TURBULENCE EFFECT ON RADIATIVE TRANSFER IN CLOUDS

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ABSTRACT

The effect of turbulent clustering of water droplets on radiative transfer is investigated by means of a three-dimensional direct numerical simulation (DNS) for particle-laden homogeneous isotropic turbulence and a radiative transfer simulation based on a Monte Carlo photon tracing method. Two kinds of radiations, namely visible and infrared radiations are considered. The former is not absorbed by droplets, while the latter is partially absorbed. The results show that the turbulent clustering does not influence the total transmittance of visible radiation, while it increases the total transmittance of infrared radiation. This is because the clustering of droplets allows more photons to pass through without being scattered than the random dispersion of droplets. The effect of clustering on radiative transfer decreases as the turbulent Reynolds number increases, and as the Stokes number decreases.

INTRODUCTION

Clouds have a large impact on the radiative heat budget on the earth. For reliable predictions of climate change, therefore, cloud radiation must be evaluated accurately. However, we still have many uncertainties in cloud radiation processes. For example, effect of turbulence on cloud radiation has not been well understood. Cloud turbulence forms inhomogeneous distribution of water droplets, often referred to as turbulent clustering or preferential concentration. The effect of turbulent clustering on radiative transfer has been discussed theoretically by a few researchers (Kostinski, 2001; Kostinski, 2002; Borovoi, 2002; Mishchenko, 2006), but has not been clarified yet. This is because their conclusions were brought by the estimates on the spatially-correlated particle distributions, which are based on some assumptions. The purpose of this study is, therefore, to investigate the effect of turbulent clustering of droplets on radiative transfer based on the particle distribution obtained from physics-based simulations.

COMPUTATIONAL METHOD

In this study, direct numerical simulations (DNS) for three-dimensional particle-laden homogeneous isotropic turbulence were performed to obtain spatial distributions of clustering droplets in turbulence. The radiative properties of the obtained media with clustering droplets were calculated based on a Monte Carlo photon tracing method.

The governing equations of the air turbulence in the DNS are the equation of continuity and the incompressible Navier-Stokes equation. The forth-order central finite-difference was used for advection and viscous terms. HSMAC method (Hirt and Cook, 1972) was applied for reducing computational cost.

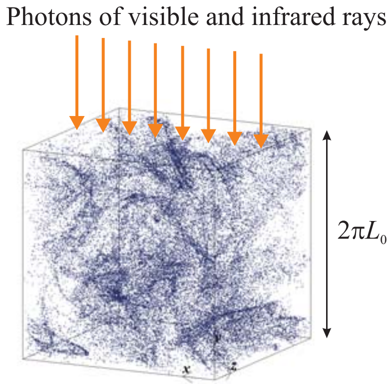

Figure 1. Schematic of computational domain.

The second-order Runge-Kutta method was used for time evolution. Steady turbulence was formed by applying the external force which keeps the intensity of large-scale eddy. The reduced-communication forcing (Onishi et al., 2011a), which can suppress the computational cost arising from the domain decomposition for parallel computing, was used for the external forcing.

The droplet motions were calculated by the Lagrangian tracking method. The governing equation of the motion is

$$\frac{dv_i}{dt} = -\frac{v_i - u_i}{\tau_p}, \tag{1}$$

where u_i is the fluid velocity, v_i the droplet velocity, and τ_p the droplet relaxation time. Droplets were assumed as Stokes particles, whose relaxation time τ_p is given as

$$\tau_p = \frac{\rho_p}{\rho_g} \frac{2r^2}{9\nu}, \tag{2}$$

where r is the droplet radius, ρ_p the water density, ρ_g the air density, and ν the kinematic viscosity. Isotropic air turbulence and droplet motions were simulated in a cubic domain of length $2\pi L_0$ (Onishi et al., 2011b), where L_0 is the representative length scale (Figure 1). Periodic boundary conditions were applied in all three directions.

The DNS was performed for two air flow conditions. Table 1 lists the computational conditions and flow properties including the RMS value of velocity fluctuation u', the Kolmogorov length scale l_η, and the turbulent Reynolds number based on the Tayler microscale Re_λ. The numbers of grid points were set to 64^3 in a low Reynolds number case, while 1000^3 in a high Reynolds number case. In both cases, the droplets were distributed randomly in the domain after the turbulence was fully developed. The droplet radius was set to 20 and 10 μm so that the Stokes number St ($= \tau_p/\tau_\eta$, where τ_η is the Kolmogorov time scale) was close to unity and 0.25, respectively. In order to keep the volume fraction of droplets, the droplets were considered to have elastic collisions.

The radiative transfer properties for the media with clustering droplets were obtained by using a Monte Carlo photon tracing method, where behaviors of a number of photons were traced stochastically. In a conventional Monte Carlo photon tracing method (Macke et al., 1999), a free path length of a photon is determined stochastically by the Beer-Lambert law. On the other hand, in our Monte Carlo photon tracing method, geometrical collisions between photons and individual droplets were taken into account. A photon was assumed to collide with a droplet closest to the photon among droplets which satisfy the following criteria:

Table 1. Numerical conditions and flow properties performed by DNS.

	L_0[m]	u'[m/s]	$l_\eta[\times 10^{-4}\mathrm{m}]$	Re_λ[-]
Low Re_λ	0.0050	0.20	2.69	54.3
High Re_λ	0.0659	0.50	2.73	340

$$\left|(\mathbf{x}_p - \mathbf{x}_0) \times \mathbf{k}\right| < r_{ext}, \tag{3}$$
$$(\mathbf{x}_p - \mathbf{x}_0) \cdot \mathbf{k} > 0. \tag{4}$$

Here, $\mathbf{x}_0$ and $\mathbf{x}_p$ are the positions of the photon and droplet. $\mathbf{k}$ is the unit traveling direction vector of photon. r_{ext} is the droplet extinction radius, which we defined as $r_{ext} = \sqrt{\sigma_{ext}/\pi}$, where σ_{ext} is the extinction cross section.

Absorption by droplets was taken into acount by using a weight $w^{(m)}$ proportional to the radiative power of each photon, where the superscript $^{(m)}$ indicates the order of collision. On a collision of order $m+1$, the weight was scaled as $w^{(m+1)} = \omega w^{(m)}$, and the photon was scattered with the weight $w^{(m+1)}$. Here, ω is the single scattering albedo of the droplet, which is defined as the ratio of the scattering cross section σ_{scat} to the extinction cross section σ_{ext}. The direction of the scattered photon was determined by the scattering angle θ and azimuth angle ϕ. The scattering angle θ was chosen based on the scattering phase function $p(\theta)$, while the azimuth angle ϕ was chosen randomly.

Photons were radiated downward ($-y$ direction) from random positions on the top boundary of the domain. Periodic boundary conditions for photon movement were applied in x- and z-directions. The photons were traced until they leave the domain from the top or bottom boundary or their weights $w^{(m)}$ become smaller than 10^{-9} due to the absorption.

In this study, radiative transfer was calculated for the wavelengths of λ=0.5 μm and 3.0 μm. The former is a visible radiation, which is not absorbed by droplets, while the latter a infrared radiation, which is partially absorbed by droplets. The extinction cross section σ_{ext}, single scattering albedo ω, and scattering phase function $p(\theta)$ for these wavelengths were obtained from the Mie scattering theory (Bohren and Huffman, 1983). In this study, absorption by gases was ignored for simplification. For reference, radiative transfer was also simulated for random dispersion of droplets.

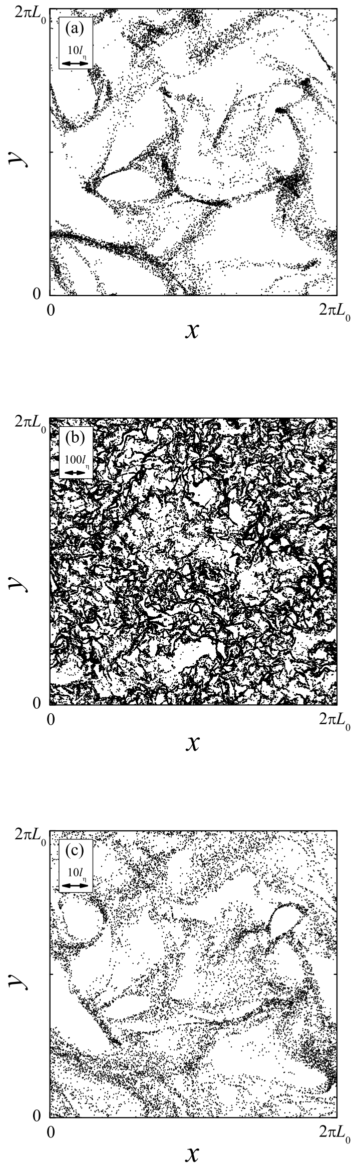

Figure 2. Droplet distributions within the range of $\pi L_0 - 2l_\eta < z < \pi L_0 + 2l_\eta$: (a) $\mathrm{Re}_\lambda = 54.3$, $\mathrm{St} = 1$; (b) Re_λ=340, $\mathrm{St} = 1$; (c) $\mathrm{Re}_\lambda = 54.3$, $\mathrm{St} = 0.25$.

RESULTS AND DISCUSSIONS

Spatial Distribution of Droplets

Fig. 2 shows the spatial distributions of droplets within the range of $\pi L_0 - 2l_\eta < z < \pi L_0 + 2l_\eta$ obtained from the three cases of DNS. Turbulent clustering is observed in the all calculated cases, but the droplets of $\mathrm{St} = 0.25$ are less concentrated in clusters than that of $\mathrm{St} = 1$. Furthermore, in the cases of $\mathrm{St} = 1$, the relative cluster size to the domain depends on Re_λ: The ratio of cluster size to the domain size in the high Reynolds number case is smaller than that in the low Reynolds number case.

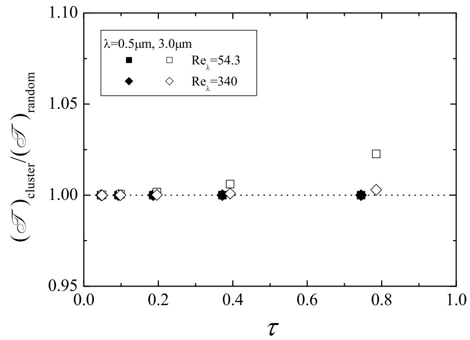

Figure 3. Effect of turbulent Reynolds number on transmittance for $\mathrm{St} = 1$.

Effect of Reynolds Number on Radiative Properties

The radiative properties, which include the transmittance $\mathscr{T}$, reflectance $\mathscr{R}$, and absorptance by droplets $\mathscr{A}_\mathrm{p}$, were evaluated. These radiative properties satisfy

$$\mathscr{T} + \mathscr{R} + \mathscr{A}_\mathrm{p} = 1. \tag{5}$$

The radiative properties of a medium with randomly-dispersed droplets are determined by the wavelength λ and the optical depth τ, which is given by the following equation:

$$\tau = \sigma_\mathrm{ext} n_\mathrm{p} \Delta y, \tag{6}$$

where n_p is the droplet number density and Δy is the depth of the cloud. In this simulation, Δy is equal to the depth of computational domain, that is $\Delta y = 2\pi L_0$. The values of the radiative properties are obtined for several values of optical depth τ, which were set by changing the droplet number density n_p.

Fig. 3 shows the ratio of transmittance of the media with clustering droplets of $\mathrm{St} = 1$ to that with randomly-dispersed droplets. Turbulent clusering does not affect the transmittance of visible radiation. On the other hand, Turbulent clusering enhances the transmittance of infrared radiation with increasing the optical depth τ. Fig. 4 shows the ratio of absorptance of infrared radiation of the media with clustering droplets of $\mathrm{St} = 1$ to that with randomly-dispersed droplets. Turbulent clustering suppresses the absorptance by clustering droplets with increasing τ. However, the enhancement of transmission and suppression of absorptance are smaller in the high Reynolds number case than in the low Reynolds number case.

In order to clarify the reason of the changes in radiative properties of infrared radiation, the relation between the transmission and the scattering by droplets are investigated. The transmittance $\mathscr{T}$ consists of diffuse transmittance $\mathscr{T}_\mathrm{diffuse}$ and direct transmittance $\mathscr{T}_\mathrm{direct}$. $\mathscr{T}_\mathrm{diffuse}$ and $\mathscr{T}_\mathrm{direct}$ are the portions of the radiation passing through the medium with and without being scattered, respectively. Figure 5 shows the ra-

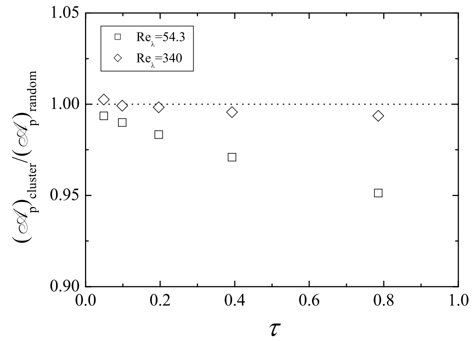

Figure 4. Effect of turbulent Reynolds number on absorptance of infarared radiation for $\mathrm{St} = 1$.

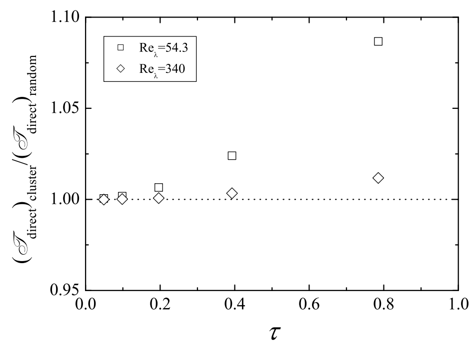

Figure 5. Effect of turbulent Reynolds number on direct transmittance of infrared radiation for $\mathrm{St} = 1$.

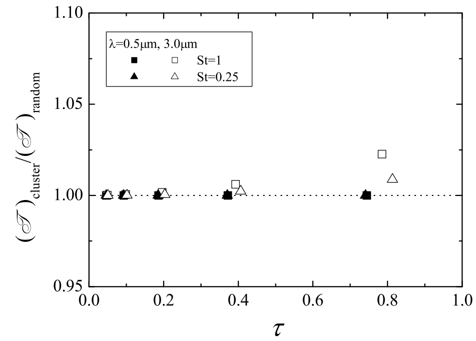

Figure 6. Effect of Stokes number on transmittance for $\mathrm{Re}_\lambda = 54.3$.

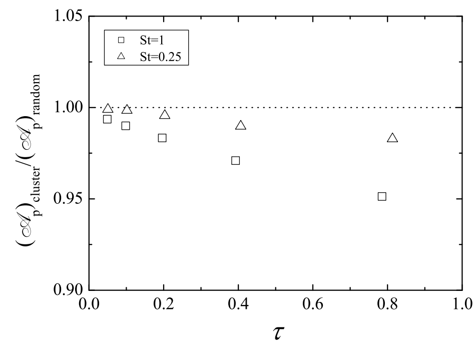

Figure 7. Effect of Stokes number on absorptance of infrared radiation for $\mathrm{Re}_\lambda = 54.3$.

tio of the direct transmittance of infrared radiation of the media with clustering droplets for $\mathrm{St} = 1$ to that with randomly-dispersed droplets. The ratio $(\mathscr{T}_{\mathrm{direct}})_{\mathrm{cluster}}/(\mathscr{T}_{\mathrm{direct}})_{\mathrm{random}}$ is larger than unity, and increases as τ increases. This result indicates that more photons are allowed to pass through without being scattered in the media with clustering droplets than in the media with randomly-dispersed droplets. The enhancement of transmittance is due to the increase of photons transmitting without being scattered, and the suppression of absorptance is due to the decrease of photons colliding with droplets. $(\mathscr{T}_{\mathrm{direct}})_{\mathrm{cluster}}/(\mathscr{T}_{\mathrm{direct}})_{\mathrm{random}}$ is closer to unity in the high Reynolds number case than in the low Reynolds number case. This is because the ratio of the cluster size to the domain size in the high Reynolds number case is smaller than that in the low Reynolds number case, and the spatial distribution of droplets is closer to the random dispersion.

Effect of Stokes Number on Radiative Properties

Figures 6 and 7 show the ratios of transmittance and absorptance of the media with clustering droplets of $\mathrm{Re}_\lambda = 54.3$ to that with randomly-dispersed droplets, respectively. As well as the case of $\mathrm{St} = 1$, turbulent clusering does not affect the transmittance of visible radiation, but enhances the transmittance of infrared radiation in the case of $\mathrm{St} = 0.25$. However, the increment of transmittance for $\mathrm{St} = 0.25$ is smaller than that for $\mathrm{St} = 1$. The absorptance by clustering droplets of $\mathrm{St} = 0.25$ is also suppressed by turbulent clustering, but the suppression of absorptance is smaller than that of $\mathrm{St} = 1$.

The changes in radiative properties of infrared radiation are due to the increase of photons transmitting without being scattered. Figure 8 shows the ratio of the direct transmittance of infrared radiation of the media with clustering droplets for $\mathrm{Re}_\lambda = 54.3$ to that with randomly-dispersed droplets. Increment of $(\mathscr{T}_{\mathrm{direct}})_{\mathrm{cluster}}/(\mathscr{T}_{\mathrm{direct}})_{\mathrm{random}}$ of $\mathrm{St} = 0.25$ is smaller than that of $\mathrm{St} = 1$. This is because concentration of droplets of $\mathrm{St} = 0.25$ is weaker than that of $\mathrm{St} = 1$. It is well-known that droplets are most concentrated when the Stokes number is close to unity. Therefore, the effect of clustering on radiative transfer also decreases as the Stokes number decreases from unity.

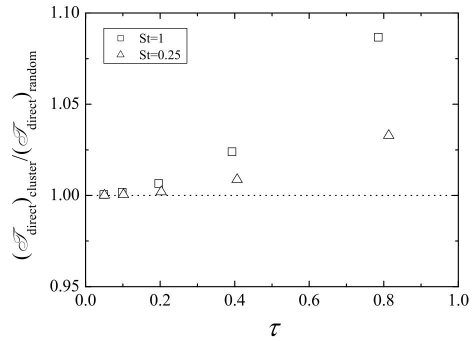

Figure 8. Effect of Stokes number of direct transmittance of infrared radiation for $\mathrm{Re}_\lambda = 54.3$.

CONCLUSIONS

The effect of clustering of droplets in turbulence on the radiative properties was investigated by means of three-dimensional DNS for particle-laden turbulence combined with radiative transfer simulations based on a Monte Carlo photon tracing method. The results show that the effect of turbulent clustering on the transmittance of visible radiation is small. They also show turbulent clustering enhances the transmittance and suppresses the absorptance of infrared radiation. This is because the clustering of droplets allows more photons to pass through without being scattered than in the random dispersion. The effect of clustering on the radiative transfer decreases as the turbulent Reynolds number increases, or as the Stokes number decreases in the range of $\mathrm{St} < 1$.

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