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COMPARISON OF ICE CLOUD PARTICLE SIZES RETRIEVED FROM SATELLITE DATA DERIVED FROM *IN SITU* MEASUREMENTS

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1. INTRODUCTION

Cloud microphysical parameterizations have attracted a great deal of attention in recent years due to their effect on cloud radiative properties and cloud-related hydrological processes in large-scale models. The parameterization of cirrus particle size has been demonstrated as an indispensable component in the climate feedback analysis. Therefore, global-scale, long-term observations of cirrus particle sizes are required both as a basis of and as a validation of parameteriza-tions for climate models. While there is a global scale, long-term survey of water cloud droplet sizes (Han *et al.* 1994), there is no comparable study for cirrus ice crystals. This study is an effort to supply such a data set.

Validation of satellite remote sensing techniques for the retrieval of cirrus microphysics has been rare. This is due to difficulties of temporally and spatially collocating satellite passing and *in situ* aircraft flight. As the pioneer effort of validation during 1986 FIRE I IFO, Smith *et al.* (1990) and Heymsfield *et al.* (1990) found that ice particle sizes retrieved by satellite remote sensing and those measured by *in situ* aircraft are considerably different. Particle sizes of about 200 µm were found from *in situ* measurements, as compared to values of ~60 µm from the remote sensing results (Wielicki *et al.* 1990). These differences were attributed both to vertical inhomogeneities of cirrus particle sizes in clouds and to a limitation in the measurement of small particle sizes by the microphysical probes (Heymsfield *et al.*, 1990; Wielicki *et al.* 1990).

There are two other possible explanations for differences between remotely sensed cirrus particle sizes and aircraft measurements. First, the phase function used in the remote sensing retrievals may be an inappropriate representation of ice crystal scattering. There are measurements from both laboratory and field observations showing that cirrus cloud scatering phase function is different from that of regular hexagonal columns or their aggregates (e.g., Francis 1995, Gayet *et al.* 1995, Spinhirne *et al.* 1996). It is possible that using phase functions based upon hexagonal columns in remote sensing may lead to underestimates of crystal sizes if the dominant particles in the cloud are highly irregular crystals (Mishchenko *et al.*, 1996). The problem is that there is no proper way to determine the dominant shapes of ice crystals in a cirrus cloud by current remote sensing instruments. A final problem is that the definitions of ice crystal sizes used in remote sensing applications and *in situ* measurements are different. Details of different definitions used in literature are discussed in the text. The above four problems have to be considered before any meaningful comparison can be performed.

Recent aircraft measurements from the Central Pacific Experiment (CEPEX) supply a better opportunity for intercomparisons between these measurements and values retrieved from satellite sensors by eliminating the first two problems. First, to overcome the lower limit of 2D-C probe, a video ice particle sampler (VIPS) was included to obtain images of particles as small as 5 µm. Second, the aircraft had 20% of its flight time at an altitude within 500 m of the cloud tops (Heymsfield and McFarquhar 1995), making the results comparable to those from satellite retrievals.

The validation strategy of the present study, while still lacking simultaneous observations from satellites and aircraft, is to compare the range of ice crystal sizes retrieved by satellite remote sensing with typical values derived from CEPEX *in situ* measurements. Definitions of particle size used in these two techniques are different, but a relationship between them is derived. We also use direct calculation of ice crystal effective diameters D_e from CEPEX *in situ* measurement data. Differences from this comparison then can be used to estimate the possible bias caused by the

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assumption of inappropriate phase functions. The results reveal a close agreement between results from the CEPEX measurements and from satellite retrievals suggesting that the use of the hexagonal column phase functions in remote sensing of particles size may be justified.

2. METHODOLOGY

The data used to retrieve ice crystal sizes is the ISCCP CX data derived from the NOAA-9 AVHRR from January, April, July, and October 1987 and 1988. The detailed description of CX data can be found in Schiffer and Rossow (1985), Rossow *et al.* (1991) and Han *et al.* (1994). The radiative transfer model used to simulate the AVHRR radiances is described in a previous paper (Han *et al.* 1994). Shapes and orientations of ice crystals are assumed to be hexagonal columns and plates randomly orientated in the atmosphere. Ray tracing techniques are used to calculate phase functions for different size distributions. Five different size distributions from observations are used, i.e., cold cirrus (D_e=23.9 μm), warm cirrus (D_e=47.6 μm), -40°C cirrus (D_e=64.1 μm), Nov. 1 cirrus (D_e=75.1 μm) and Cirrus uncinus (D_e=123.6 μm). Phase functions of these five size distributions for channels 1 and 3 are applied in the model for calculations of multiple scattering.

The particle size retrieval is initiated with a cloudy pixel which is determined by the ISCCP cloud detection procedure. The retrieval procedure is limited to latitude ±50° due to difficulties with proper cloud detection and retrieval of optical thicknesses over highly reflective surfaces at extreme solar zenith angles. To alleviate possible 3-D effects, this analysis is limited to image pixels viewed near nadir for which the reflected radiation is less affected by cloud geometry. Ice clouds in this study are determined to be those clouds defined by T_c < 240K. The detailed retrieval scheme, sensitivity tests for effect of partial cloud cover and supercooled water contamination are decribed in Han *et al.* (1996).

3. COMPARISON WITH *IN SITU* MEASUREMENTS

With a better *in situ* measurement dataset and using the same definition of particle size, it is still uncertain how different the particle size results may be between those retrieved by satellite remote sensing and those measured by *in situ* measurements. The differences can be used to estimate the potential effect of assuming phase functions based upon simple hexagonal crystals instead of fractals.

3.1 Different Definitions of Particle Sizes

There are many different definitions of cloud particle sizes, each used for different purpose (e.g., Foot, 1988; Wielicki *et al.*, 1990; Ebert and Curry, 1992; Heymsfield and McFarquhar, 1996; Fu and Liou, 1993). For water clouds, the best parameter describing the scattering light is the effective radius r_e (Hansen and Travis 1974). r_e has been widely used in remote sensing of water cloud microphysics (Foot 1988, Nakajima and King 1990, Han *et al.* 1994). For ice crystals, however, the non-spherical shape leads to many different ways to describe particle sizes. While many of the definitions are very useful for characterizing particle sizes for *in situ* measurements, they are not appropriate in remote sensing techniques because the information about the areas of irregular shapes is not available. For example, Foot (1988) defined a generalized r_e in a way analogous to that of water droplets which can be used for any particle shape. But the D_j in the numerator of his expression cannot be derived from scattering properties. It is related to cross sectional area A_j in different ways depending on particle shape, which need to be obtained from *in situ* measurements. For remote sensing purposes, Fu and Liou (1993) defined D_e as the ratio between particle volume and cross-sectional area. These two quantities are related to the absorption coefficient and scattering coefficient, respectively (Pollack and Cuzzi 1980).

The relationships between different size definitions are by no means straightforward. For example, D_e cannot be regarded as about twice as large as r_e, as is the case for water droplets. Using measured data, Ou *et al.* (1995) correlated the values of D_e of Fu and Liou (1993) and r_e used by Wielicki *et al.* (1990) using measured data and developed a fourth-degree polynomial.

We examine the relationship between two definitions of ice crystal size: 1) D_e used for our retrieval and 2) r_e used in CEPEX by Heymsfield and McFarquhar (1996). This relationship is based on the fact that for a certain ice crystal size distribution in a specific cirrus cloud, while the definition of effective particle size can be different, the ice water content and the extinction coefficient β_{ext} should be the same. For D_e, we have the relation b_{ext}=IWC(-6.656x10^{-3}+3.686/D_e) (Fu and Liou, 1993), where IWC is the ice water content. For r_e, a regression from Figure 6 of Heymsfield and McFarquhar (1996) gives β_{ext}=IWC(3.3459x10^{-3}+3.0981/r_e). The resulting relationship between D_e and r_e is D_e=3.686r_e/(1.0x10^{-2}r_e+3.098). Figure 1 shows this relationship which reveals that

1) D_e is slightly larger than the r_e values when particle size is small (r_e < 60 μm), and 2) smaller than the r_e values when particle size is large (r_e > 100 μm). The typical range of r_e of about 50 μm to 100 μm in the CEPEX measurement (Heymsfield, personal communication) is similar to values of D_e of 50 μm to 90 μm.

Also shown in Figure 1 are relationships between D_e and three other r_e definitions reported in the literature. They are r_e definitions used by Wielicki *et al.* (1990), Ebert and Curry (1992) and Foot (1988). The fourth-degree polynomial reported by Ou *et al.* (1995) is used for relationship between D_e and the r_e definition used by Wielicki *et al.* (1990). For other r_e definitions, the relationship between D_e and r_e (Ebert and Curry 1992) is $D_e = 3.686r_e/(1.010\times10^{-2}r_e + 2.431)$. The relationship between D_e and r_e (Foot 1988) is $D_e = 3.686r_e/(6.656\times10^{-3}r_e + 1.500)$, which has been derived by Moss *et al.* (1995).

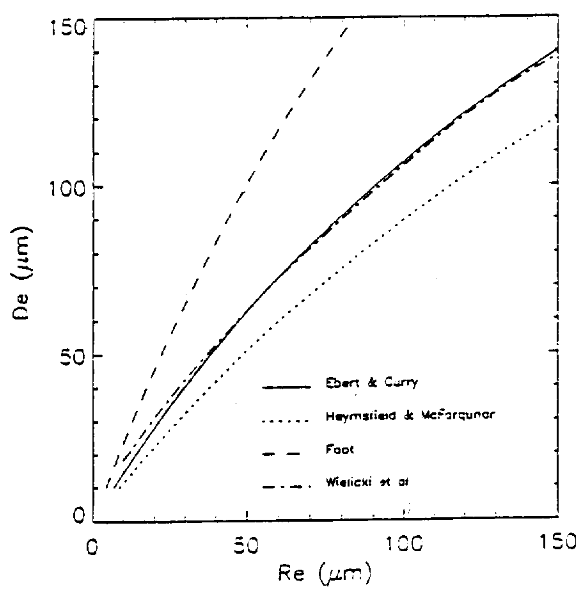

Figure 1. Comparison of different definitions of ice crystal size.

3.2 Results of Satellite Retrievals

A validation against FIRE I cirrus IFO data has been conducted using AVHRR LAC data. The land surface reflectances for channels 1 and 3 over the Wausau region (Wisconsin) were determined as 0.167 and 0.038, respectively. For this case, the average value of D ~59.2 μm, which is consistent with the results of Ou *et al.* (1995) and Wielicki *et al.* (1990). Note that Wielicki *et al.* were using LANDSAT data and using a different definition of r_e and different phase functions.

A near-global survey of ice crystal effective sizes D_e has been conducted for Jan, Apr, Jul, and Oct of 1987 (Han *et al.*, 1996). The results show that there is no distinct contrast between continental and maritime clouds, as found for water cloud droplets (Han *et al.* 1994). It appears that the microphysics of low-level liquid water clouds are affected by CCNs near the ground whereas the microphysics of cirrus clouds are influenced by upper air aerosols. Observations of CCN vertical profiles from five different geographical locations (Hoppel *et al.* 1973) found that at higher altitudes (around 3.5 km), there are no systematic differences between oceanic and continental environments.

For comparison with CEPEX results, over the region 165°E to 170°W and 2°N and 18°S (region of CEPEX measurements), the average value of D_e = 53.2 μm.

3.3 Results of CEPEX and Kwajalein Measurements

The CEPEX observations were conducted in March and April 1993 in the central Pacific area. The microphysical measurements were made by a Lear Jet, which can reach altitudes up to 13.5 km, flying in anvils within the area bounded by 165°E to 170°W and 2°N to 20°S. The Lear Jet was equipped with a PMS-2DC, a PMS-2DP, a FSSP-300, oil coated slides and a video ice particle sampler (VIPS) (Heymsfield and McFarquhar 1996, McFarhuhar and Heymsfield 1996).

Figure 2 is an example of size distributions derived from VIPS images (thin lines) and 2D-C measurements (thick lines) during CEPEX at -39.8°C, 10.9 km, April 4, 1993 (after Heymsfield and McFarquhar 1996). The measurements were made in anvils far from their convection cores. Using the aspect ratio suggested by Ebert and Curry (1992), D_e can be calculated accordingly. It is 79.4 mm for using 2D-C probe only and 40.4 μm for 2D-C plus VIPS. This result shows the importance of including VIPS in the *in situ* measurements.

The calculation of D_e is also conducted for the *in situ* measurement data in the vicinity of Kwajalein, Marshal Islands (8°N, 168°W), in 1973. In the Kwajalein experiment, the particle sizes were measured using a PMS 1D-C probe (range from 20 to 3000 μm in 20 μm intervals), a PMS 1D-P probe (range from 140 to 2100 μm in 140 mm intervals) and a PMS axial scattering spectrometer probe (range from 2 to 30 μm in 2 μm intervals) (Heymsfield and McFarquhar 1996). The measurements were collected with a WB57F aircraft, which can reach altitude up to 20 km. Using the data presented in Heymsfield and McFarquhar (1996), values of D_e were calculated for Dec. 18 and 19, 1973. These are vertical profiles of ice crystal sizes. For Dec. 18, 1973, the altitudes are 16.4, 12.8, 11.9 and 11.7 km, respectively. The corresponding D_e values are: 60.6, 40.9, 43.8, and 50.1 µm, respectively. For Dec. 19 1973, the altitudes are 14, 13.3, 12.7, 12.2, and 11.7 km respectively. The corresponding D_e values are: 30.4, 32.8, 50.8, 57.2, and 44.6 µm.

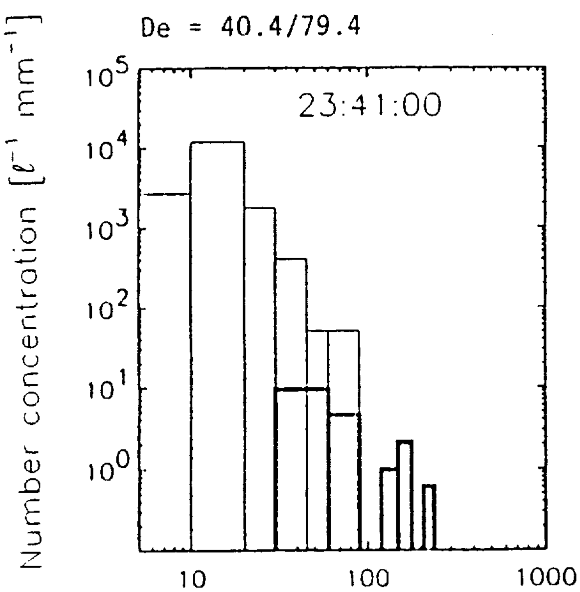

Figure 2. Example of ice particle size measured during CEPEX on April 4, 1993.

3.4 Discussion

The above results show that for the same region, at the same season, the result from satellite remote sensing, $D_e = 53.2$ µm, is very close to that obtained from CEPEX *in situ* measurements, $D_e = 57.2$ µm. Although this is not a direct comparison between coincident observations, there are no significant differences, such as found in the FIRE I IFO experiment (Wielicki *et al.* 1990). This improvement comes from 1) the inclusion of VIPS; 2) the near cloud top flights in taking the *in situ* measurements; 3) the hexagonal phase function assumed for the remote sensing results; and, more importantly, 4) the unified particle size definition used for different techniques.

The close agreement also suggests that although we are uncertain about the adequacy of the relatively simple assumption of the dominant shapes of ice particles for a particular cirrus cloud, the possible bias caused by this assumption is not significant. This is because the complexity of different shapes and orientations in real clouds. Note that sensitivity tests conducted between hexagonal columns and aggregates or fractals (Macke 1993, Mishchenko *et al.* 1996) are based on monodispersed ice crystal shape alone, i.e., they consist of one particle shape only. In any real cirrus cloud, many different particle shapes coexist, and their radiative effect may cancel each other. For example, some of the aggregated crystals may cause an overestimate of particle size, but quasi-spherical shape particles may cause underestimates of particle size. The total scattering properties, and thus the retrieved values of D_e, depend not only on size distributions but also on "shape distributions".

4. SUMMARY AND CONCLUSION

A near-global survey of cirrus ice crystal sizes is conducted using ISCCP satellite data analysis. The retrieval scheme uses phase functions based upon hexagonal crystals calculated by a ray tracing technique. The results show that global mean values of D_e are about 60 µm. This study also investigates the possible reasons for the significant difference between satellite retrieved effective radii (~60 µm) and aircraft measured particle sizes (~200 µm) during the FIRE I IFO experiment. They are 1) vertical inhomogeneity of cirrus particle sizes; 2) lower limit of the instrument used in aircraft measurements; 3) different definitions of effective particle sizes; and 4) possible inappropriate phase functions used in satellite retrieval.

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