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UTILIZATION OF EQUIVALENT SPHERES OF EQUAL VOLUME AND SURFACE AREA FOR ESTIMATION OF THE ASYMMETRY PARAMETER FROM MICROPHYSICAL OBSERVATIONS

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1. INTRODUCTION

Understanding the scattering properties of complex ice particles is essential to understanding the role of clouds in climate. Ray-tracing studies (Fu, 1998; Takano and Liou, 1989a; Takano and Liou, 1995) have focused on simple ice crystal shapes such as columns and plates. The scattering properties of highly complex ice crystals would be computationally prohibitive to calculate using traditional ray-tracing techniques. Korolev and Sussman, (2000) noted that most ice particles observed in clouds are irregular in shape. Examples of irregular ice crystals as well as rarely seen pristine ice crystals observed by the Stratton Park Engineering Company (SPEC Inc.) cloud particle imager probe (CPI) during the Cirrus Regional Study of Tropical Anvils and Cirrus Layers - Florida Area Cirrus Experiment (CRYSTAL-FACE) field project in southern Florida in July 2002 are shown in figure 1.

To simplify cloud radiative property calculations, cloud particles are often represented as equivalent spheres. This approach facilitates the use of the computationally simple Mie theory for the calculation of the scattering properties. Ice particles have been represented by spheres with equal volume as well as spheres with equal projected area. These equivalent sphere theories require one sphere for each particle in the cloud. Liou and Takano (1994) have shown that equal volume and equal area spheres are inadequate for modeling purposes. The third equivalent sphere type, studied by Grenfell and Warren (1999), Neshyba et al (2003) and Grenfell et al (2005), uses spheres with an equal volume to surface area ratio (hereafter EVSA). Grenfell and Warren (1999) give a numerical description of EVSA

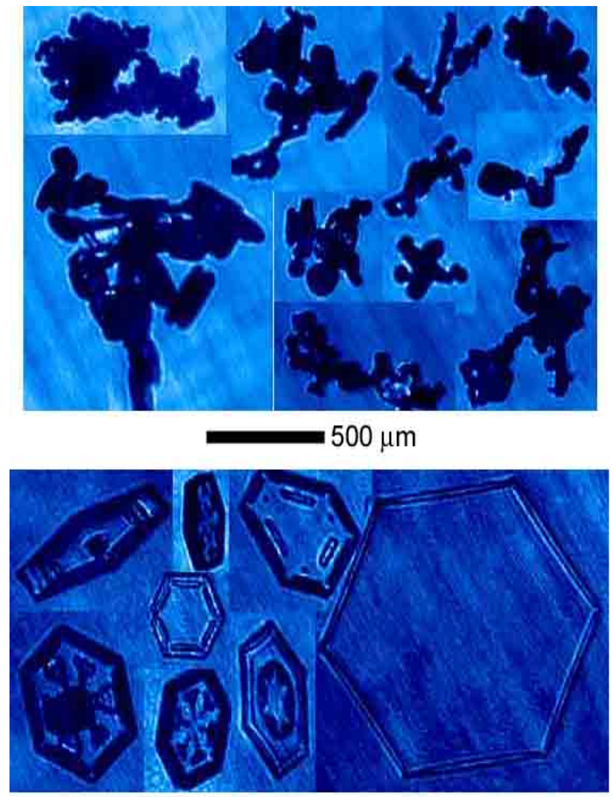

Figure 1: Ice particles observed during the CRYSTAL-FACE field project. The ice crystals were imaged with the Cloud Particle Imager (CPI) probe. Examples of highly irregular particles are shown above, some pristine particles (which represent less than 0.1% of observed particles during CRYSTAL-FACE) are shown below.

spheres. For the EVSA sphere theory, numerous spheres can be used to represent single complex ice crystals. The inside surface of internal or concave structures is represented by outside surfaces of the spheres (Neshyba et al, 2003), giving the EVSA sphere population a higher optical depth than the ice cloud that it is representing.

Two-stream radiation transfer models use the asymmetry parameter and cloud optical depth to

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estimate the amount of light that passes through clouds (Mitchell et al 1996). The asymmetry parameter is defined as the average cosine of the scattering angle, weighted by the intensity of the scattered light as a function of angle. The EVSA sphere asymmetry parameter values are modified to account for the change in the optical depth that necessarily occurs in the transformation from ice particles to EVSA spheres.

This paper presents calculations of the combined asymmetry parameter-optical depth properties of ice clouds estimated using EVSA spheres as compared to directly measured values. The EVSA sphere sizes are determined by detailed analyses of aircraft microphysical data. Section 2 gives an overview of the aircraft data used in this study. Section 3 details the transformation from ice cloud particle size distributions to EVSA sphere populations. In section 4, the scattering properties of EVSA spheres are compared to the scattering properties derived using the direct measurements of asymmetry parameter. Section 5 presents a summary of the work as well as discusses possible future research.

2. OVERVIEW OF AIRCRAFT DATA

The in-situ measurements used in this study were collected aboard the University of North Dakota Citation aircraft during the CRYSTAL-FACE field project in southern Florida in July of 2002. The clouds observed were predominately convectively generated ice cloud layers at temperatures from 0 to –70°C. These clouds are well known to have highly irregular ice particle shapes as seen in Figure 1.

For particle size distribution measurements, particles larger than 45 μm in maximum dimension (*D*) were measured with the Particle Measuring Systems (PMS) 2-Dimensional cloud probe (2DC) and the SPEC Inc. High Volume Precipitation Sampler (HVPS) cloud probe. Heymsfield et al. (2002) discusses the techniques used to calculate the raw particle size distributions from the 2DC and HVPS. The PMS Forward Scattering Spectrometer Probe (FSSP) was used for measurement of particles smaller than 45 μm. The FSSP concentrations may be in error due to ice particle sizing uncertainties as well as to the breakup of large ice particles on the inlet of the probe (Field et al. 2003); however, errors did not significantly affect the results of this work, as the equivalent spheres calculated from larger ice particles (75-300 μm) were more dominant in the integrated asymmetry parameter calculation. Composite size distributions were obtained by merging the spectra obtained from the three probes.

For the purpose of this analysis the composite particle size distribution data were averaged over five second time periods throughout the CRYSTAL-FACE dataset. Area ratio, defined as the projected area of a particle as imaged by a 2-D probe divided by the area of the smallest circle that would completely enclose the particle, was measured by the 2DC and HVPS, and an average value for the particles in each of the size bins was calculated. Small particles measured by the FSSP were assumed to have an area ratio of 0.80, a reasonable assumption for small frozen droplets that have undergone some growth. Area ratio measurements are used in the estimate of total particle surface area (Schmitt and Heymsfield, 2005). Ice particle volume was estimated with the mass-dimensional relationship given in Heymsfield et al (2004) and by assuming that ice has a density of 0.91 g/cm^3. The Heymsfield et al (2004) mass-dimensional relationship was developed using the CRYSTAL-FACE dataset.

The Gerber Scientific Inc. Cloud Integrating Nephelometer (CIN) probe was used for direct measurements of the asymmetry parameter of a volume of cloud particles. The CIN probe shines a visible light laser (625 nm wavelength) through a population of cloud particles and measures near-forward and near-backward scattered light intensities to estimate the asymmetry parameter. Gerber et al. (2000) and Garrett et al (2001) describe the CIN probe and its functionality. The CIN probe detects particles 2 μm and larger. The CIN measured asymmetry parameter value was averaged for five-second time periods to match the time periods for the composite size distributions. The accuracy of the asymmetry parameter values is estimated to be about +/- 0.01 (Gerber et al 2000). Data from July 11th, 16th, 18th, 21st, 23rd, 25th, 26th, 28th and 29th were used, resulting in a dataset containing 5640 valid points or approximately 8 hours of in-cloud time.

3. ICE TO SPHERE CONVERSION

A population of EVSA spheres was estimated from the size distributions by analyzing the average particle properties for each size bin independently. For each size bin in the total particle surface area was estimated using results from Schmitt and Heymsfield (2005)

$$A_s = A_p * 5.6 * A_r^{(-0.6)}, \qquad (1)$$

where A_s is the total particle surface area, A_p is the projected area, and A_r is the area ratio. Heymsfield et al (2004) derived a mass-dimensional relationship that was used to estimate an average mass of particles within each size bin.

$$m = 0.0061 * D^{2.05}, \qquad (2)$$

where *m* is the particle mass in grams and *D* is the observed particle maximum dimension in units of centimeters. The mass-dimensional relationship shown in Eq. 2 was derived from the same particle dataset used in this study in conjunction with results from the Counterflow Virtual Impactor (CVI) ice water content measurement. The mean particle volume per bin was estimated by dividing the particle mass by 0.91 g/cm^3. EVSA sphere sizes and concentrations were calculated from the total particle surface area and total particle volume using the techniques described by Grenfell and Warren (1999). Typical EVSA sphere sizes ranged from ~3 μm to 100.0 μm (size parameters of 30 to 1000 for the wavelength used by the CIN probe). Mie theory for spheres and the refractive index of ice were used to calculate the asymmetry parameter for each individual sphere size. A projected area weighted average value of asymmetry parameter values was then calculated based on the size and concentration of EVSA spheres. The ratio of the projected area of the EVSA spheres to the projected area of the ice particle population was also estimated. Typically the calculated values of asymmetry parameter for the size distributions were between 0.86 and 0.90. These values were much higher than the CIN measured values for the asymmetry parameter, which were generally between 0.7 and 0.8. This illustrates that the EVSA sphere theory is not able to directly predict the asymmetry parameter. The cloud scattering properties as represented by the asymmetry parameter and the cloud optical depth are more useful for determining the utility of the EVSA theory.

4. SCATTERING PROPERTY COMPARISON

To facilitate a meaningful comparison between the EVSA sphere scattering properties and the direct measurements of the asymmetry parameter, it is necessary to systematically adjust the asymmetry parameter estimates to account for the change in optical depth caused by use of the EVSA sphere theory. Liou (2002) developed a similarity relationship to relate alternative representations of scatterers in radiative transfer theory. The relationship is

$$\tau_1 \omega_1 (1 - g_1) = \tau_2 \omega_2 (1 - g_2), \qquad (3)$$

where τ is the optical depth, ω is the single scattering albedo, and *g* is the asymmetry parameter. The subscripts 1 and 2 represent the two different scattering media being compared. The two single scattering albedo terms cancel as ice does not absorb appreciably at the CIN wavelength. The optical depth can be calculated from

$$\tau = Q_{ext} A_p dz, \qquad (4)$$

where Q_{ext} is the extinction efficiency of the cloud particles and *dz* is the geometric thickness of the cloud layer. When Eq. 4 is substituted into Eq. 3, the *dz* and Q_{ext} terms on both sides of the equation cancel out. The cloud physical thickness is the same for both situations, and Q_{ext} can be assumed to be 2.0 by the geometric optics approximation for both populations. The surviving term from Eq. 4 is A_p, the projected area, which leads to

$$A_{p1}(1 - g_1) = A_{p2}(1 - g_2), \qquad (5)$$

where A_{p1} and A_{p2} are the projected areas of the ice particle population and the EVSA sphere population respectively. Thus, to compare the scattering properties of the EVSA spheres with the measured asymmetry parameter values, it is most reasonable to compare the values of $(1\text{-}g_{CIN})$ to $P_r(1\text{-}g_{sph})$ where P_r is the ratio of the projected areas of the two particle populations

$$P_r = \frac{P_{sph}}{P_{ice}}, \qquad (6)$$

where P_{sph} is the projected area of the equivalent spheres and P_{ice} is the projected area of the ice particles. Fig. 2 shows $(1\text{-}g_{CIN})$ plotted versus $P_r(1\text{-}g_{sph})$ for the nine CRYSTAL-FACE research flights. The 1:1 line is drawn to aid the eye. While the values for equivalent spheres and CIN both are generally between 0.24 and 0.30, there appears to be no direct correlation.

The agreement in the range of values calculated for the EVSA scattering properties and the direct measurement calculation shows that the EVSA theory warrants further investigation. The particle volume and the surface area used to calculate the EVSA sphere sizes are both derived from parameterizations which could add noise to the calculations.

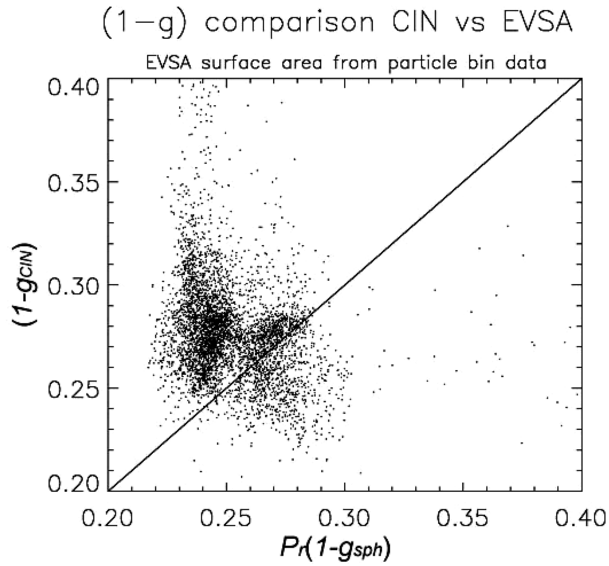

Figure 2: *(1-g_{CIN})* plotted versus *P_r(1-g_{sph})* for the UND Citation CRYSTAL-FACE research flights on the 11th, 16th, 18th, 21st, 23rd, 25th, 26th, 28th and 29th of July, 2002. The EVSA sphere sizes were determined by evaluating data from individual size bins in the size distribution.

5. SUMMARY AND CONCLUSIONS

The asymmetry parameter of particle populations has been calculated from in-situ aircraft measurements taken during the CRYSTAL-FACE field project. Equivalent spheres with equal total volume and equal total surface area were used. The equivalent sphere size was estimated for each size bin in the measured particle size distribution and a cloud asymmetry parameter was estimated by calculating a projected area weighted average. The asymmetry parameter was calculated using Mie theory and the results were scaled by a similarity relationship to account for the change in optical depth caused by using the equivalent spheres. The resulting calculations were compared to direct measurements of asymmetry parameter from the CIN probe. The results show that the EVSA theory estimates are in the correct range, but the results were not correlated to the measured values.

This work demonstrates that the EVSA sphere theory shows promise for the estimation of the asymmetry parameter from direct aircraft measurements. It is thought that the current state of the particle probe measurements may be insufficient to capture all of the detail necessary for accurate calculations using the EVSA technique. Particle volume and surface area were calculated from parameterizations that did not take particle habit or irregular particle complexity into account.

Future work will include surface area estimates that are based on CPI data to better understand the particle complexity. The CPI images will be used directly to more accurately estimate the ratio of particle surface area to projected area. This will refine the calculation of EVSA sphere size.

Total ice water content and cloud extinction measurements can also be used to calculate one EVSA sphere size to represent an entire cloud, thus providing a more realistic potential explanation of the effective radius that is derived from remote sensing measurements. Additional research should be done to investigate the EVSA theory at different absorbing wavelengths and to evaluate the EVSA theory for calculations of radar reflectivities.

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