hansen and Travis (1974):

$$n(r) = r^{(1-3b)/b} e^{-r/ab} \quad (1)$$

where *r* is the radius of the water cloud particle, *a* is the effective radii, and *b* is the effective variance. The single-scattering properties of water droplets, including the asymmetry factor, single scattering albedo, extinction efficiency, and scattering phase function.

The following table lists cloud size parameters that used for calculating size distributions of spherical particles:

Type	Density g cm^{-3}	MW $r_{min} = 0.1\mu m$, $r_{max} = 8000\mu m$			IR/VIS/UV $r_{min} = 0.1\mu m$, $r_{max} = 500\mu m$		
		Variance of size	sphere	Non-sphere	Variance of size	sphere	Non-sphere
Liquid	1.0	0.12 (stratocumulus)	Yes		0.12 (stratocumulus)	Yes	
Rain	1.0	1/3 (Marshall-Palmer) [2]	Yes		1/3 (Marshall-Palmer)	Yes	
Ice	0.916	0.18 Nov. 1 cirrus	Yes		0.18 Nov. 1 cirrus	Yes	
Snow	0.1	1/3 (Marshall-Palmer)	Yes		1/3 (Marshall-Palmer)	Yes	
Graupel	0.4	1/3 (Marshall-Palmer)	Yes		1/3 (Marshall-Palmer)	Yes	
Hail	0.916	1/3 (Marshall-Palmer)		Yes	0.1		Yes

The density is used in the calculation of dielectric constant where air and ice are mixed.

3. Phase Function Truncation

The computational time is proportional to N^3 (the number of streams used in multiple scattering calculations). The CRTM cloud LUT contains sets of fitting coefficients for 4, 6, 8, and 16 streams to meet the different required accuracies and computational resources.

The phase function may be approximated by the forward peak part near zero degree and a truncated phase function expressed as a Legendre expansion:

$$P(\theta) \cong 2f\delta(1-\cos(\theta)) + (1-f)P_{truc}(\theta) \quad (2) \qquad \text{where } P_{truc}(\theta) = \sum_{l=0}^{M} \omega_l P_l(\theta) \quad (3)$$

Obviously, the truncation factor f depends on the truncated M streams, so called delta-M truncation. The expansion coefficients ω_l are obtained by using normalization and orthogonal condition of Legendre polynomial.

Hu et al.(2000) used the same approximation, but determine the expansion coefficients by fitting the approximate with actual phase function beyond a truncated scattering angle.

delta-M: only choose the number of stream (M); delta-fit: choose M and a truncated angle.

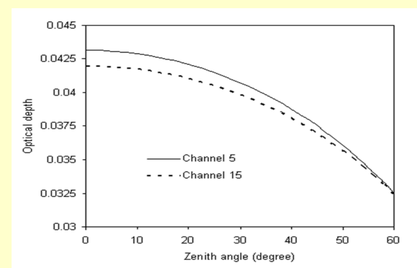
To achieve the same accuracy in multiple scattering calculations with the truncated phase functions as with the non-truncated phase functions, an adjustment must be made to the optical thickness and single-scattering albedo via the following relations:

$$\tau' = (1-f\omega)\tau, \quad (4) \qquad \omega' = \frac{(1-f)\omega}{1-f\omega} \quad (5)$$

Truncation factor and reconstructed phase function for intensity need to be positive!

4. Error Estimate between CRTM and LBL Models

In cloud multiple scattering, common radiative transfer model requires optical depth at any stream follow the cosine law of the viewing/scattering angles. Monochromatic or line-by-line model meets the condition. However, the CRTM is a sensor (or channel) based fast radiative transfer model. It is a polychromatic spectral model.



Left figure shows the CRTM computed a layer optical depth scaled to nadir for HIRS/3 channels 5 and 15. In monochromatic case, the layer optical depth should be independent from the zenith angle. The variation of the layer optical depth with zenith angles reflects the polychromatic effect.

To investigate the polynomial effect on the TOA brightness temperature, we compared the CRTM cloud radiance calculation against line-by-line calculation. Both use the same radiative transfer solver and cloud LUT.

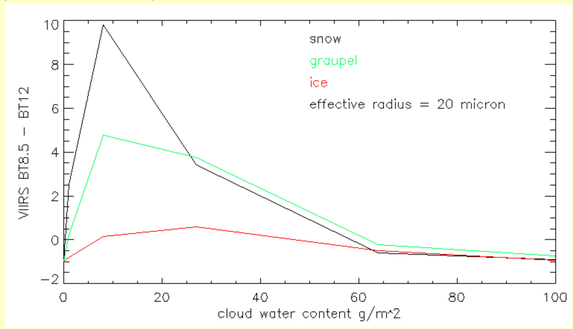
Table 2. Differences in HIRS/3 BTs between OPTRAN- and LBL in the presence of a cirrus cloud of approximately 1 km thick at an altitude of about 300 hPa. The SSA is set to 0.8 and OD is set at two different values, 2.7 and 11. The LBL calculated BTs are also listed as reference. In the table, O refers to OPTRAN-CRTM.

Chan #	0°				60°			
	OD = 2.7		OD = 11		OD = 2.7		OD = 11	
	LBL (K)	O – LBL (K)	LBL (K)	O – LBL (K)	LBL (K)	O – LBL (K)	LBL (K)	O – LBL (K)
1	239.84	-0.01	239.84	-0.01	243.28	-0.13	243.28	-0.13
2	227.92	-0.01	227.92	-0.01	231.36	0.06	231.36	0.06
3	226.10	-0.01	225.98	-0.01	227.84	0.09	227.82	0.09
4	229.86	0.00	228.28	0.01	226.93	0.10	226.47	0.10
5	239.72	-0.01	234.08	0.03	232.62	0.17	230.27	0.18
6	247.93	0.00	238.02	0.04	237.37	0.15	232.55	0.17
7	255.45	-0.03	241.45	0.02	242.99	0.19	234.82	0.21
8	275.67	0.08	253.34	0.05	260.58	0.03	240.99	0.02
9	255.65	0.18	241.89	0.05	242.63	0.26	235.81	0.33
10	267.89	0.04	247.13	0.03	252.91	0.10	238.08	0.06
11	250.75	0.01	241.00	0.00	241.86	0.19	235.80	0.13
12	234.82	-0.05	233.26	-0.04	231.21	-0.01	230.52	0.01
13	269.91	-0.26	250.27	-0.19	254.56	-0.22	237.89	-0.13
14	257.10	-0.10	242.56	-0.07	241.97	0.03	233.03	0.05
15	249.26	-0.38	238.36	-0.30	237.10	0.18	231.57	0.20
16	244.26	-0.31	235.97	-0.22	234.26	0.13	230.79	0.15
17	275.58	0.10	253.70	0.09	260.43	0.11	240.92	0.04
18	282.25	-0.02	259.99	-0.03	269.41	-0.03	244.63	-0.03
19	282.87	-0.15	261.71	-0.13	270.62	-0.08	245.71	-0.11

CRTM-OSS developed by AER has been implemented and can avoid the polynomial issue in Cloud radiance simulation.

5. Simulation of VIIRS Thermal Band for Cloud Detection

Densities of ice clouds have a large variability. The density hasn't been considered for non-spherical ice cloud yet. Because of the limitation, the CRTM model wasn't able to simulate the large difference of the brightness temperatures between VIIRS thermal channels at 8.5 µm and 12 µm. The difference between the two VIIRS channels is used to determine thin ice cloud. For clear-sky cases, the difference is usually negative. While for thin cirrus, the difference can be positive and up to about 9 Kelvin in the VIIRS measurements.



For same size distribution, the difference (BT(8.5) – BT(12)) depends on the ice density.

Non-spherical particle of density of 0.9 g/m3 is used for ice cloud (Ping Yang). It wasn't able to simulate the large difference for ice cloud.

Spherical particles of densities of 0.1 g/m3 for snow and 0.4 g/m3 for graupel are used. For snow cloud, the large difference can be simulated.

6. Discussion – What may be the criteria in phase function truncation?

Originally, the phase function truncation removes (positive truncation factor f) the strong forward peak and adjusts the optical depth and single scattering albedo (see eqs.(4) and (5)) in RT model to compensate the "loss" of the forward peak. It was found that the truncation factor can be negative and the approximate phase function can be negative, too.

Questions: 1. Should the truncation factor f be positive?
2. Should the truncated phase function positive for all scattering angles?