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The applicability of physical optics in the millimetre and sub-millimetre spectral region. Part II: Application to a three-component model of ice cloud and its evaluation against the bulk single-scattering properties of various other aggregate models

Anthony J. Baran[a,*], Hiroshi Ishimoto[b], Odran Sourdeval[c], Evelyn Hesse[d], Chawn Harlow[a]

[a] Met Office, Exeter, UK
[b] Meteorological Research Institute, Nagamine 1-1, Tsukuba 305-0052, Japan
[c] Institute of Meteorology, Universität Leipzig, Leipzig, Germany
[d] University of Hertfordshire, Centre for Atmospheric and Instrumentation Research, Hatfield, Hertfordshire AL10 9A, UK

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ABSTRACT

The bulk single-scattering properties of various randomly oriented aggregate ice crystal models are compared and contrasted at a number of frequencies between 89 and 874 GHz. The model ice particles consist of the ten-branched plate aggregate, five-branched plate aggregate, eight-branched hexagonal aggregate, Voronoi ice aggregate, six-branched hollow bullet rosette, hexagonal column of aspect ratio unity, and the ten-branched hexagonal aggregate. The bulk single-scattering properties of the latter two ice particle models have been calculated using the light scattering methods described in Part I, which represent the two most extreme members of an ensemble model of cirrus ice crystals. In Part I, it was shown that the method of physical optics could be combined with the T-matrix at a size parameter of about 18 to compute the bulk integral ice optical properties and the phase function in the microwave to sufficient accuracy to be of practical value. Here, the bulk single-scattering properties predicted by the two ensemble model members and the Voronoi model are shown to generally bound those of all other models at frequencies between 89 and 874 GHz, thus representing a three-component model of ice cloud that can be generally applied to the microwave, rather than using many differing ice particle models. Moreover, the Voronoi model and hollow bullet rosette scatter similarly to each other in the microwave. Furthermore, from the various comparisons, the importance of assumed shapes of the particle size distribution as well as cm-sized ice aggregates is demonstrated.

1. Introduction

There is a need to generate the bulk single-scattering properties of ice crystals in the millimetre and sub-millimetre parts of the spectrum, owing to the launch in the early 2020s of the space-based Ice Cloud Imager (ICI) instrument [1]. Moreover, these properties are also required to facilitate interpretation of multi-frequency radiometer data from the ICI airborne demonstrator instrument called the International Sub-millimetre Airborne Radiometer (ISMAR) [2]. The purpose of these instruments is to, partly, make use of their sensitivity to the presence of cirrus and ice cloud, so that properties such as column-integrated ice water content (IWC), called the ice water path (IWP), and bulk ice particle size can be retrieved from polarised multi-frequency observations. It has been known since circa 1990s that the microwave and sub-millimetre spectral regions are particularly sensitive to the IWP and bulk ice crystal size [3–6]. This sensitivity is due to ice at these frequencies being relatively weakly absorbing, thereby causing incident microwave radiation from beneath the cirrus to be scattered out of the line of sight of the instrument. This scattering process leads to depressions in the above-cirrus or ice cloud measured brightness temperature relative to the clear-sky brightness temperature, and it is these brightness temperature depressions that are known to be directly proportional to the IWP [3].

The IWP is related to a numerical weather prediction (NWP) and climate model prognostic variable, IWC. Currently, the performance of such general circulation models (GCMs) in predicting the global distribution of IWC and/or the IWP is known to be poor; see, for example, the studies described in Refs. [7–9]. Indeed, in the most recent report of the International Panel on Climate Change

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[*] Corresponding author.
E-mail address: anthony.baran@metoffice.gov.uk (A.J. Baran).

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(IPCC) the following is stated on page 589: “representation of cirrus in GCMs appears to be poor” [10]. With such a poor representation of cirrus and/or ice mass in GCMs, which, in turn, feeds through to the representation of the hydrological cycle, there is a clear need for more direct global observations of the IWP and ice cloud microphysics through the utilisation of sub-millimetre-wave observations.

To make use of future sub-millimetre global observations of cirrus requires the further development of bulk single-scattering properties of observed atmospheric ice crystals. The brightness temperature depressions previously alluded to in the sub-mm-wave spectral region will depend on assumptions about the particle size distribution, the shape and mass of the ice crystals, and their orientation with respect to an incident beam. It is known that the fractal nature of ice crystals follows particular power laws that describe their mass or density and area, and the mass of aggregating ice crystals generally follows mass–dimension relationships that are proportional to D^2, where D is the maximum dimension of the ice crystal [11–13]. There have been a number of attempts to construct idealised ice crystal models with specific mass–size relationships and apply these models to the development of databases of ice crystal optical properties in the microwave, and apply them to observations; see, for instance, the studies by Refs. [14–22]. The simulation of microwave brightness temperatures, between the frequencies of 10 and 183 GHz, using NWP-generated global model fields was found by Ref. [18] to be generally better using the sector snowflake model of Ref. [14] than by the assumption of soft ice spheres. The reason for this more generally improved simulation of observed brightness temperatures by a snowflake model was shown by Ref. [19] to be that it was an “average” representation of all other ice optical properties that they considered for the same mass of ice; they also found similar favourable behaviour for the eight-branched hexagonal ice aggregate model of Ref. [15], which was originally developed by Ref. [23]. Moreover, the assumption of the soft ice sphere was found not to be generally consistent at all of the frequencies considered by Ref. [19]. This “averaged” bulk optical property behaviour by a single shape of snowflake or ice aggregate might be sufficient to apply to frequencies in the microwave and sub-millimetre spectral regions to retrieve the IWP and bulk ice crystal size. However, previous studies that have assumed the eight-branched hexagonal aggregate have shown that the model generally over-predicts in-situ estimates of IWC by factors of about 2 [24]. This is because this model predicts a mass–dimension relationship that is proportional to D^3 and not D^2. The same study concluded that it is better to assume a shape distribution of ice crystals to predict in-situ estimates of IWC. This was achieved by weighting each of the various members of the shape distribution at each size bin of the PSD, such that the observed IWC was reproduced to well within a factor of 2. In that study, it was necessary to apply such a weighting at each size bin owing to each particle model mass being proportional to D^3, but each model had differing pre-factor values in its mass-dimension relationship. Therefore, the shape distribution of idealised model particles could be made to behave as if their integrated mass values were produced by particles with mass being proportional to D^2. The sector snowflake model of Ref. [14] predicts a density–D relationship of the following form: $\rho \sim D^{-3/2}$, which implies a mass–D relationship also of the form $\sim D^{3/2}$. However, as stated earlier, current microphysical observations of ice aggregation and theory suggest that the mass of aggregating ice crystals should be proportional to D^2, which implies a density–D relationship of the form $D^{-1.0}$. The sector snowflake model of Ref. [14], with such a density profile, at large D values, will predict very low-density particles, as they will become very thin at those D values, relative to density models that predict a $D^{-1.0}$ relationship. These very low-density particles will become weakly interactive with microwave emission from the lower atmosphere and, as a consequence of being very low-density, they will become weakly interacting large particles, or WILPs for short. Thus, in the tropics, where very large D particles can occur, the sector snowflake model will be expected to predict microwave and sub-millimetre brightness temperatures that will probably be too warm relative to observation.

An alternative to simulating microwave scattering by single ice crystal models, soft spheres or soft spheroids is to assume an ensemble model of cirrus ice crystals. To this end, Ref. [25] developed the ensemble model of cirrus ice crystals. This model, which is shown in Fig. 1 in Ref. [25], consists of six shapes, which are a hexagonal ice column of an assumed aspect ratio, AR, of unity (i.e. the ratio of hexagonal column length to diameter), the six-branched bullet rosette, and then hexagonal monomers are randomly attached to build four ice aggregate models, which consist of three-, five-, eight- and, finally, ten-branched hexagonal ice aggregates. The latter aggregate models can cover the largest ice crystal sizes found in the particle size distribution (PSD), whilst the former members can populate the smaller end of the ice crystal PSD. Alternatively, weights can be assigned to each member of the ensemble model at each PSD bin size to compute the bulk ice optical properties and/or the total mass of ice contained in the PSD, similar to Ref. [24]. The applicability of the ensemble model in simulating observations of cirrus from across the spectrum from different types of ice cloud in the mid-latitudes has been previously demonstrated by Ref. [17]. In that reference, it is shown that by combining the ensemble model with a representative moment estimation parameterisation of the PSD, as developed by Ref. [26], observations obtained in the visible, infrared, microwave and radar regions of the spectrum could be simulated to good accuracy. The ensemble model’s predicted bulk ice optical properties have also been validated by global observations of cirrus obtained at visible and infrared wavelengths [27,28].

In this paper, we consider the two most extreme members of the ensemble model of cirrus ice crystals, the first and sixth members only, which are the hexagonal ice column of aspect ratio unity and the ten-branched hexagonal column aggregate. Hereinafter, to simplify the wording, the terms “branched” and “hexagonal” are dropped so that each of the assumed aggregate models is described more simply, owing to all models being composed of hexagonal ice crystals. For example, the latter model is described as the ten-column aggregate. The bulk single-scattering properties of these two models are computed using the light-scattering methods described in Part I. In Part I, it was shown that the physical optics method was applicable in the microwave region down to size parameters of about 18, where the size parameter was defined as $\pi D/\lambda$; this same definition of the size parameter is used in this paper [29]. The bridging between the electromagnetic and physical optics methods applied at size parameters smaller or greater than 18, respectively, was achieved using the ray tracing with diffraction on facets (RTDF) method developed by Ref. [30]. It was argued in Part I that the applicability of RTDF down to such low size parameters in the microwave region was possible, owing to treating diffraction at each of the facets on the ray-tracing paths in addition to diffraction at the projected cross-section of the model ice crystal. Furthermore, the real refractive indices of atmospheric ice in the microwave are generally about 1.77; with such a large real refractive index, the processes of scattering are dominated by diffraction and reflection, both of which are treated accurately by RTDF. In principle, other physical optics methods could also be utilised in the microwave region in the same way as that shown in Part I, such as the methods developed by Refs. [31–33]. By replacing all electromagnetic solutions at a size parameter of 18 or greater with RTDF solutions, it was shown in Part I that the bulk integral ice optical properties of hexagonal columns of aspect ratio unity and eight-column aggregates could be replicated using the