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Numerical calculation of apparent IR radiation of cloud

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ABSTRACT

The infrared detection has been one of important approaches for aerial target detection, but the existence of clouds in the sky makes target detection difficult, so it is of great significance to research the features of infrared radiation of clouds. Combining Mie scattering theory, the calculation model of infrared radiation on the cloud appearance was put forward and this model mainly considered two parts including direct and scattering radiation. The calculation methods of direct radiation, primary scattering and multiple scattering were discussed in detail to put forward the specific methods for numerical computation. Based on the calculation model, cumulus was taken as the example to calculate its radiation of wave band of long-wave infrared and analyze its radiation characters. The calculation results showed that: both perpendicular incidence and scattering could make great contributions to apparent radiation of cloud and could not be ignored; as for the distribution of direction angles, the radiation of clouds decreased with increase of direction angles as a whole; in the aspect of spectrum distribution, spectral radiance feature of the clouds was complicated function of wave length. Finally, the calculation results were verified using clouds imaging experiment of which the result also effectively proved the correctness of the calculation model.

1. Introduction

The infrared detection has been one of important approaches for aerial target detection, but the existence of clouds in the sky makes target detection difficult as the clouds may disturb or shelter the aerial target [1]. Therefore, it is of great significance to research the features of infrared radiation of clouds.

The calculation of wave band of long-wave infrared (8–14 μm) are mainly carried out through gray body or black body assumption according to existing literatures, but this kind of calculation model is so simple that its calculation preciseness is low and the actual infrared radiation of clouds cannot be reflected [2–4]. Another method is to obtain the calculation method through actual test and data fitting [5] and this method can obtain relatively credible results but it lacks theoretical foundation and a general result would not be gotten owing to the significant impact caused by the environment on test. The theoretical analysis and calculation were conducted for downward radiation of clouds starting with radiation transfer equation in the literature [6], but this model failed to take scattering into consideration. What is more, there are some traditional methods, such as Monte Carlo, DISORT and matrix-operator, that could adopt to calculate the radiation of cloud, but they are too complex and their physical meanings are vague.

So the method of calculation of cloud extinction coefficient, scattering coefficient and absorption coefficient with Mie scattering would be firstly introduced in this paper; and then the method of cloud delamination would be adopted to establish a calculation model of cloud apparent radiation that classifies the radiation of clouds into two parts: direct and scattering radiation and respectively discusses the calculation methods of direct and scattering radiation; finally, the cumulus will be taken as the example on basis of calculation model of cloud appearance radiation to calculate radiance of cumulus appearance and analyze its characteristics. In this paper, unless otherwise specified, all variables are values of spectrum.

2. Mie scattering theory

The scattering properties of cumulus, stratus and other water clouds that are mainly composed of water drops can be analyzed through Mie scattering theory [7]. For the single spherical particle, Mie scattering sectional area C_s and extinction sectional area C_e can be represented as [8]:

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$$C_s = \frac{\lambda^2}{2\pi}\sum_{n=1}^{\infty}(2n+1)(|a_n|^2 + |b_n|^2) \tag{1}$$

$$C_e = \frac{\lambda^2}{2\pi}\sum_{n=1}^{\infty}(2n+1)\mathrm{Re}(a_n + b_n) \tag{2}$$

where a_n and b_n are Mie scattering coefficient; absorption sectional area can be represented as $C_\alpha = C_e - C_s$; ratio of scattering cross section area and geometric cross section area of particle is referred to as scattering efficiency factor of particle K_s.

Phase function of scattering is represented as:

$$\Phi(\theta, a) = \frac{2(i_1 + i_2)}{K_s a^2} \tag{3}$$

where i_1 and i_2 are scattered radiant intensity function; a is dimension parameter of scattering particles and $a = 2\pi r/\lambda$; r is cloud droplet radius and λ is wave length of incident light.

As for the particle swarm with specific particle distribution characteristics, the computation expression of scattering phase function is [8]:

$$\Phi(\theta, a) = \frac{\lambda^2}{\pi^2} \cdot \frac{\int_{r_1}^{r_2} n(r)\frac{i_1+i_2}{2}dr}{\int_{r_1}^{r_2} n(r)K_s dr} \tag{4}$$

Therein $n(r)$ is radius distribution function of particles. Assume particle number density of a scattering group containing single particles is N_s, then the scattering coefficient is defined as [9]:

$$\sigma_s(\lambda) = C_s N_s \tag{5}$$

Then for the radius scattering particle swarm containing non-single particles, the scattering coefficient can be:

$$\sigma_s(\lambda) = \int_{r_1}^{r_2} C_s n(r) dr \tag{6}$$

The unit of scattering coefficient σ_s is m^{-1}.

In the same way, extinction coefficient σ_e and absorption coefficient σ_α can be obtained through calculation.

$$\sigma_e(\lambda) = \int_{r_1}^{r_2} C_e n(r) dr \tag{7}$$

$$\sigma_\alpha(\lambda) = \sigma_e(\lambda) - \sigma_s(\lambda) \tag{8}$$

Take cumulus as the example, according to Gamma distribution of its particle size [10,11], σ_e, σ_α and σ_s at 8 μm are respectively 0.1705 m^{-1}, 0.0485 m^{-1} and 0.1221 m^{-1} through Mie scattering theory and the phase functions are shown in Fig. 1.

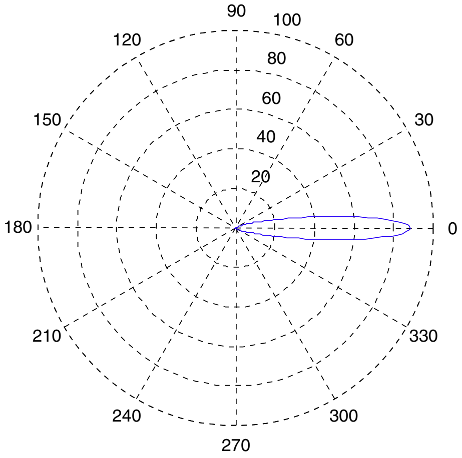

Fig. 1. Directional diagram of scattering phase function.

3. Modeling of cloud apparent radiation

3.1. Direct radiation of cloud

The radiance of clouds at any θ directions should contain: self-emitted radiation of cloud at gazing direction, i.e. direct radiation; incident radiation from other directions that scattered into the gazing direction by the cloud at gazing direction i.e. scattering radiation. The shape of cloud is assumed to be oblate cuboid with sufficient width [12] as shown in Fig. 2. The clouds will be divided into N layers equally of which the temperature and particles distribution are approximately uniform and the thickness of every layer is Δh.

The radiance of direct radiation can be obtained easily and its expression is:

$$L_d(\theta) = \sum_{n=1}^{N}\varepsilon_n(\theta)L_b(T_n)\prod_{K=1}^{n-1}\tau_K(\theta) \tag{9}$$

Therein $\varepsilon_n(\theta)$ is emissivity of the cloud at No. n layer at θ direction; T_n is temperature of cloud at No. n layer; $L_b(T_n)$ is the radiance of black body with temperature of T_n; $\tau_K(\theta)$ is transmittance of the cloud at No. k at θ direction. The expression of transmittance can be obtained through Lambert's law:

$$\tau_K(\theta) = \exp[-(\sigma_s + \sigma_e)\Delta s/\cos(\theta)] \tag{10}$$

The existing literatures had different expressions about the calculation of emissivity. A simple derivation will be conducted for emissivity terms as follows. As shown in Fig. 3, the vertically incident radiation with power $P(0, 0)$ will attenuate after transmitting the clouds and after the distance h, radiant power of original radiation is:

$$P(0,h) = P(0,0)\exp(-\sigma_e h) \tag{11}$$

Owing to concurrence of radiation absorption and scattering, the attenuating radiation is neither completely absorbed nor scattered but the absorption and scattering will occupy a part respectively and concur. Then the absorbed radiation at distance traveled dh at h can be represented as:

$$dP_\alpha(0,h) = P(0,h)\sigma_\alpha dh = P(0,0)\sigma_\alpha\exp(-\sigma_e h)dh \tag{12}$$

The absorbed radiation at H path through integration of 0–H is:

$$\begin{aligned} P_\alpha(0,H) &= \int_0^H P(0,0)\sigma_\alpha\exp(-\sigma_e h)dh \\ &= \frac{\sigma_\alpha}{\sigma_e}P(0,0)[1-\exp(-\sigma_e H)] \end{aligned} \tag{13}$$

In a similar way, the scattered energy $P_s(0, H)$ is:

$$\begin{aligned} P_s(0,H) &= \int_0^H P(0,0)\sigma_s\exp(-\sigma_e h)dh \\ &= \frac{\sigma_s}{\sigma_e}P(0,0)[1-\exp(-\sigma_e H)] \end{aligned} \tag{14}$$

We can find that $P_\alpha(0, H)$, $P_s(0, H)$ meet:

$$\frac{P_\alpha(0,H)}{P_s(0,H)} = \frac{\sigma_\alpha}{\sigma_s} \tag{15}$$

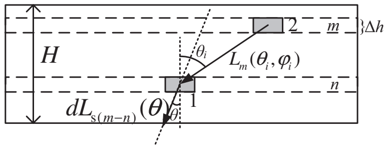

Fig. 2. Schematic diagram of radiation model.