Efficient radiative transfer model for thermal infrared brightness temperature simulation in cloudy atmospheres

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1. Introduction

Satellite observation provides an effective way to monitor the earth-atmospheric system over regional and global scales in high spatiotemporal resolution. A forward radiative transfer model with high accuracy and computational efficiency is a critical component in the process of the cloud and gas inversion, and it can also be used to calibrate satellite instrument and evaluate numerical model. This study develops an efficient radiative transfer model (ERTM) to simulate thermal infrared (TIR) brightness temperatures observed by the Advanced Himawari Imager (AHI) onboard the Himawari-8 satellites for cloudy atmospheres.

2. Methodology

2.1 Radiative transfer calculation

For the infrared radiative transfer equation

$$\mu\frac{dI(\tau,\mu)}{d\tau}=I(\tau,\mu)-\frac{\omega}{2}\int_{-1}^{1}P(\mu,\mu')I(\tau,\mu')d\mu'-(1-\omega)B(\tau)$$

μ : cosine of zenith angle τ : the optical depth
ω : the single-scattering albedo
$B(\tau)$: the Planck function at optical depth
P : the azimuthal independent phase function

To calculate the intensity at arbitrary zenith angles in multiple layers

$$\mu\frac{dI(\tau_{1,n}+\tau,\mu)}{d\tau}=I(\tau_{1,n}+\tau,\mu)-\frac{\omega_n}{2}\sum_{l=0}^{3}\omega_{ln}P_l(\mu)\sum_{j=-2}^{2}a_jP_l(\mu_j)I(\tau_{1,n}+\tau,\mu_j)-(1-\omega_n)B_ne^{-f_n\tau}$$

where the explicit expression of $I(\tau_{1,n}+\tau,\mu_j)$ can be obtained at the Gaussian quadrature points at each atmospheric level through the analytical adding method based on the infrared invariance principle (4DDA; Zhang et al., 2016), By substituting $I(\tau_{1,n}+\tau,\mu_j)$ to the equation, the solution can be obtained.

2.2 Gaseous absorption by AMCKD

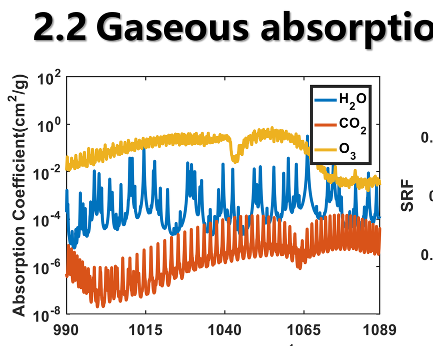

Fig 1. Absorption coefficient k (cm^2/g) as a function of wavenumber (cm^{-1}) at the reference conditions of 285 K and 1000 hPa.

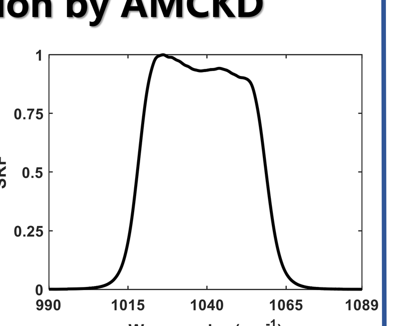

Fig 2. The instrument spectral response function of the AHI 990-1089 cm^{-1} channel (B12).

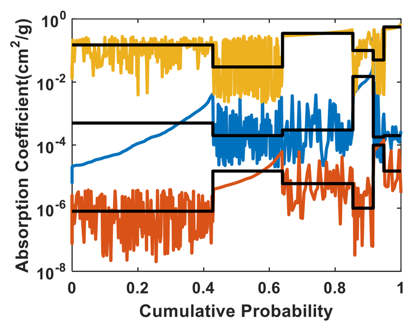

Fig 3. Rearrangements of absorption coefficients in cumulative probability space (CPS) for three gases.

The average transmittance is expressed as:

$$\mathrm{Tr}(w)=\int_0^1 e^{-wk(g)}dg=\sum_{i=1}^{N}e^{-w\langle k(g_i)\rangle}g_i$$

u: total amount of absorbent, $k(g)$:absorption coefficient, g: cumulative probability function, g_i: interval weight, α_i :correction factor,

$\langle k(g_i)\rangle=\frac{\alpha_i}{g_i}\int_{G_{i-1}}^{G_i}k(g)dg$:average absorption coefficient.

Divide the cumulative probability space (CPS) into N intervals, and select different gas sorts on each interval, and the same sorting rules are applied to the other gases in the same interval. After alternate sorting, the average transmittance is expressed as:

$$\mathrm{Tr}(w)=\sum_{i=1}^{N}e^{-(w_1\langle k_1(g_i)\rangle+w_2\langle k_2(g_i)\rangle+w_3\langle k_3(g_i)\rangle)}g_i$$

2.3 Cloud Optical Properties

The optical properties of ice cloud particles are obtained from a highly irregular ice particle model called Voronoi aggregate developed by Ishimoto et al. (2012) . The optical properties of water particle are computed through the Lorenz-Mie theory.

Taking volume extinction coefficient for example, the bulk optical properties of clouds are calculated based on Gamma distributions:

$$\beta_e=\frac{\int_{r_{min}}^{r_{max}}AQ_{ext}n(r)dr}{\int_{r_{min}}^{r_{max}}Vn(r)dr}$$

Q_{ext}:extinction efficiency β_e: extinction coefficient
$n(r)$: particle size distributions
A: cross-sectional area of particle
V: volume of particle

For particular wavelength, the fitting function of the bulk optical properties with effective radius as the independent variable:

$$\beta_e=\sum_{i=1}^{i=n}a_i r_{\mathrm{eff}}^{\alpha_i}$$

a_i : fitting coefficient r_{eff} : effective radius
α_i : fitting indice

Considering the spectral response function of AHI spectral bands and the Planck function:

$$\beta_e'=\frac{\int_{\lambda_{min}}^{\lambda_{max}}\beta_e(\lambda)srf(\lambda)B(\lambda,T)d\lambda}{\int_{\lambda_{min}}^{\lambda_{max}}srf(\lambda)B(\lambda,T)d\lambda}$$

$srf(\lambda)$: spectral response function
$B(\lambda,T)$: Planck function

2.4 Flowchart

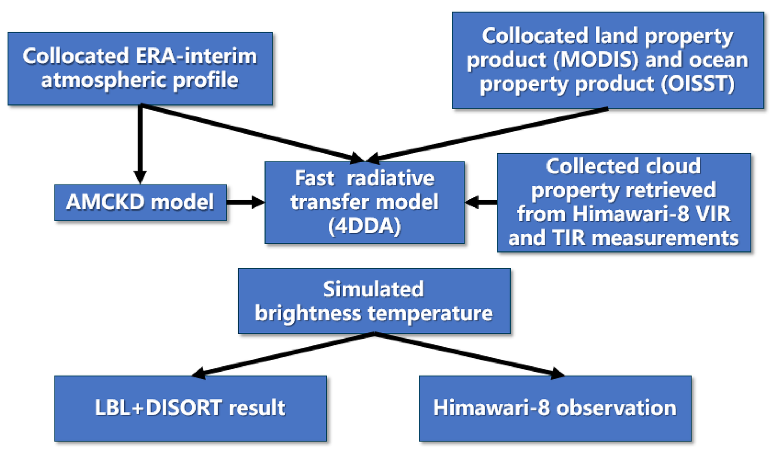

Fig4. Flow chart of the application of ERTM (AMCKD model, a cloud optical property parameterization and δ-4DDA) in the simulation of AHI observation.

The transmissivity of absorbing gases is calculated in AMCKD models taking the atmospheric profile as input. The gaseous transmissivity, cloud properties, temperature profile and surface condition is input into 4DDA radiative transfer model to generate brightness temperatures and the simulated results are compared with AHI observations and LBL+DISORT to evaluate precision and time efficiency.

3. Results and Discussion

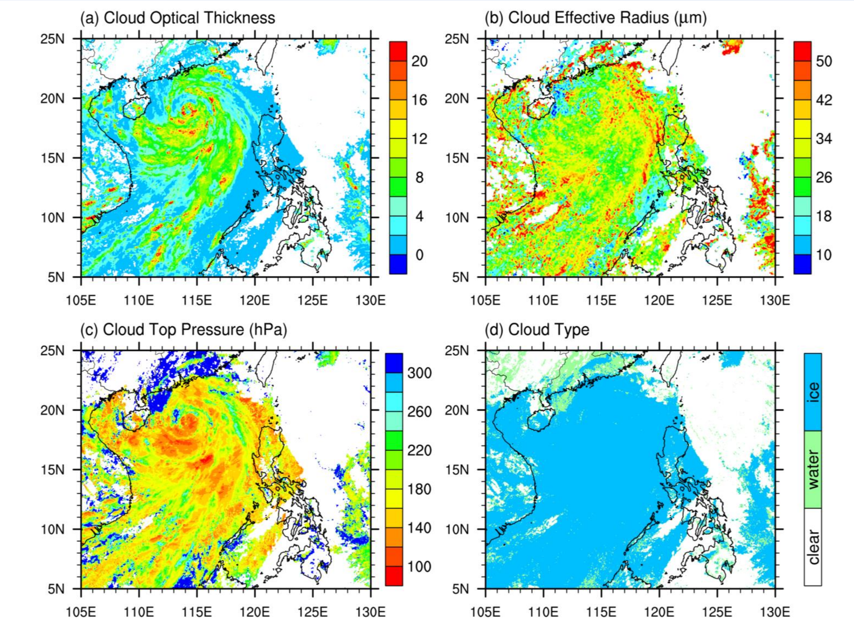

Fig 5. Cloud property for Typhoon MUJIGAE on 1 October 2015 at 6:00 UTC (a) Cloud optical thickness, (b) Cloud effective radius (μm), (c) cloud top pressure and (d) cloud type retrieved from Himawari-8 TIR measurements.

Typhoon MUJIGAE which was the strongest typhoon in 2015 is used as a case in this study. Fig 5 shows the cloud property for Typhoon MUJIGAE on 1 October 2015 at 6:00 UTC retrieved from Himawari-8 TIR measurements through the Integrated Cloud Analysis System (ICAS) (Iwabuchi et al. 2018).

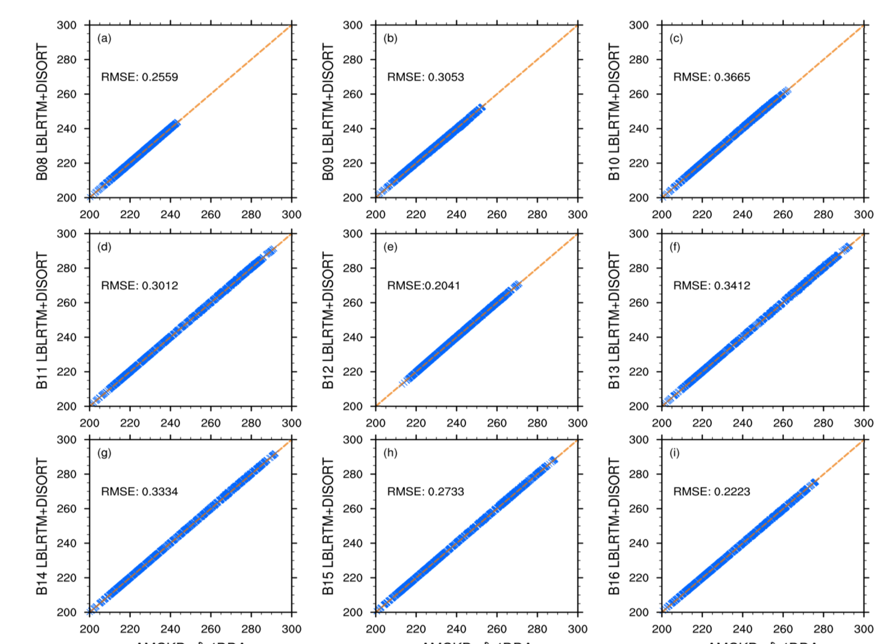

Fig. 6. Comparison between brightness temperatures simulated by ERTM and results of the benchmark model for one thousand cloudy pixels at each TIR channel.

One thousand cloudy pixels are randomly selected from the simulated region to compare the simulated BTs by ERTM with the benchmark results in the practical case. The simulations by ERTM have a high agreement with the standard results, and almost all pixels fall on the 1:1 line at each TIR channel.

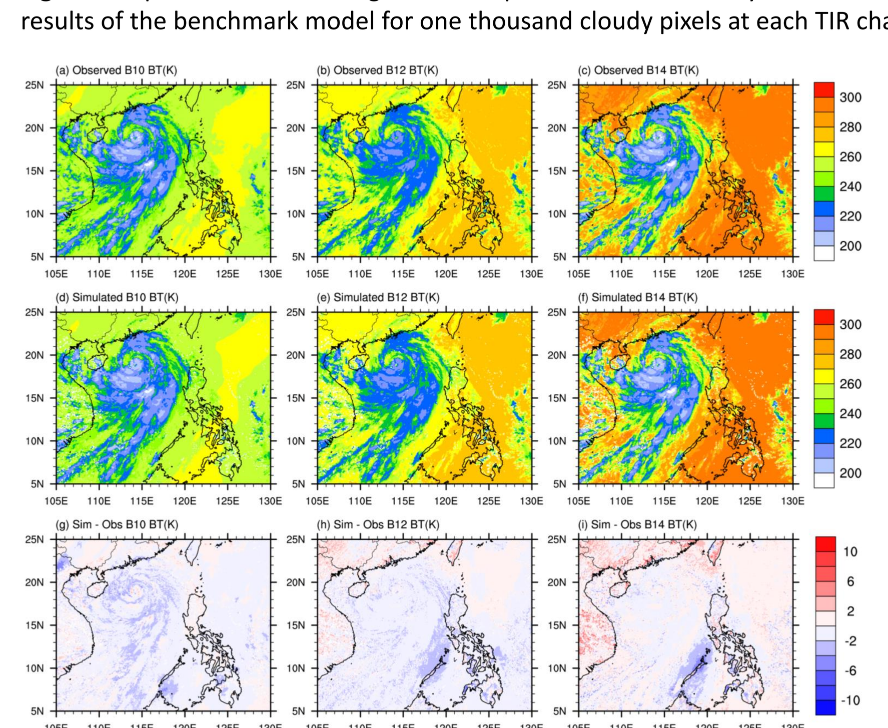

Fig. 7. Comparison between AHI observations (first row) and simulated brightness temperatures (second row) at the TIR B10 (7.35 μm) , B12 (9.63 μm), and B14 (11.24 μm) channels. The differences between AHI observations and simulated brightness temperatures are shown in the third row.

To further assess the performance of the ERTM, simulated BTs are compared with observations from AHI. Generally, the distribution pattern of observed brightness temperatures is highly consistent with that of simulated brightness temperatures, demonstrating that the ERTM has excellent capability to simulate BTs for the clear and cloudy atmosphere.

Table 1. Comparison of the runtime of ERTM, AMCKD with δ-4 DISORT, AMCKD with δ-32 DISORT, AMCKD with δ-64 DISORT, and benchmark model.

	ERTM	AMCKD + δ-4 DISORT	AMCKD + δ-32 DISORT	AMCKD + δ-64 DISORT	LBLRTM + δ-64 DISORT
Runtime	1	233	284	377	95258

4.Conclusion

- An efficient radiative transfer model (ERTM) is developed to simulate thermal infrared brightness temperatures observed by the Advanced Himawari Imager (AHI) in this study. The ERTM contains an alternate mapping correlated k-distribution method (AMCKD), a parameterization for cloud optical property, and a rapid infrared radiative transfer scheme.
- The efficiency and accuracy of ERTM are evaluated by comparing with the benchmark model which is composed of discrete ordinate radiative transfer (DISORT) and line-by-line radiative transfer model (LBLRTM). The simulated brightness temperatures by ERTM are highly consistent with the rigorous results and AHI observations in the application to the Typhoon Mujigae case. The computational efficiency of ERTM is approximately five orders of magnitude higher than that of the benchmark model.

5. Main reference

Wenwen Li, Feng Zhang, Yi-Ning Shi, Hironobu Iwabuchi, Mingwei Zhu, Jiangnan Li, Wei Han, Husi Letu, and Hiroshi Ishimoto, 2020: Efficient radiative transfer model for thermal infrared brightness temperature simulation in cloudy atmospheres, Optics Express, 28, 25730-25749.

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