Light scattering by ice particles in the Earth's atmosphere and related laboratory measurements

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The microphysical properties of ice crystals, such as size, shape, concavity and roughness, are important in the context of radiative properties of ice and mixed phase clouds. Limitations of current cloud probes to measure such properties can be circumvented by acquiring light scattering patterns instead of particle images. Recent *in situ* cloud data from the SID-3 probe is shown which is consistent with ice particles with rough surfaces being dominant.

INTRODUCTION

Cloud feedbacks remain the largest source of uncertainty in climate models. In particular, uncertainties exist concerning the radiative forcing of clouds containing ice crystals, most notably cirrus. Indeed, whether cirrus clouds warm or cool the Earth's surface depends on ice crystal morphology. Reducing this uncertainty requires detailed *in situ* characterization of cloud particles, so that the scattering properties of the clouds can be correctly represented in models. Also, detailed knowledge of the scattering properties of various cloud particle types is needed for accurate retrieval of cloud microphysical properties from remote sensing. One of the main barriers to achieving these goals is the inability of cloud probes to determine the contribution of small ice crystals (that is crystals smaller than about 50 μm) to the total distribution. This is due to crystal breakup on the inlets of these probes [1] and their inability to resolve the geometric structure of small ice crystals because of the conflicting demands of high optical resolution and large sample volume [2,3].

In addition to size and shape, two other important properties of ice particles, surface roughness and concavity, are known to profoundly affect radiative properties of ice clouds, e.g. the asymmetry parameter g [4,5,6]. The measured g of smooth and rough ice analogues is typically 0.8 and 0.63, respectively, at visible wavelengths [7]. This means that, in simple terms, the rough ice particles in this example might back-reflect nearly twice as much solar radiation as their smooth counterparts. Since the longwave g is not expected to vary by as much, the overall radiative forcing of cirrus might shift towards negative values, an issue of great importance in the context of climate change. However, little *in situ* data on ice roughness exists: mainly indirect evidence, e.g. the absence of atmospheric halos [6,8] or the shape of phase functions [9]. As for the concavity of ice particles, it is thought to occur frequently but is seldom quantified, mainly due to cloud probe limitations [10]. Here, we examine the recovery of size, shape, concavity and roughness of ice particles from scattering data, so as to bypass the optical resolution limitations of cloud probes.

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ICE PARTICLE CHARACTERIZATION USING SCATTERING PATTERNS

Particle size, shape and concavity

Several light scattering cloud probes, jointly known as Small Ice Detectors (SID) have been developed over the last decade at the University of Hertfordshire. Successive models obtain scattering patterns with progressively higher angular resolution. The earlier designs rely on multi-element detectors measuring mainly the azimuthal scattering. The first one, SID-1, was intended to discriminate between water droplets and ice crystals by determining their sphericity, and relies on six photomultipliers arranged symmetrically around the azimuth [11]. This instrument was superseded by SID-2 probes, containing between 24 and 28 detector elements arranged azimuthally in an annulus [12]. Despite their simplicity, azimuthal scattering patterns can also provide the size, concavity and aspect ratio of prismatic ice crystals [13] through comparison with the Ray Tracing with Diffraction on Facets (RTDF) scattering model [14]. Some particle information is retained even in the azimuthal frequency spectrum, as shown by the recovery of the size and aspect ratio of prismatic ice crystals [15] although, not surprisingly, such frequency analysis is limited to cases when some *a priori* information on particle shape exists, and even then some ambiguity can remain [13,16].

High-resolution two-dimensional (2D) scattering patterns offer high potential for detailed particle characterization [17]. The latest SID probes, collectively known as SID-3, use intensified CCD cameras to capture 2D patterns. It is possible to recover the shape of small ice particles by comparing such patterns to the RTDF scattering model [18]. In the next section we examine the application of 2D patterns to ice particle roughness.

Particle roughness

An indication that ice roughness can be quantified from 2D scattering is provided by experimental patterns from ice analogue crystals with smooth and rough surfaces, which show distinct differences: while the former have sharp, well-defined bright arcs and spots, the latter have much more random, "speckly" appearance, but with greater azimuthal symmetry [7]. The first *in situ* cloud data using the SID-3 probe was obtained during the UK Met Office CONSTRAIN campaign in Scotland in February 2010. Fig. 1 shows a random selection of particles observed in cirrus and mixed phase clouds. Comparison with laboratory ice analogue data, also shown in Fig. 1, demonstrates qualitatively that the image texture of the majority of the *in situ* patterns is consistent with the presence of significant roughness.

Image texture can be quantified using statistical measures, such as the gray-level co-occurrence matrix (GLCM), which deals with the spatial relationships of pairs of gray values of images pixels. In the past, GLCM was applied to retrieving surface roughness from laser speckle images of surfaces [19]. Here, four features of GLCM were chosen: contrast, correlation, energy and homogeneity, in addition to image entropy. They were calculated for 2D patterns from cirrus and mixed phase cloud particles as well as smooth and rough ice analogues, and correlated with a subjective measure of pattern speckle. Energy had the strongest correlation with the subjective pattern speckle: -0.7. A combined contrast-energy-homogeneity feature had correlation similar in magnitude with opposite sign, but showed slightly larger difference for test patterns of smooth and rough analogues. Interestingly, the

GLCM energy shows good correlation with surface roughness and is most robust with respect to variation of "*the setup configuration, the position, and the orientation of the surface to be measured*" in the context of laser speckle [19]. Distributions of the statistical features for a random sample of 500 patterns from CONSTRAIN are shown in Fig. 2. Like for the qualitative comparison in Fig. 1, the properties of most of the patterns were consistent with the presence of significant particle roughness, at levels exceeding that found in the moderately rough analogue crystal used as a reference. The spread of roughness was slightly wider in cirrus.

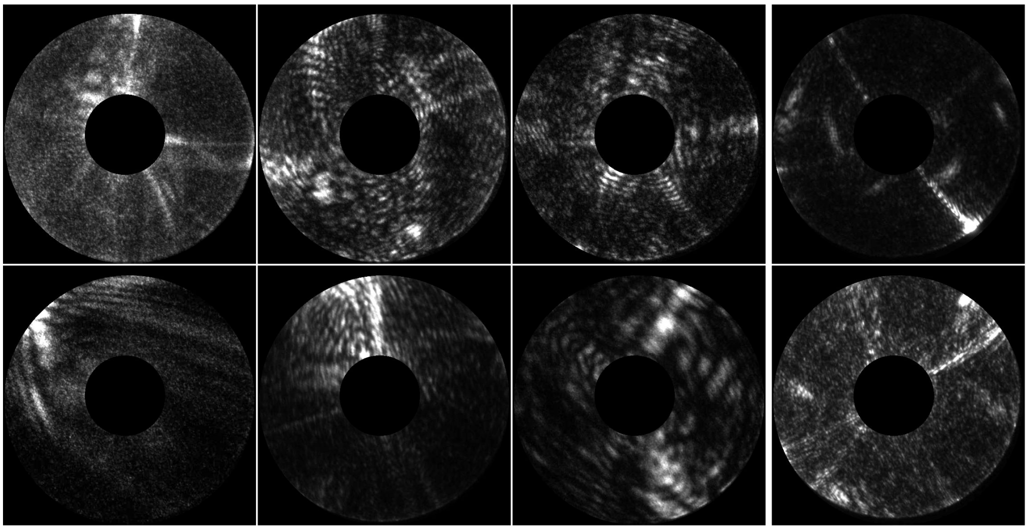

Figure 1. Six randomly selected SID-3 patterns from ice particles seen during CONSTRAIN cirrus (top) and mixed phase (bottom) flights, compared to patterns from ice-analogue rosettes with smooth (top right) and moderately rough surfaces (bottom right).

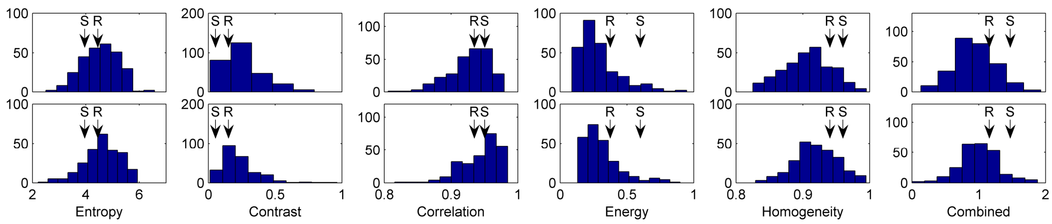

Figure 2. Frequency distributions of statistical features of 2D patterns from cirrus (top row) and mixed phase (lower row) flights. Arrows show values for the smooth (S) and moderately rough (R) ice analogues from Fig. 1. The "combined" feature is (energy + homogeneity – contrast). Note that all but entropy and contrast are anticorrelated with roughness.

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