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Effects of Temperature and Orientation on 3.2mm Radar Backscattering from Ice Crystals

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Abstract—**Millimeter wave radar signals depending on backscattering characteristics of particles and particles size distribution can be used to inverse the microphysical parameters of clouds, but ice clouds are composed of non-spherical ice crystals, so various factors of impacting on the scattering from non-spherical particles must be considered. However, there are few papers that account for the influence of temperature and orientation on the backscattering characteristics of hexagonal ice crystals with 3.2mm radar in detail. The effects are investigated by modeling the discrete dipole approximation (DDA) method in this paper. At vertical radar wave, the value of backscattering cross sections of hexagonal ice crystals with horizontal orientation (2D) is twofold more than random orientation (3D). With the antenna elevation angle increases, there is a large increase of radar cross sections for hexagonal columns, but a slight change for hexagonal plates with 2D. The contributions from orientations must be considered in calculating scattering characteristics of non-spherical ice crystals. Backscattering cross sections change slightly about 2.75% when the temperature changes from 0° to 173°. It should also be noted that aspect ratio has a large impact on radar cross sections. Such calculations can extend scattering characteristics database of ice particles. In this paper, we provide some ideas for exploring the scattering from ice crystal and theoretical basis for using the 3.2mm radar echo to inverse the characteristics of clouds.**

I. Introduction

It has been recognized that clouds play an important role in climate changes and weather modification. Ice clouds are composed of all kinds of non-spherical ice crystals so the effects of non-spherical particles on backscattering characteristics must be taken into account. Now, scattering computation for non-spherical ice crystals is still a challenging subject in the world. At current climate models, it is a common approach to apply equivalent ball Mie theory approximation for the scattering characteristics and parametric studies of ice clouds [1], [2]. Because of the scattering characteristics of particles as a function of particle sizes, temperature, shape, orientation, components and other factors, the equivalent ball Mie theory approximation obviously can't meet the needs. At present, several different computation techniques are available for scattering of ice crystals such as the discrete dipole approximation (DDA) [3]-[5], the finite difference time domain (FDTD) [6], [7], transition matrix approach (T Matrix)[8], physical-geometric optics hybrid (PGOH) method[9],[10], anomalous diffraction theory (ADT) [11] , ray-by-ray integration (RBRI) [12] and the generalized multi-particle Mie (GMM) methods. T Matrix techniques are generally used for scattering computations from a homogeneous and symmetrical particle. DDA and FDTD showed its high potential for computing scattering and absorption by a target of arbitrary shape. But due to the limit of computer's memory and speed, they aren’t suitable for computing scattering and absorption by particles with size parameters greater than 20 [1], [13]. ADT is ordinary applicable to sizes much greater than the incident wavelength, but computational accuracy is lower. In recent years, millimeter wave radars are an excellent tool for probing the properties of ice clouds [14], [15], it is urgent to find the relationship between the scattering characteristics of non-spherical ice crystals and radar echo. Secondly, it is also urgent to set up scattering characteristics database of the non-spherical particle with a variety of shapes for radiant transmission and the atmospheric remote sensing. Therefore, it is necessary to deeply study the various factors of impacting on the scattering characteristics of non-spherical particle. The particles orientation is one of the important factors and the temperature of the particles will affect the complex refractive index. Guo et al had some results of interference fluctuations of phase functions and backscattering cross sections for ice crystals with specific orientations [12]. Ping yang et al reported the effects of the polarization state of an incident quasi-monochromatic parallel beam of radiation and the orientation of a hexagonal ice particle with respect to the incident direction on the extinction process [16]. Zhang found there are significant difference of backscattering cross sections between the horizontal and the random orientation by using FDTD [11]. Liu generated an extensive scattering database by using the DDA method for 11 crystal shapes, over the frequency range 15 to 350 GHz [17]. But there are very few papers in the literature dealing with 3.2mm

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backscattering from ice crystals with different temperature and orientation in detail. Because original ice crystals are hexagonal columns and plates, therefore, the effects of temperature and orientation on 3.2 millimeter radar cross section for hexagonal columns and plates are investigated by modeling DDA. The sensitivity of the backscattering cross sections (σ) to selected aspect ratio is also explored.

II. 3.2MM RADAR BACKSCATTERING FROM ICE CRYSTALS: PLATE, COLUMN

A. Effects Of Orientation On The Backscattering Cross Sections

Due to the aerodynamic balance, ice crystals are general oriented randomly with maximal dimension at horizontal plane (2D) when turbulence and wind are slight. As a result, the axis of hexagonal plates is vertical and the axis of hexagonal columns is horizontal to the surface of the earth. When wind and turbulence are strong, non-spherical ice crystals may be randomly oriented in three-dimensional space (3D) [18]. There are three orientations are mainly adopted according to analysis above in this paper, vertical orientation (1D), horizontal orientation (2D) and random orientation (3D). Vertical orientation means that both of their axes are vertical to the surface of the earth. There are two possible causes for an inaccuracy of the computed results, 1) the inter-dipole spacing is not sufficiently small and 2) there is an insufficient number of orientations in representing random orientation [18]. Considering the symmetry of ice crystals and ensuring the calculating precision, calculations for 8 × 1× 8 and 8 × 9× 8 particle orientations are respectively represent horizontal orientation (2D) and random orientation (3D).

The oriented regulation and the coordinate system [13] are shown in fig.1. Term K is the direction of incident waves which propagate along the x axis. Term α is angle between incident waves and horizontal planes, namely the antenna elevation angle. Vector a1 is along the hexagonal prism axis. Terms β and φ are angles for target around hexagonal prism axis and x axis respectively.

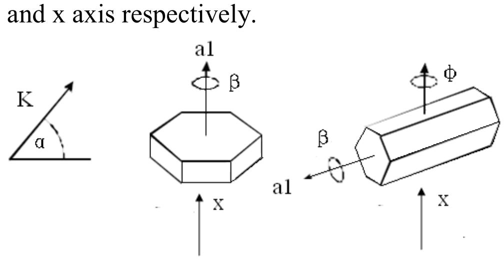
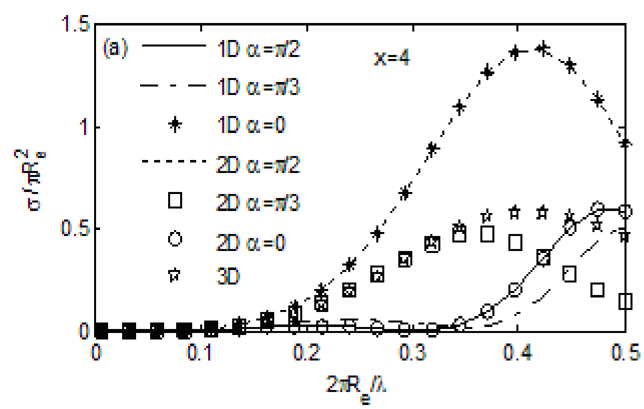


Fig. 1. Oriented regulation and coordinate system of ice crystals

The crystal shape is described by the aspect ratio x=L/D which is defined as the ratio of crystal length L to the hexagonal side D. The following geometries have been selected to assess the effect of particle shape, x=4, 2, 1, 1/3, 1/10. With regard to application for 3.2mm cloud radar, such calculations of backscattering characteristics are made for wavelength λ=3.2mm, complex refractive index m=1.7805+0.00170i applicable to clear ice at T=253K (Kelvin degree). The particle size with respect to the wavelength is most commonly expressed by the size parameter 2πRe/λ. Backscattering cross sections (σ) are written as normalized to the sphere geometric cross section, $\sigma/(\pi R_e^2)$ and sometimes named efficiency cross sections. The results are shown in fig.2, where radar wave is linear plane polarized wave. Angles α=0 (0°), π/2 (90°), π/3 (60°) are selected respectively in the study.

Fig.2 indicates that the influence of the orientation on the backscattering cross sections is significant. Backscattering cross sections σ with 2D and 1D are relevant with the incident angle α. At vertical radar wave, the value of backscattering cross sections of hexagonal ice crystals with 2D is twofold more than 3D. The actual difference of the two cases is associated with aspect ratio and dimension of ice crystals. Also at vertical radar wave, the smaller x is, the bigger difference is between backscattering cross sections of ice crystals with 2D and 3D, and maximum difference reaches about 10 times for x=1/10. With α increase, there is a large increase of radar cross sections for hexagonal columns, but a slight change for hexagonal plates with 2D, so hexagonal columns or plates can be estimated according to the cases above. We also notice that σ of hexagonal columns with 1D are smallest, compared with the other two orientations. As a result, the contributions from orientations must be considered in calculating scattering characteristics of non-spherical ice



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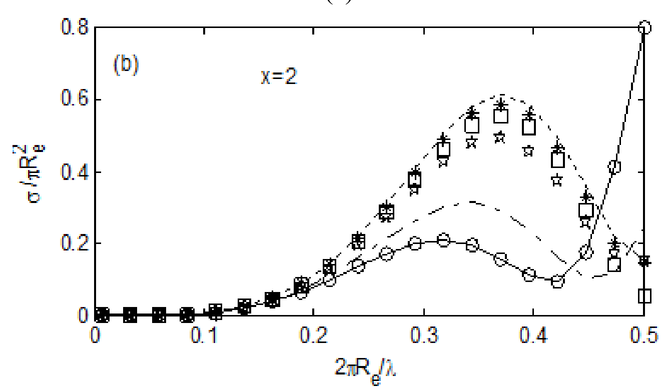

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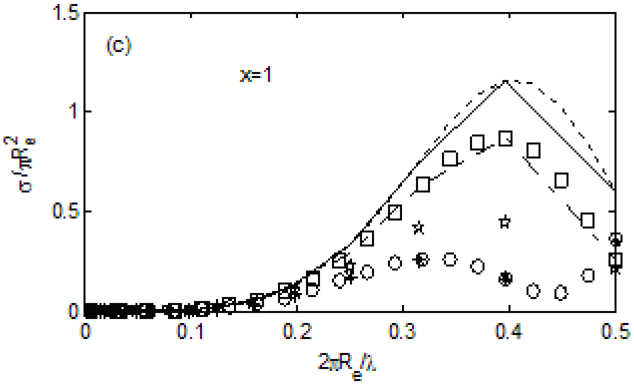

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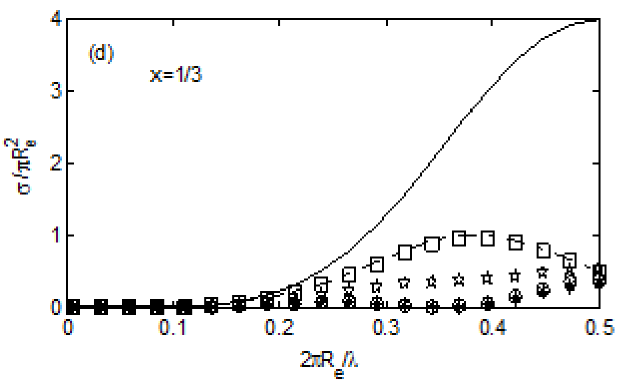

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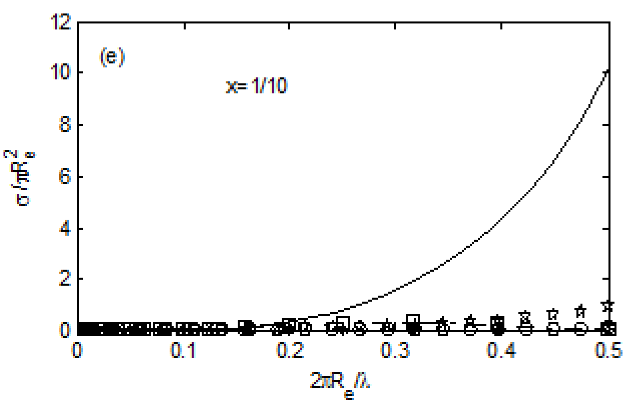


(e)

Fig. 2. Normalized backscattering cross sections as a function of the size parameters 2πRe/λ, for x=4, 2, 1, 1/3, 1/10

crystals. Such calculations for different orientation can extend scattering characteristics database of ice particles.

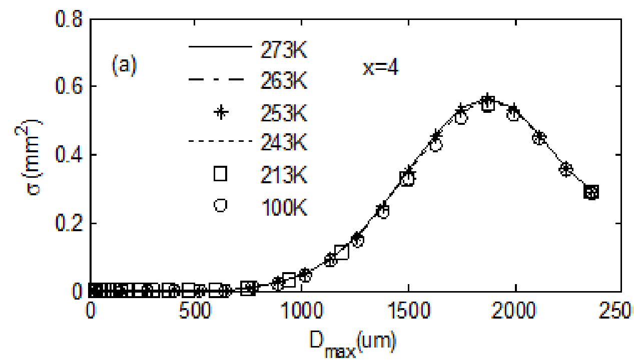
B. Effects Of Temperature On The Backscattering Cross Sections

The temperature of ice cloud which changes from about 253 K to 213 K and even under 213 K [19] can influence on the complex refractive index of ice, $m=n+ik$. The real part n of the refractive index for ice is nearly constant (n=1.78) and independent of temperature and wavelength, from λ=100*um* to 100*cm*. The imaginary part varies with wavelength, increases with temperature [20]. Warren reviewed the complex refractive index [21] for ice particles from ultraviolet to microwave. In this paper, the complex refractive index of ice is calculated by using the formula reviewed by Ma¨tzler [22] for selected temperature.

Fig.3 shows backscattering cross sections σ as a function of maximum dimension D_{max} for selected aspect ratio and temperature, where orientation is assumed 2D. Fig.3 illustrates that the influence of temperature on the backscattering cross sections for ice particles is slight. When we have a close-up view of the figure, we can find, before the σ reaching the maximum, σ increase slightly with temperature, while after the maximum, σ increase with the temperature decrease for x=1or 2. It is also noticed that D_{max} corresponding the biggest σ is different for different aspect ratio. Fig.3. (f) reveals that the error of σ as a function of temperature for Re=800mm, where error is defined as

$$\Delta\sigma_b = (\sigma_{bT} - \sigma_{bT=273k}) / \sigma_{bT=273k} \quad (1)$$

Parameters σ_{bT} and $\sigma_{bT=273K}$ are backscattering cross sections at different temperature and 0° respectively. Backscattering cross sections obviously change slightly about 2.75% when the temperature changes from 0° to 173°. The main cause



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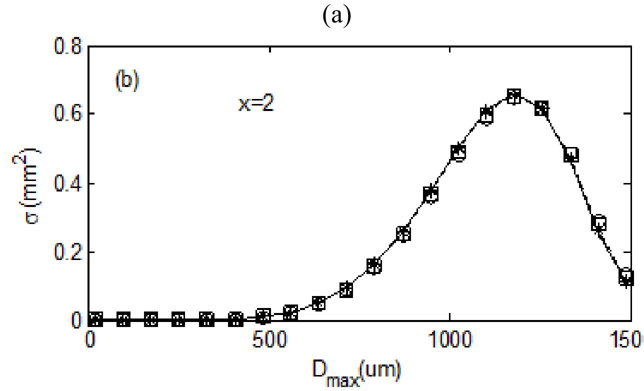

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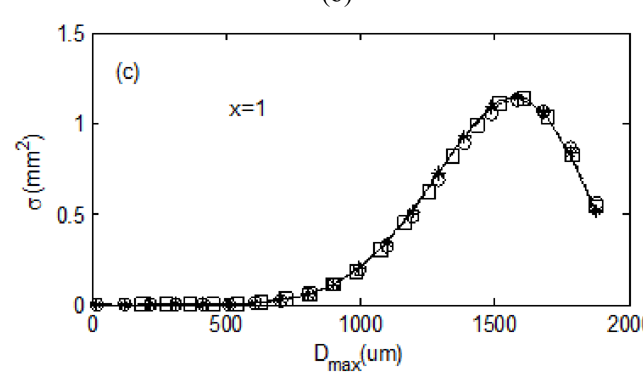

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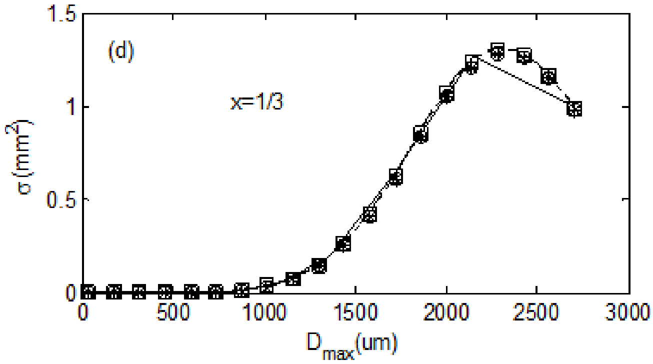

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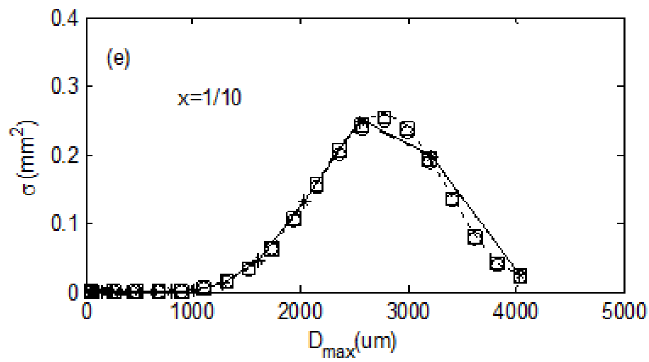

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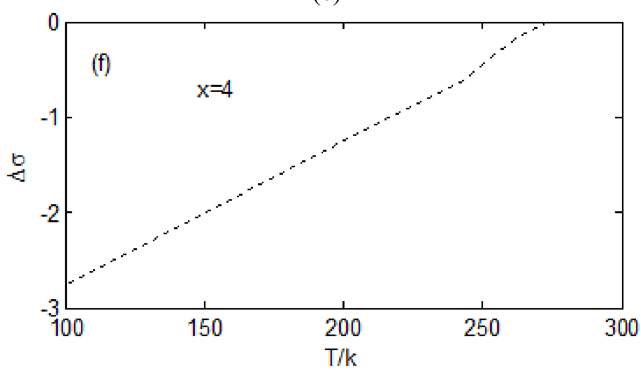


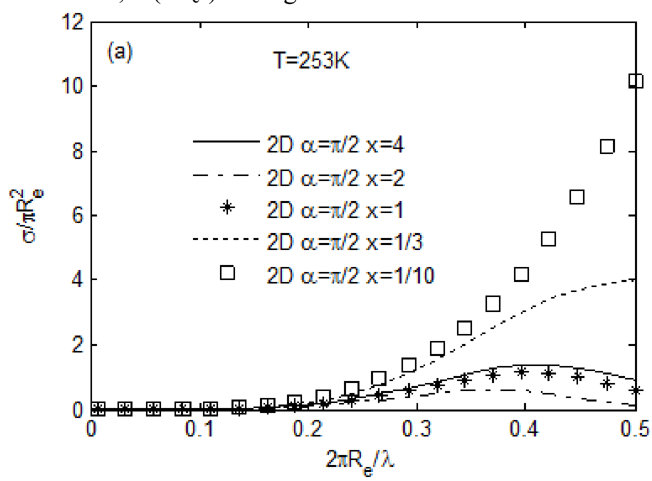
(f)

Fig. 3. Influence of temperature to the backscattering cross sections for hexagonal ice particles. (a), (b), (c) , (d) and (e) show backscattering cross sections as a function of maximum dimension Dmax respectively for x=4, 2, 1, 1/3, 1/10 and selected temperature, (f) shows error of backscattering cross sections as a function of temperature.

is imaginary refractive index for ice particles is smaller and real refractive index changes slightly with temperature. Otherwise, the lowest temperature of ice crystals is around 190K, so error of backscattering cross section for the actual temperature is about less than 1.5% which can be ignored in common conditions.

C. Influence Of Aspect Ratio On The Backscattering Cross Sections Of Hexagonal Ice Particles

Fig.4 shows the influence of aspect ratio on the backscattering cross sections of hexagonal ice particles. Fig.4 (a) and (b) display normalized backscattering cross sections $\sigma/(\pi R_e^2)$ as a function of the size parameters $2\pi Re/\lambda$ with 2D and 3D for T=253K. Those curves reveal two kinds of inverse cases. Normalized backscattering cross sections increase for hexagonal plates but decrease for hexagonal columns with aspect ratio decrease. The reasons are that the smaller aspect ratio is, the larger area of the hexagonal plane and the smaller area of the rectangular plane are for vertical radar wave. When orientation is 3D, for $2\pi R_e/\lambda<0.4$, $\sigma/(\pi R_e^2)$ increase with aspect ratio of ice particles increase, and for x=1 , $\sigma/(\pi R_e^2)$ gradually become the largest. But for $2\pi R_e/\lambda<0.4$ and x=2 or 4, $\sigma/(\pi R_e^2)$ emerge fluctuations .



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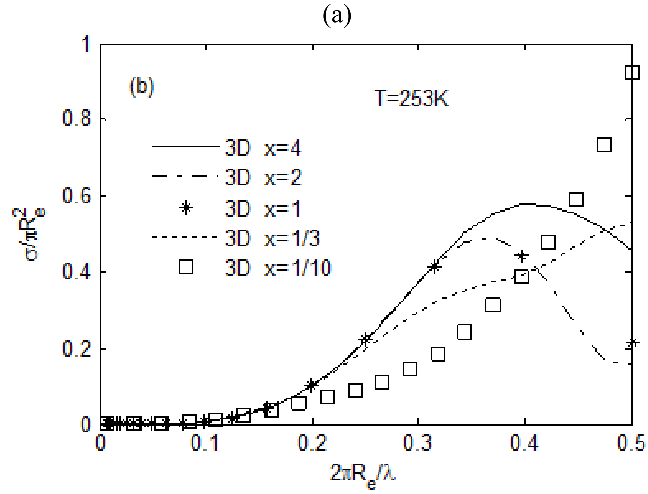

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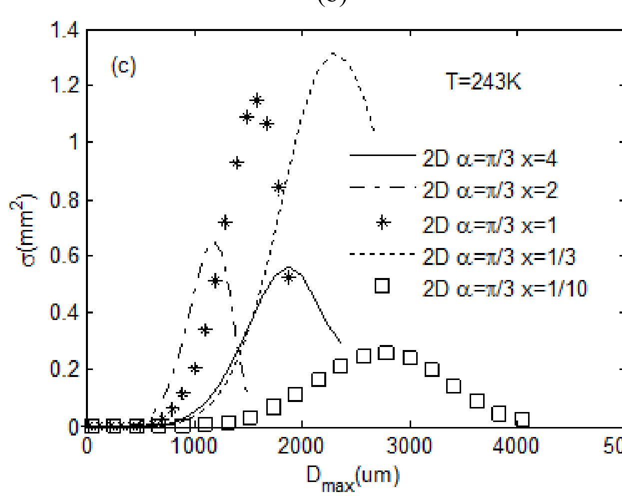

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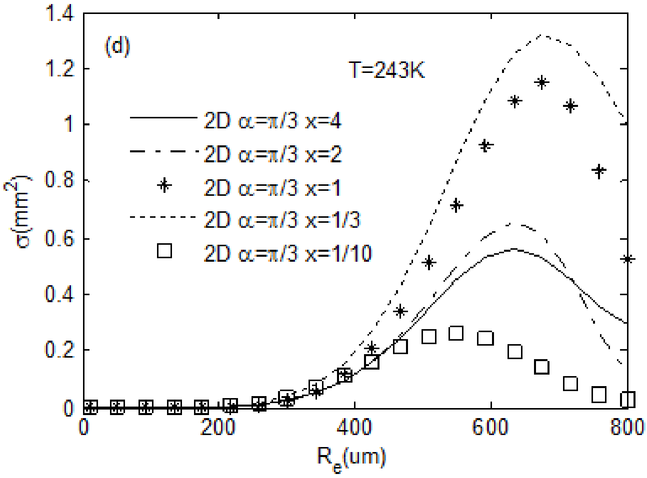

(d)

Fig. 4. Influence of aspect ratio to the backscattering cross sections for hexagonal ice particles. (a) and (b) show normalized backscattering cross sections as a function of the size parameters 2πRe/λ. Ice particles orientation is respectively 2D and 3D, for T=253K. (c) and (d) show backscattering cross sections as a function of Re and D_{max} respectively with different aspect ratio for T=243K, orientation is 2D.

Fig.4 (c) and (d) show backscattering cross sections as a function of the equivalent radius Re and maximum dimension D_{max} respectively with different aspect ratio for T=243K . Fig.4 (c) shows maximum dimension D_{max} corresponding maximum of σ change with aspect ratio. Fig.4 (d) reveals σ increase with aspect ratio decrease except x=1. Comparing (a) with (d), for hexagonal plates with x=1, they illustrate that σ change remarkable from maximum at α=90° to minimum at α=60°. Comparing (c) with (d), we find that σ expressed by D_{max} or equivalent radius Re is different.

III. CONCLUSION

The paper mainly aims at the application for 3.2mm (94GHz) cloud radar. The backscattering characteristics of hexagonal ice crystals for 3.2mm radar at different temperature and orientation are discussed. Such calculations for different orientation can extend scattering characteristics database of ice particles. In this paper, we provide some ideas for exploring the scattering by ice crystal and theoretical basis for using the millimeter wave radar echo to inverse the characteristics of clouds.

In this document, we only take into account hexagonal columns and plates, other non-spherical ice crystals such as aggregates, the bullet rosettes and other shapes should be considered. The ensembles backscattering and the relation between radar reflectivity factor (z) and attenuation for non-spherical ice particles should be discussed in next work.

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