JP3.9

DEVELOPMENT OF LIGHT SCATTERING ALGORITHMS FOR NON-SPHERICAL CLOUD PARTICLES: APPROXIMATION AND EXACT SOLUTIONS

Takashi Y. Nakajima *
Earth Observation Research Center, NASDA , Tokyo, Japan
Teruyuki Nakajima
Center for Climate System Research, University of Tokyo, Tokyo, Japan
Yuzou Mano
Meteorological Research Institute
Kyu Yoshimori
Iwate University
Alexander A. Kokhanovsky
Bremen University

1. INTRODUCTION

It becomes more and more popular to use visible to infrared satellite-borne spectrometers such as AVHRR to investigate the current status and/or long-term trend of the warm cloud microphysical properties (optical thickness, effective radius and so on) that are still major unsolved problems of climate change. (e.g. Han et al. 1994, Nakajima and Nakajima 1995, Kawamoto et al. 2001). However, since we haven't known exact light scattering properties of non-spherical cloud particle, especially in the particle size comparable to the wavelength, it is difficult to retrieve such information of ice clouds by use of remote sensing. Thus, we are developing a non-spherical scattering solver based on Geometrical Optics Approximation (GOA) and Combined Surface Integral Equation Method of Muller Type (SIEM/M) applicable to asymmetric nonspherical particle.

2. APPLICATION OF GOA TO THE ICE CLOUD REMOTE SENSING

Figure 1 illustrates one-month mean of the optical thickness of ice cloud in 1990 retrieved from AVHRR aboard NOAA satellite. We used scattering properties of hexagonal columns obtained by a GOA approach (Kokhanovsky and Nakajima 1998) under an assumption that the scattering ice particles are much larger than wavelengths. First of all, we tried to retrieve both optical thickness and effective radius simultaneously as same method as water cloud remote sensing. However, the inversions didn't converge in the most pixels due to fatal errors in the optical parameter values of GOA especially in 3.7-micron (Channel 3 of AVHRR) and 10.8-micron (Channel 4) wavelength. Therefore, only optical thicknesses were retrieved by 0.64-micron (Channel1) wavelength. This is a limit of GOA application.

3. SIEM/M FORMULA

It was difficult to retrieve particle size and cloud top temperature of ice cloud by use of GOA results as shown in section 2. Thus, we used the Muller type Fredholm's 2nd kind formulations as a combined integral equation to calculate the exact solution of non-spherical scattering.

Corresponding author address: Takashi Y. Nakajima, Earth Observation Research Center, National Space Development Agency of Japan 1-8-10, Harumi, Chuo-ku, Tokyo 104-6023, Japan

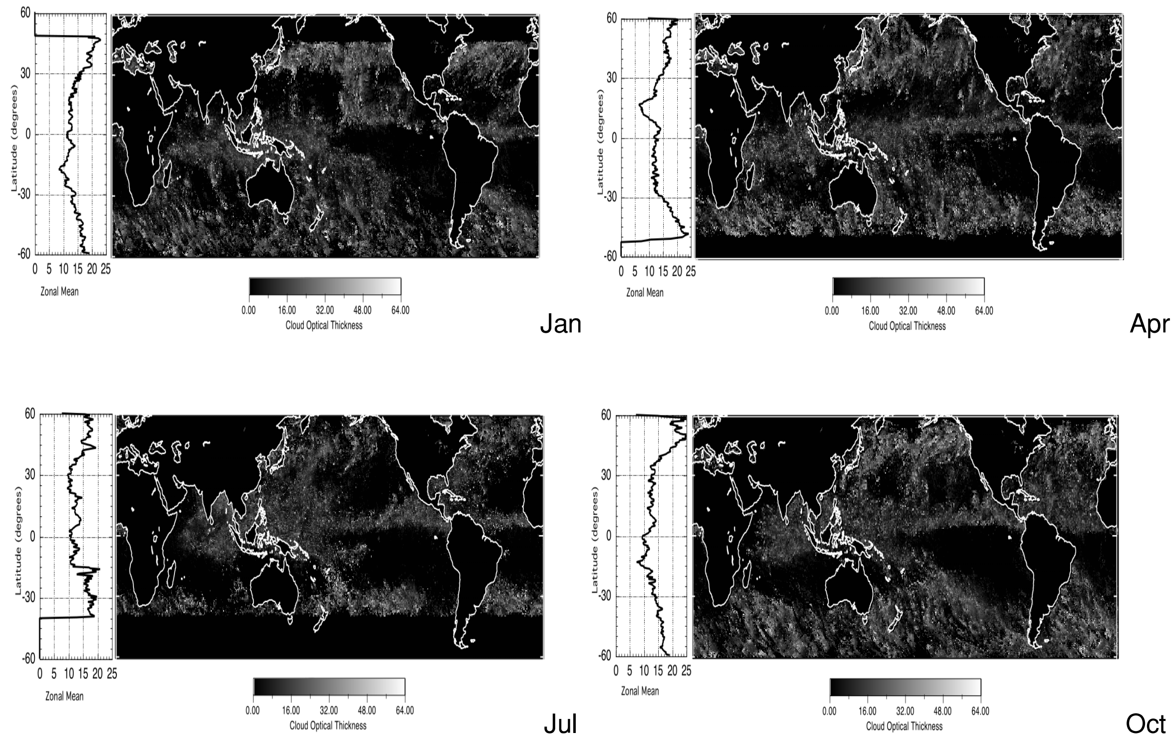


FIG.1 Monthly average of ice cloud optical thickness with optical thickness less than 64 obtained by use of GOA light scattering properties. [January, April, July, and October]

$$\mathbf{i}\times\mathbf{E}^{inc} = -\frac{1}{2}\left(\tilde{m}^2+1\right)\mathbf{K} - \mathbf{i}\times\int_s \left\{ jk_2^2\mathbf{J}\left(\tilde{m}^2G_1-G_2\right)+k_2\mathbf{K}\times\nabla'\left(\tilde{m}^2G_1-G_2\right)+j\left(\mathbf{J}\cdot\nabla'\right)\nabla'\left(G_1-G_2\right)\right\}ds' \quad (1)$$

$$\mathbf{i}\times\mathbf{H}^{inc} = \mathbf{J} - \mathbf{i}\times\int_s \left\{ jk_2^2\mathbf{K}\left(\tilde{m}^2G_1-G_2\right)-k_2\mathbf{J}\times\nabla'\left(G_1-G_2\right)+j\left(\mathbf{K}\cdot\nabla'\right)\nabla'\left(G_1-G_2\right)\right\}ds' \quad (2)$$

where, **Einc** and **Jinc** are the incident electromagnetic field, **J** and **K** is unknown electric and magnetic current on surface of the particle. **j** is the imaginary unit. $\tilde{m}$ is the relative complex refractive index of the scattering particle. **i** is the normal vector on the surface of the scattering particle. **k2** is the wavenumber of the incident electromagnetic wave. The stability of the Fredholm's 2nd kind formulations was well examined by Mano (2000).

G1 and **G2** are the Green's function of 3-dimensional Helmholts equation per the incident wavenumber **k2** for inside and outside of the scattering particle.

$$G_1(\mathbf{r},\mathbf{r}') = \frac{e^{-j\tilde{m}k_2|\mathbf{r}-\mathbf{r}'|}}{4\pi k_2|\mathbf{r}-\mathbf{r}'|}, \quad G_2(\mathbf{r},\mathbf{r}') = \frac{e^{-jk_2|\mathbf{r}-\mathbf{r}'|}}{4\pi k_2|\mathbf{r}-\mathbf{r}'|} \quad (3)$$

where, **r** and **r'** denote observation point and integration point on the surface. Once **J** and **K** are obtained by Eqs (1) and (2), scattering amplitude **F**, the scattering cross section **Cs** , and the extinction cross section **Ce** are given by,

$$\mathbf{F}(\mathbf{r}) = \frac{jk_2^2}{4\pi}\left[\mathbf{i}_r\times\xi\mathbf{i}_r\times\int_s\mathbf{J}\exp\left(jk_2\mathbf{r}'\cdot\mathbf{i}_r\right)ds'+\mathbf{i}_r\times\int_s\mathbf{K}\exp\left(jk_2\mathbf{r}'\cdot\mathbf{i}_r\right)ds'\right] \quad (4)$$

$$C_s = \frac{1}{k_2^2A_0^2}\int|F|^2 d\Omega \quad (5)$$

4. RESULTS OF RONDAMLY ORIENTED HEXAGONAL COLUMN

Figure 2 shows *Qext* obtained by the exact spherical (Mie) theory with the equivalent-volume-sphere-radius (solid curve) and by SIEM/M with homogeneous hexagonal column particles with the aspect ratio of 1.0 with small absorption by $\tilde{m}$= (1.39, -6.99x10^{-3}) corresponding 3.7-μm channel of AVHRR to ice, and randomly oriented results (squared dots) as a function of size parameter α . In Fig 2, *Qext* values are similar to the values obtained by an exact Mie code since the shape of hexagonal column with aspect ratio 1.0 is somewhat relatively similar to sphere. In size parameter α =25, the difference between Mie and SIEM/M is larger than those of less than 25 due to error

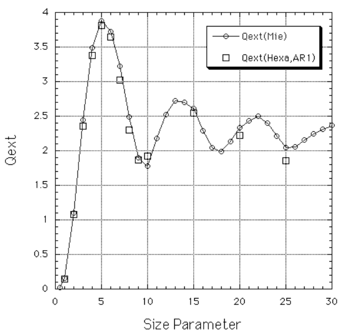


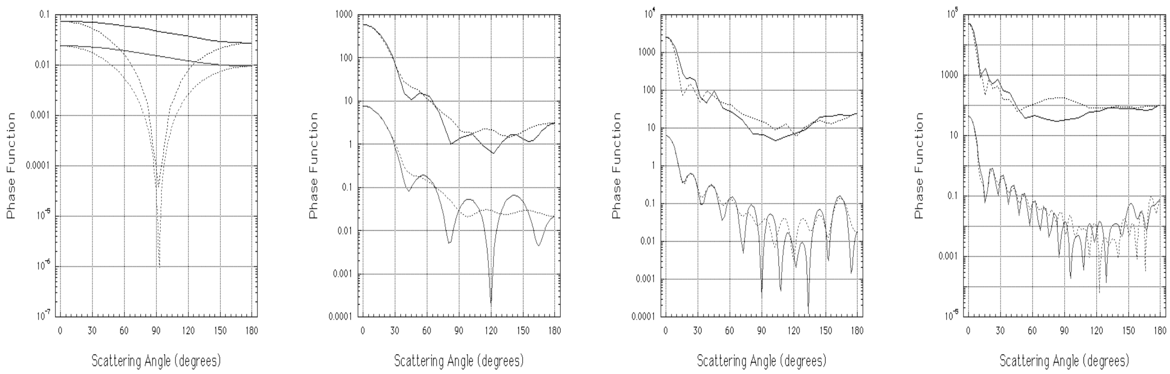
FIG.2 Extinction efficiency factors obtained from exact spherical (Mie) theory with the equivalent-volume-sphere-radius (solid curve) and from SIEM/M with the homogeneous hexagonal column particles as Fig. 4-13 except for randomly oriented results (square dots). Both results were obtained with $\tilde{m}$= (1.39, -6.99x10^{-3}) assuming 3.7-μm channel and ice particles.

in calculations which can be potentially improved by setting more number of nodes on particle surface.

Figure 3 is obtained by same calculations as Fig. 2 except for phase functions of size parameters α =1 (a), 5 (b), 10 (c) and 20 (d). We found large difference in shapes of the phase functions with larger α whereas small differences with smaller α. Fast oscillations in the phase functions appeared in the result of Mie at relatively larger α, are disappeared by merging the phase functions obtained by each randomly orientation of the hexagonal column particle, except for a noteworthy scattering angle region around 20° to 30°. This perturbation appeared in this angle region is an optical phenomenon well known as halo due to hexagonal structure of the particles. The presence of halo in 3.7-μm wavelength was predicted by the GOA results. Mishchenko and Macke (1999) investigated the phase functions of circular cylinder using T-matrix and GOA, and lead to a result that well-defined halo optical phenomena should be appeared when the size parameter of the non-spherical particle are up to hundred and more. Our results thus reveal that relatively small size parameters (such as $\alpha \approx 20$) of randomly oriented hexagonal particles could generate a small but remarkable signal of halo phenomenon. This size parameter is comparatively smaller than considered before.

Acknowledgement

The researches were partly supported by NASDA EORC GLI Science project and CREST, Japan Science and Technology Corporation.



(a) (b) (c) (d)

FIG.3 Phase function of spherical (Mie) (lower curves) and hexagonal column particles (upper curves) with size parameters of α =1 (a), 5 (b), 10 (c) and 20 (d), with an artificial offset in upper curves. Phase functions of parallel (solid curves) and perpendicular (dashed curves) to the $\mathbf{E}_{inc}$ are shown.

References

Han, Q., W. B. Rossow, and A. A. Lacis, 1994: Near-global survey of effective droplet radii in liquid water clouds using ISCCP data. *J. Climate*, 7, 465-497.

Kawamoto. K, T. Nakajima, and T. Y. Nakajima, 2001: A global determination of cloud microphysics with AVHRR remote sensing. *J. Climate*, 14, 2054-2068.

Kokhanovsky, A. A. and T. Y. Nakajima, 1998: The dependence of phase functions of large transparent particles on their refractive index and shape. *J. Phys. D: Appl. Phys.*, 31, 1329-1335.

Nakajima T. Y. and T. Nakajima, 1995: Wide-area determination of cloud microphysical properties from NOAA AVHRR measurement for FIRE and ASTEX regions. *J. Atmos. Sci.*, 52, 4043-4059.

Mano, Y., 2000: Exact solution of electromagnetic scattering by a three-dimensional hexagonal ice column obtained with the boundary-element method. *Appl. Opt.* 39, 5541-5546

Mishchenko, M. I. and A. Macke, 1999: How big should hexagonal ice crystals be to produce halos? *Appl. Opt.*, 38, 1626-162