Impact of ice particle shape on short-wave radiative forcing: A case study for an arctic ice cloud

Michael Kahnert\textsuperscript{a,}\textsuperscript{*}, Anne Dagrun Sandvik\textsuperscript{b}, Marina Biryulina\textsuperscript{c}, Jakob J. Stamnes\textsuperscript{d}, Knut Stamnes\textsuperscript{e}

\textsuperscript{a}Swedish Meteorological and Hydrological Institute, Folkborgsvägen 1, S-601 76 Norrköping, Sweden
\textsuperscript{b}Bjerknes Centre for Climate Research, Allégaten 70, N-5007 Bergen, Norway
\textsuperscript{c}Geminali AS, P.O. Box 165, Lilleaker, 0216 Oslo, Norway
\textsuperscript{d}Department of Physics and Technology, University of Bergen, Allégaten 55, N-5007 Bergen, Norway
\textsuperscript{e}Department of Physics and Engineering Physics, Stevens Institute of Technology, Castle Point on Hudson, Hoboken, NJ 07030, USA

Received 18 July 2007; received in revised form 16 October 2007; accepted 18 October 2007

Abstract

We used four different non-spherical particle models to compute optical properties of an arctic ice cloud and to simulate corresponding cloud radiative forcings and fluxes. One important finding is that differences in cloud forcing, downward flux at the surface, and absorbed flux in the atmosphere resulting from the use of the four different ice cloud particle models are comparable to differences in these quantities resulting from changing the surface albedo from 0.4 to 0.8, or by varying the ice water content (IWC) by a factor of 2. These findings show that the use of a suitable non-spherical ice cloud particle model is very important for a realistic assessment of the radiative impact of arctic ice clouds. The differences in radiative broadband fluxes predicted by the four different particle models were found to be caused mainly by differences in the optical depth and the asymmetry parameter. These two parameters were found to have nearly the same impact on the predicted cloud forcing. Computations were performed first by assuming a given vertical profile of the particle number density, then by assuming a given profile of the IWC. In both cases, the differences between the cloud radiative forcings computed with the four different non-spherical particle models were found to be of comparable magnitude. This finding shows that precise knowledge of ice particle number density or particle mass is not sufficient for accurate prediction of ice cloud radiative forcing. It is equally important to employ a non-spherical shape model that accurately reproduces the ice particle’s dimension-to-volume ratio and its asymmetry parameter. The hexagonal column/plate model with air-bubble inclusions seems to offer the highest degree of flexibility.

\textcopyright{} 2007 Elsevier Ltd. All rights reserved.

Keywords: Arctic ice clouds; Radiative forcing; Climate

\textsuperscript{*}Corresponding author.
\textit{E-mail address:} michael.kahnert@smhi.se (M. Kahnert).

0022-4073/$ - see front matter \textcopyright{} 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jqsrt.2007.10.016
1. Introduction

Correct treatment of the interaction of radiation with mixed-phase and ice clouds is important for the proper performance of climate models. To quantify the radiative properties of ice clouds, information is required about (i) ice particle size distribution, (ii) particle shape, (iii) particle composition (inclusions), (iv) cloud horizontal extent, and (v) cloud vertical structure. Due to lack of information it has been customary to prescribe many of these parameters in climate models. Thus, in climate models one could fix the ice particle size at some mean value (values between 50 and 80 μm have been used), and reduce the plane-parallel cloud optical depth by an empirical factor (less than unity) \cite{1} to account for horizontal inhomogeneity. To avoid fixing the particle size, one could tie it to quantities such as the mean ice water content (IWC) and the mean particle size ($\bar{D}$), both of which can be parameterized in terms of cloud temperature ($T_c$), a quantity predicted in climate models \cite{2–5}. Such an approach has been used recently in an attempt to include a more realistic treatment of cloud radiative interactions in an atmospheric global circulation model (GCM) \cite{6}.

In this paper we focus exclusively on the microphysical properties of ice cloud particles and their radiative effect in the solar part of the spectrum. In particular we study the effect of cloud particle shape on the cloud radiative forcing. In several studies of optical properties of ice clouds idealized assumptions about particle shapes and vertical structure were made \cite{7–9}. Also, in solar broadband radiative transfer simulations it has been found that use of a suitable particle shape is more important than knowledge of the correct size distribution \cite{10}.

Several attempts have been made to parameterize the optical properties of ice clouds to facilitate their inclusion in climate models. Thus, Fu \cite{11} developed a parameterization suitable for the solar spectral range, which was extended to apply to the thermal infrared range by Fu et al. \cite{12}. Ice particle size distributions inferred from mid-latitude and tropical cirrus were used in these parameterizations, and idealized hexagonal crystal shapes were assumed. Key et al. \cite{13} extended this parameterization for the short-wave spectral region to include typical particle shapes encountered in cirrus clouds: bullet rosettes, solid and hollow columns, as well as plates and aggregates \cite{8,14–16}. In a recent study \cite{5} existing parameterizations of cloud optical properties, despite differences in detail, were found to yield similar broadband behaviour. Also, current representations of ice particles in GCMs were found to perform satisfactorily for given size and shape distributions of ice particles. On this background, the primary purpose of the present paper is to explore the impact of ice particle shape on cloud radiative forcing, based on the observed vertical structure of the particle size distribution in an arctic cloud.

Several investigations have studied the performance of different particle models for interpreting remote-sensing observations of ice clouds. Thus, Baran et al. \cite{17,18} tested the suitability of various particle models for interpreting dual-viewing multispectral radiance data and found a combination of randomized ice aggregates with an analytical phase function to perform best. This analytical phase function was also compared to those computed from various non-spherical particle models in an attempt to interpret nephelometer observations \cite{19}. It was found that the analytical phase function performed better than those obtained from the non-spherical particle models for this purpose. Doutriaux-Boucher et al. \cite{20} and Labonnote et al. \cite{21,22} studied the use of different ice particle models in cloud retrieval algorithms applied to POLDER observations and obtained good results with inhomogeneous hexagonal model particles. Baran et al. \cite{23} found bullet-rosette and aggregate particles with random distortions to be suitable for interpretation of POLDER data.

These studies indicate that the usefulness of different non-spherical particle models depends strongly on the application. Currently used particle models differ not only in shape, but also in other aspects, such as randomized displacements of the particle surface, small-scale surface roughness, randomized aggregation, or inhomogeneities in the form of air-bubble or soot inclusions. Due to the large number of possible particle model designs and the diverse requirements in various applications, it is important to undertake not only phenomenological performance tests of different particle models, but also to develop an intuitive and physical understanding of the relation between particle shape and corresponding optical and radiative properties. One motivation of the present study is to help develop such an intuitive understanding of the applicability of different particle shapes for simulating the radiative forcing of arctic ice clouds.

Observations indicate that the lower part of a cirrus cloud tends to be dominated by large ice particles, whereas small ice particles typically are found at the top of the cloud \cite{15}. Here we perform a case study in
which we use a vertical structure of the size distribution of the ice cloud particles based on field data from an aircraft experiment carried out over the Arctic Ocean in the Spring of 1998 [24]. We study the effects of cloud particle shape by comparing results from four different particle models.

The paper is organized as follows. In Section 2 we describe four different models of ice particle shapes and their optical properties. In Section 3 we discuss the field data used to describe the vertical structure of the ice cloud particle number density and size distribution, as well as the ice-cloud optical properties derived from these input data and the results from Section 2. Section 4 is devoted to the investigation of the short-wave radiative effects resulting from use of the optical properties of ice clouds introduced in Section 3, and in Section 5 we study how the results in Section 3 change when we assume a given ice water content (IWC) instead of a given particle number density. Discussion and conclusions are provided in Section 6.

2. Modelling optical properties of ice cloud particles

In preparation for a radiative forcing study involving an arctic ice cloud, we created a database for optical properties of ice particles. Computations were performed for 27 different particle sizes in the (unevenly sampled) interval between 5 and 3000 μm, as well as for wavelengths between 200 and 2600 nm. In the wavelength interval between 200 and 1500 nm, which contains 87% of the total solar energy, we used equidistant sampling intervals of 50 nm. In the wavelength interval between 1500 and 2600 nm, which contains 10% of the total solar energy, we performed computations only for wavelengths of 1750, 2000, 2300, and 2600 nm. Thus, our overall sampling interval between 200 and 2600 nm contains 97% of the total solar energy.

To produce accurate broadband solar radiation results, it is more important to use realistic ice cloud particle shapes than to use correct size distributions [10]. Thus, it is particularly important to employ and test different kinds of non-spherical particle models. Moreover, in order to mimic the featureless angular scattering behaviour of realistic ice cloud particles, it is important that model particles contain elements of randomness, such as random distortions of particle geometry and surface roughness, as well as randomly distributed internal inhomogeneities.

The following ice cloud particle models were considered:

(i) **Inhomogeneous hexagonal plates.** Following Ref. [25], the length \( l \) and diameter \( d \) of the crystals were assumed to be related as \( l = 2.02d^{0.449} \), where \( d \) is given in μm. This relation is valid for plates with \( d \geq 3.6 \) μm. The crystals’ inhomogeneity was modelled by use of air-bubble inclusions, an idea due to Macke et al. [26]. Following Refs. [21,22], the air-bubbles were assumed to have an effective radius of \( r_{\text{eff}} = 1.0 \) μm, an effective variance of \( \sigma_{r_{\text{eff}}} = 0.1 \), and a mean separation of 15 μm.

(ii) **Inhomogeneous hexagonal columns.** Following Refs. [25,27], the crystal dimensions were assumed to be related according to \( d = 0.7l \) for \( l \leq 100 \) μm, and \( d = 6.96l^{0.5} \) for \( l > 100 \) μm. The inhomogeneity was modelled by use of air-bubble inclusions in the same way as for the hexagonal plates.

(iii) **Six-branch bullet rosettes with a rough surface.** For the bullets we assumed the same relation between length and diameter as in item (ii). In addition, the height \( h \) of the pyramidal tip of the bullet was assumed to be \( h = 0.25l \) [7] if \( d/2 \leq h \), and \( h = d/2 \) otherwise. As suggested by Baran and Labonnote [23], the surface roughness was assumed to be 40%. The maximum size \( D \) of the bullet rosette was \( D = 2l + 2h \). Because the kinds of rosette shapes considered here are most abundant among the larger crystals in ice clouds, computations for these model particles were only performed for \( D \geq 100 \) μm.

(iv) **Second-generation randomized Koch fractals.** Such particles, which were introduced [7] and extensively applied in the late 1990s (see e.g. Refs. [8,10,28,29]), have a relatively high mass–dimension ratio, typical for particles smaller than 100 μm, but rather untypical for larger ice particles [10]. Thus, for wavelengths longer than about 1400 nm, where ice absorption becomes significant, these particles tend to overestimate absorption relative to scattering, which results in an underestimation of the single-scattering albedo (SSA) [10]. Therefore, these particle models have become less popular in remote-sensing applications. However, to develop an intuitive understanding of the relation between model particle shape and computed cloud radiative forcing we can gain valuable information from comparison of results for these relatively compact particles with those of other shapes. A random distortion of a regular Koch fractal is achieved by performing random displacements of the particle edges, where the...
The degree of randomization is defined as the maximum displacement length divided by the total length of the crystal segment. In our study, we chose a randomization of 25%.

The particles were assumed to be randomly oriented. All computations were performed by use of a Monte Carlo ray-tracing code developed by Macke et al. [7]. In this code, surface roughness is mimicked by a stochastic distortion of the particle geometry, so that in each reflection–refraction event the crystal facet involved in the event is randomly tilted within a range of tilt angles ±θt, where the distortion parameter θt/90° is a measure of the surface roughness.

Note that the smallest size parameters x = 2πD/λ in our database (where D denotes the maximum dimension of the particle) are about x = 12. The geometrical-optics approximation (GOA) is strictly valid in the limit as x → ∞. According to earlier investigations on the validity range of the GOA [30], ray-tracing results for size parameters of about 12 are not expected to be sufficiently accurate for computation of spectral differential scattering properties of single particles. However, we are primarily interested in climate applications, i.e. in average quantities obtained by integration over sizes, wavelengths, and scattering angles. Calculations of averaged optical properties are usually less sensitive to error sources affecting spectral differential scattering properties. Moreover, for any given particle size, the smallest size parameters pertain to the longest wavelengths, which make a relatively small contribution to the broadband solar energy. However, the contribution of the small ice crystals to the total optical depth can be important. For instance, if we had limited the size range to particles larger than 20 μm, the cloud optical depth computed with inhomogeneous hexagonal plates would have been reduced by 7%. Therefore, we chose to include particles as small as 5 μm in our calculations. Thus, we assume that the error in broadband irradiance calculations incurred by the use of the GOA is small compared to that incurred by neglecting the contribution of smaller particles.

![Fig. 1. Extinction cross section in μm² simulated with rough-surface bullet rosettes ("rosette", solid line), second-generation randomized Koch fractals ("koch", dashed line), inhomogeneous hexagonal plates ("hex-plate", dash-dotted line), and inhomogeneous hexagonal columns ("hex-column", dotted line).](image-url)
The single-scattering optical properties obtained for our four different particle models are presented in Figs. 1–3. Fig. 1 shows the extinction cross section $C_{\text{ext}}$ as a function of the maximum dimension $D$ of the particles. In the GOA, $C_{\text{ext}}$ is independent of wavelength, and twice the average geometrical cross section of the particle. For a general definition of $C_{\text{ext}}$ see Ref. [31]. As expected, we see that the randomized Koch fractals, due to their large mass–dimension ratio, tend to give the largest values of $C_{\text{ext}}$. For particle sizes larger than 250 $\mu$m, the different particle models give results that differ by increasing amounts. The inhomogeneous hexagonal columns yield lower values for the extinction cross section than the inhomogeneous hexagonal plates, whereas the results obtained for bullet rosettes lie between those obtained for hexagonal columns and plates.

The SSA is defined as

$$SSA = \frac{C_{\text{sca}}}{C_{\text{ext}}} = \frac{C_{\text{sca}}}{C_{\text{abs}} + C_{\text{sca}}},$$

where $C_{\text{sca}}$ and $C_{\text{abs}}$ denote the scattering and absorption cross sections, respectively. Ice is weakly absorbing over a large part of the wavelength range considered in this study (i.e. wavelengths shorter than about 1400 nm). Thus, the SSA of ice particles is close to unity over this part of the spectrum. As the wavelength increases, deviations from unity are first observed at near infrared (NIR) wavelengths longer than about 1400 nm. Fig. 2 depicts the SSA as a function of the maximum dimension of the particles. We show results for a wavelength of $\lambda = 1500$ nm, where light absorption by ice is significant. Inhomogeneous hexagonal columns and plates yield values that lie close to one another and that are relatively large compared to those for the other two particle models for particle sizes larger than about 100 $\mu$m. The Koch fractals yield the smallest values of the SSA. As mentioned earlier, Koch fractals have a large mass–dimension ratio, whereas realistic ice particles, especially those of larger sizes, often are of the rosette-type or random aggregates. Therefore, using Koch fractals, one is likely to underestimate the SSA due to the relatively large volume of these particles relative to their average projected cross-sectional area. Bullet rosettes are likely to mimic better the shape of realistic ice particles that are larger than 100 $\mu$m, since they are less compact with a smaller mass–dimension

![Fig. 2. SSA as a function of the particles' maximum dimension $D$ at a wavelength of $\lambda = 1500$ nm. The correspondence between line style and particle model is the same as in Fig. 1.](image-url)
ratio. Thus, they give rise to more scattering relative to absorption, resulting in higher SSA-values. Indeed, bullet rosettes yield values of the SSA that are significantly higher than those obtained with the use of Koch fractals (in particular for larger particle sizes), but lower than those obtained from inhomogeneous hexagons. The high values of SSA obtained for the inhomogeneous hexagonal particles are due to non-absorbing air-bubble inclusions, which give rise to a relatively large scattering cross section even for wavelengths at which ice is absorbing.

The asymmetry parameter \( g \) is defined as

\[
g = \frac{1}{2} \int_{0}^{\pi} p(\Theta) \cos \Theta \sin \Theta \, d\Theta,
\]

where \( \Theta \) denotes the angle between the incident and scattered directions of propagation. The normalized phase function \( p \) is a measure for the angular distribution of the scattered intensity. The asymmetry parameter is the average cosine of the scattering angle \( \Theta \) weighted by the phase function. It is a measure for the partitioning between the amount of radiation scattered into the forward and backward hemispheres, respectively. If \( g > 0 \), then, on average, forward-scattering dominates over backward-scattering. The opposite is true for \( g < 0 \).

Fig. 3 shows computed values of \( g \) for the four particle models as a function of size in the wavelength interval between 200 and 1500 nm. One observes quite different qualitative behaviours and significant quantitative differences. To highlight the qualitative differences, the left column shows results on different colour scales adapted to each particle model. To emphasize the quantitative differences, the same results are plotted in the right column on a common colour scale. We shall first focus on the left column and discuss the qualitative differences of the four particle models.

For hexagonal plates (first row) and columns (second row), the values of \( g \) decrease as the particle size increases, whereas the dependence on wavelength shows a maximum around 800 nm. For bullet rosettes (third row) we obtain the lowest values of \( g \) for the smallest particle sizes and the shortest wavelengths. The results obtained for Koch fractals (fourth row), on the other hand, show little size dependence, and a distinct increase with wavelength is only observed in the NIR spectral region for wavelengths longer than 1400 nm.

For Koch fractals (fourth row), side-scattering and backscattering appear to be caused primarily by internal reflections. Thus, there is little variation in \( g \) over a large range of sizes and shapes (apart from a few local minima), and a steep increase of \( g \) for wavelengths around 1400 nm at which ice absorbs significantly, so that internal reflections are quenched, resulting in more forward-scattering, and thus higher values of \( g \).

The characteristics of \( g \) for bullet rosettes (third row) are somewhat more complex. On the one hand, there is an increase of \( g \) for wavelengths at which ice absorbs due to quenching of internal reflections, analogous to what we found for Koch fractals. On the other hand, for small size parameters one clearly observes, even for longer wavelengths, less anisotropic scattering (i.e. smaller values of \( g \)). This behaviour is associated with multiple reflections among the branches of the rosette. We recall that the length \( l \) and the diameter \( d \) of each bullet are related as \( d \sim \sqrt{l} \). Thus, the bullet branches become more elongated as the particle size increases. As a result, the chance for multiple reflections among the branches decreases with increasing size, resulting in reduced side-scattering, and hence in higher values of \( g \).

Regarding the dependence of \( g \) on size and wavelength, hexagonal plates and columns give qualitatively similar results that are distinctly different from those obtained using the other two particle models. The decrease of \( g \) with particle size, which we observe for plates and columns, is due to the fact that larger particles contain more air-bubble inclusions, which results in more side-scattering. The wavelength-dependence of \( g \) for inhomogeneous columns and plates mainly reflects the wavelength-dependence of the asymmetry parameter of the air-bubble inclusions in the ice particles (not shown), which has a maximum around 800 nm.

A comparison of the results plotted on a common colour scale (right column) illustrates the quantitative differences obtained with the different particle models. In general, hexagonal columns yield the lowest asymmetry parameters, whereas bullet rosettes yield the largest values of \( g \).

The high variability in the optical properties of our particle models leads us to expect correspondingly high variations in predicted cloud optical properties. This aspect will be further investigated in the next section.
Fig. 3. Asymmetry parameter \( g \) as a function of wavelength and maximum particle dimension \( D \) for hexagonal plates (first row), hexagonal columns (second row), bullet rosettes (third row), and Koch fractals (fourth row). The left column shows results on different colour scales to highlight the qualitative differences, the right column shows results on a common colour scale to emphasise the quantitative differences.
3. Modelling of ice-cloud optical properties based on microphysical assumptions

3.1. In situ flight measurements and parameterization of altitude profiles of ice particle size distributions

Assessment of the accuracy of computed radiative properties of real ice clouds based on microphysical observations is notoriously difficult, because accurate cloud microphysical observations over the entire size range synchronized with radiative measurements for validation purposes are usually rare. In this study, we make no attempt to accurately reproduce the radiative flux of an actual cloud. Rather, our main goal is to study the sensitivity of radiative cloud properties relevant for climate studies to assumptions made about ice particle shape, and to elucidate the relation between microphysical shape assumptions, optical properties of single particles, and radiative properties of ice clouds. However, to make our study as realistic as possible, we base our radiative transfer simulations on observed cloud microphysical properties recorded for an actual ice cloud during an in situ airborne cloud measurement campaign that was carried out in the period April 9–29, 1998 as part of the First International Satellite Cloud Climatology Project (ISCCP) Regional Experiment-Arctic Cloud Experiment (FIRE-ACE). The FIRE-ACE campaign was held in conjunction with the Surface Heat Budget of the Arctic Ocean (SHEBA) Experiment. The FIRE-ACE campaign focused on all aspects of arctic cloud systems. The campaign headquarters were located in Fairbanks, Alaska with measurements extending well over the Arctic Ocean (ship and aircraft).

In this work we use a data set that was collected during flight #16 (April 28, Inuvik-Barrow) by the Canadian National Research Council Convair 580 aircraft. The aircraft was equipped with a CPI (Cloud Particle Imager) instrument, which yielded direct in situ measurements of ice crystal (particle) size distributions. Cloud microphysics data obtained during the experiment are available on the FIRE III ACE Data Sets web site: http://eosweb.larc.nasa.gov/PRODOCS/fire/table_fire3_ace.html. The database contains output files with particle size data resulting from an analysis of CPI data performed by Boudala et al. [32].

In the FIRE III ACE Data Sets all cloud particles are divided into three types: circles, needles, and irregulars, and the concentration of each particle type is provided. The data are arranged in time and size order. During FIRE-ACE flight #16 the concentration of needles was negligible, and the concentration of irregulars was high. Following [28], we model altitude-dependent size distributions of circles and irregulars as either uni-modal or bi-modal distributions. The uni-modal size distribution is assumed to obey an exponential function:

\[ n_1(r) = N_1 \exp\left(-\frac{r}{r_{m1}}\right), \]

where \(N_1\) and \(1/r_{m1}\) are respectively the maximum number of particles and the slope of the size distribution.

The bi-modal distribution is considered to be the sum of the first maximum peak, represented by an exponential as in Eq. (3), and a second maximum peak, represented by the gamma distribution function:

\[ n_2(r) = \frac{N_2}{\Gamma(b)} \left(\frac{b}{r_{m2}}\right)^b r^{b-1} \exp\left(-\frac{b}{r_{m2}} r\right). \]

Here \(N_2\) is the maximum number of particles in the second mode of the distribution, \(r_{m2}\) is the mean particle radius, and \(b\) determines the shape of the distribution.

The parameters of the two distributions, i.e. \(N_1\), \(r_{m1}\), \(N_2\), \(b\), and \(r_{m2}\) were estimated through fitting of the experimental data to parameterized curves, represented either by Eq. (3) or by the sum of Eqs. (3) and (4). In most cases, the second peak was significantly weaker for the analysed data set than the first peak (not shown).

Assuming large-scale horizontal variations of the ice particle distributions, we estimated altitude profiles of size distributions by averaging over the time duration of the flight at any given altitude.

Fig. 4 gives an overview of the resulting physical properties of ice cloud particles observed during FIRE-ACE flight #16 on April 28, 1998. The left and middle panels show the normalized size distributions of circles and irregulars, respectively, at three different altitudes. The right panel depicts vertical profiles of particle number densities (i.e. size distribution profiles integrated over size) for each type of ice particles.
3.2. Ice cloud particle models

The CPI measurements were limited to the size range between 100 and 800 µm. Although the particles within this size range are likely to make the main contribution to the ice-cloud optical depth, the contribution of particles outside this size range is not negligible. Therefore, we based our simulations of ice-cloud optical properties on a parameterization of the size distribution obtained from fits to the CPI data in the size interval between 100 and 800 µm and an extrapolation to a size range between 5 and 3000 µm. The parameters of the bi-modal distributions were estimated through minimization of misfits between experimental and analytical size distributions with the least-mean-squares method, where the average discrepancy was less than 10%.

Because the circles are oblate objects, we employed the inhomogeneous hexagonal plate model to simulate the contribution of these particles to the cloud optical properties. To simulate the contribution of irregulars to the cloud optical properties we tested the four models described below.

(A) Inhomogeneous hexagonal plates covering the size interval [5 µm, 100 µm], and six-branch bullet rosettes with a rough surface covering the size interval [100 µm, 3000 µm].
(B) Second-generation randomized Koch fractals for the entire size range.
(C) Inhomogeneous hexagonal plates for the entire size range.
(D) Inhomogeneous hexagonal columns for the entire size range.

Smaller ice cloud particles tend to be more compact, whereas aggregated and rosette-type particles more often are encountered among larger ice cloud particles. With model (A) we mimic a collection consisting of both small compact and large aggregated ice cloud particles.

Fig. 5 shows simulated optical properties of circles (corresponding to the solid line in right panel of Fig. 4 combined with the size distributions in the left panel of Fig. 4) as a function of altitude. The left panel shows the asymmetry parameter $g$ at three different wavelengths. We obtained relatively small values of $g$ and little...
variation with altitude at UV wavelengths. Also, there was little variation of \( g \) with altitude at visible and NIR wavelengths. The middle panel shows the extinction \( d\tau_{\text{ext}}/dz \), where \( \tau_{\text{ext}} \) denotes the extinction optical depth and \( z \) represents the vertical coordinate. As mentioned earlier, \( C_{\text{ext}} \) and thus \( \tau_{\text{ext}} \) are independent of wavelength in the GOA. Note that the extinction profile is not well correlated with the profile of the particle number density for circles in Fig. 4. This behaviour is related to the fact that a high number density often is caused by a large number of small ice cloud particles, which usually do not make the dominant contribution to the ensemble-averaged optical cross section. The ice cloud SSA in the NIR (right panel) shows little variation with altitude and lies around 0.96, a value consistent with that presented in Fig. 2.

Fig. 6 shows profiles of the extinction \( d\tau_{\text{ext}}/dz \) for irregular ice cloud particles (corresponding to the dashed line in the right panel of Fig. 4 combined with the size distributions in the middle panel of Fig. 4) simulated with our four different particle models. Models (A), (C), and (D) yield rather similar results, but the inhomogeneous hexagonal plates [model (C)] largely yield the highest values, the columns [model (D)] yield the smallest values, and the rosettes/plates mixture [model (A)] yields intermediate values. The results of Koch fractals [model (B)] are clearly different from those of models (A), (C), and (D). Owing to their compactness and hence their relatively large physical cross section, Koch fractals yield results for the extinction that are up to twice as large as those obtained for the other three particle models.

Simulated altitude profiles of \( g \) for irregular ice cloud particles computed for all four models (A)–(D) are presented in Fig. 7. The variation of \( g \) with altitude is weak, but the wavelength-dependence is pronounced. Also, there are significant differences between the results obtained with the different ice cloud particle models. The inhomogeneous hexagonal column [model (D)] sticks out with fairly low values of \( g \), whereas the rosettes/plates mixture [model (A)] generally yields the highest values of \( g \), except at \( \lambda = 1500 \text{ nm} \), where models (A) (rosettes/plates) and (B) (Koch fractals) give about the same results. These results are consistent with those shown in Fig. 3.
Fig. 6. Vertical profiles of the extinction for “irregulars” simulated with model (A) (hexagonal plates and rosettes, solid line), model (B) (Koch fractals, dashed line), model (C) (hexagonal plates, dash-dotted line), and model (D) (hexagonal columns, dotted line).

Fig. 7. Vertical profiles of the asymmetry parameter $g$ for “irregulars” at three different wavelengths. The correspondence between line style and particle model is the same as in Fig. 6.
Fig. 8 presents altitude profiles of the SSA for irregular ice particles at $\lambda = 1500$ nm simulated with the four particle models. The inhomogeneous hexagonal plate and column models (C) and (D) show little variation of the SSA with altitude. This behaviour is consistent with the finding in Fig. 2 that for these particles the SSA depend weakly on particle size. Thus, a variation in the size distribution with altitude (see the middle panel in Fig. 4) has little effect on the SSA. Fig. 2 shows that the opposite is true for bullet rosettes and Koch fractals, i.e. for sizes larger than 100 $\mu$m, these models predict a strong dependence on particle size. Thus, models (A) and (B) display a strong dependence of the SSA on altitude, which is caused by the variation of the particles’ size distribution with altitude and the size dependence of the SSA for these particle models. Also, the relative magnitudes of the SSA in Fig. 8 obtained for the four particle models correspond to what one would expect from the results shown in Fig. 2.

4. Radiative transfer computations

4.1. Methods

To investigate the effect of the different ice cloud particle models on the short-wave radiative transfer in the arctic atmosphere, we carried out calculations with the radiative transfer model libRadtran [33]. Version 2 of the standard plane-parallel DISORT algorithm by Stamnes et al. [34] was used as the radiative transfer solver (DISORT2). A standard subarctic summer atmosphere [35] and optical properties from the four ice cloud particle models as estimated in Section 3 were used as input to libRadtran. We represented the cloud as a vertically inhomogeneous slab with optical properties as shown in the preceding figures. Radiative transfer calculations were performed for 31 separate wavelengths in the range from 200 to 2600 nm, as described in Section 2. The simulated radiative fluxes (irradiances) were then integrated over the wavelength region from $\lambda = 200$ to 2600 nm to get the total fluxes presented in Fig. 9. The solar zenith angle was set equal to 63.5°. No data for the surface albedo were available for the specific date on which our cloud microphysical input data
were observed. During Spring the surface albedo of the Arctic Ocean can vary considerably due to open leads and meltwater on the surface of the sea ice. Therefore, we used two different values for the surface albedo in our calculations. A surface albedo of 0.4 was chosen to represent sea ice partially covered with meltwater ponds, and a surface albedo of 0.8 was chosen to represent partially snow-covered sea ice without meltwater. In either case the surface was modelled as a Lambertian reflector. In the absence of more detailed information, we neglected the spectral dependency of the surface albedo.

4.2. Vertical variation of SW radiative fluxes

Figs. 9(a), (b), and (c) show the direct downward flux, the diffuse downward flux, and the diffuse upward flux, respectively, computed for a surface albedo of 0.4. The net flux (direct downward flux plus diffuse downward flux minus diffuse upward flux) is shown in Fig. 9(d). Corresponding clear-air fluxes are included for comparison. At the top of the atmosphere (TOA), the incoming flux for a solar zenith angle of 63.5° is 592 W/m².
As can be seen in Fig. 9(a), the direct flux decays rapidly on penetration into the cloud. At an altitude of roughly 5000 m, it is equal to the diffuse downward flux in Fig. 9(b). By comparing the direct downward flux in Fig. 9(a) with the extinction profile in Fig. 6, we see that the steep decreases in the direct downward flux at altitudes of about 2.5 and 5.5 km correspond to maxima of the extinction. Moreover, ice cloud particle models (A), (C), and (D) yield nearly identical results for the direct downward flux, whereas model (B) yields a considerably smaller direct downward flux. This finding is consistent with that in Fig. 6, where we see that the extinction of ice cloud particle models (A), (C), and (D) are comparable, but much smaller than that for model (B). The difference between the direct downward flux predicted by model (B) and that predicted by the other three models is remarkably large. At the bottom of the atmosphere (BOA) the direct downward flux of model (B) is attenuated to 23 W/m², which is about 50 W/m² more than the attenuation obtained from either of models (A), (C), and (D). In fact, the largest difference at the BOA between the direct downward fluxes obtained from ice cloud particle models (A), (C), and (D) is only 8 W/m².

In Figs. 9(b) and (c) one observes an increase in the diffuse downward flux and a decrease in the diffuse upward flux at altitudes of 2.5 and 5.5 km, corresponding to the maxima of the extinction shown in Fig. 6. Ice cloud particle model (B), which predicts the largest extinction, yields the largest diffuse downward flux inside the cloud and below it. Analogously to what we found for the direct downward flux, models (A) and (C) yield similar results for the diffuse downward flux, whereas the results for model (D) are seen to differ much more from those of models (A) and (C) than one would expect in view of their similar extinction profiles (see Fig. 6). Above the cloud model (D) yields a larger diffuse upward flux than models (A) and (C), while inside the cloud and below it, model (D) predicts smaller diffuse downward and upward fluxes. The deviation between the diffuse flux obtained from model (D) and that obtained from either model (A) or (C), is due to the difference between the asymmetry parameter of model (D) and that of either model (A) or (C). As shown in Fig. 7, model (D) yields much smaller asymmetry parameters at all altitudes and for all wavelengths than model (A) or (C). Thus, the particles of model (D) scatter less anisotropically and produce more backscattering above the cloud and less forward-scattering inside the cloud and below it. Models (B) and (D) predict larger diffuse downward fluxes above the cloud than model (A) or (C) due to enhanced multiple scattering caused by larger diffuse upward fluxes of model (B) or (D) than of model (A) or (C).

The differences between the four ice cloud particle models become even more clear when we compare the net fluxes shown in Fig. 9(d). Model (B) yields the smallest net flux due to its large optical depth, and model (D) yields the second-smallest net flux due to its small asymmetry parameter. Next, we consider whether the strongest impact on the net flux is due to the optical depth or the asymmetry parameter of the ice cloud. At the BOA, Fig. 9(d) shows a pronounced difference between the net flux obtained from ice cloud particle model (B) and that obtained from either of the other three models. This indicates that the BOA net flux is mainly determined by the cloud’s optical depth. In contrast, the TOA net fluxes obtained from models (B) and (D) are comparable (see Table 1), implying that the impacts of the optical depth and the asymmetry parameter on the cloud albedo, and thus on the TOA net flux, are comparable. Note that in our results the TOA net fluxes differ only slightly from the net fluxes at the tropopause (not shown), which is a key parameter for the large-scale tropospheric temperature field.

Fig. 9(d) shows that the difference between the net fluxes obtained from ice cloud particle models (A), (C), and (D) is as large as 10 W/m² at the BOA, despite the similar extinction profiles (see Fig. 6) of these three particle models. This relatively large difference accounts for about 25% of the cloud radiative forcing
(see Fig. 10). At the TOA, the largest difference between the net fluxes obtained from models (A), (C), and (D) is 19 W/m², which corresponds to about 50% of the cloud forcing. The main cause of these large differences is the difference between the asymmetry parameters of the models, as shown in Fig. 7.

Fig. 8 shows that model (B) predicts the smallest cloud SSA, and thus the largest absorption compared to scattering than any of the other particle models. A small SSA is expected to reduce the cloud albedo and thus increase the TOA net flux. In spite of that, model (B) yields the smallest TOA net flux due to the high impact of multiple scattering and generation of diffuse upward flux. Thus, the small SSA is of minor importance compared to the large optical depth (Fig. 6), because the SSA is close to unity over a large range of the solar spectrum. As the wavelength increases, SSA deviations from unity are first observed at NIR wavelengths longer than 1400 nm, which contribute only some 10% to the broadband solar flux. Thus, differences in the SSA between different ice cloud particle models play a minor role for fluxes and radiative forcing rates when integrated over the wavelength range considered in this study.

4.3. Transmitted flux, absorbed flux, and cloud SW radiative forcing

The radiative fluxes obtained from the different ice cloud particle models are summarized in Table 1 for a surface albedo of 0.4, and Table 2 shows corresponding values obtained for a surface albedo of 0.8. By comparing these two tables, we can estimate the relative importance of ice cloud particle shape and uncertainty in the surface albedo as error sources in radiative forcing simulations. Here radiative forcing is defined as the difference in the net flux between a cloudy and clear atmosphere, i.e.

\[ \Delta F = F_{\text{net}}(\text{clouds}) - F_{\text{net}}(\text{clear sky}). \]  

(5)

We emphasize once more that our study is limited to the short-wave radiative forcing up to 2600 nm. The total radiative forcing is the sum of the short- and long-wave radiative forcings.

The radiative forcing, as defined in (5), is negative for all particle models. The values for the cloud radiative forcing obtained from the different ice cloud particle models vary by at most 23 W/m² at the TOA and...
26 W/m² at the BOA (cf. models (A) and (B) in Table 1). In comparison, results for the cloud forcing obtained using the two different values for the surface albedo (0.4 and 0.8) vary by at most 48 W/m² at the TOA and at the BOA (cf. results for model (B) in Tables 1 and 2). Thus, these two sources of uncertainty yield maximum errors in radiative forcing simulations that are of the same order of magnitude, although the errors associated with uncertainty in the surface albedo are about twice as large. Note, however, that we have assumed a fairly large range of uncertainty for the surface albedo.

We compared the transmitted fluxes at the bottom of the atmosphere (total down, BOA) as well as the total absorbed flux in the atmosphere computed for our four different particle models. The partitioning between the absorbed solar energy between the atmosphere and the surface is important for the surface energy budget, which impacts evaporation and precipitation, and hence the whole hydrological cycle. The largest difference for the transmitted flux at BOA (44 W/m²) is observed for particle models (A) and (B) for a surface albedo of 0.4 (see Table 1). The corresponding maximum difference obtained for the different surface albedos is 41 W/m² (cf. results for model (B) in Tables 1 and 2). The maximum difference in the total absorbed flux in the atmosphere obtained with our four different particle models was found to be 12 W/m² (compare results for models (B) and (D) in Table 1). On the other hand, a variation in the surface albedo from 0.4 to 0.8 yielded a maximum difference in the total absorbed flux of 11 W/m² (cf. results obtained for models (A) and (B) in Tables 1 and 2). Thus, the uncertainties in the downward flux at the BOA and in the absorbed flux associated with the use of our four different ice cloud particle models were found to be comparable to those associated with the use of different surface albedo values of 0.4 and 0.8.

Fig. 10 shows the vertical variation of the radiative forcing obtained from the different ice cloud particle models for a surface albedo of 0.4. For all particle models, the maximum absolute value of the cloud forcing was observed at an altitude between 2 and 6 km, i.e. inside the cloud. Ice cloud particle model (D) (inhomogeneous hexagonal columns) was found to cause a cloud forcing that was about 25–50% larger than that due to model (A) (mixture of inhomogeneous plates and six-branch bullet rosettes), while the cloud forcing of model (C) (inhomogeneous plates only) was found to lie in between those due to models (A) and (D). The Koch fractals [model (B)] was found to yield forcing rates that at some altitudes deviated by more than 15 W/m² from those due to model (D) (inhomogeneous hexagonal columns), and by as much as 35 W/m² from those due to model (A). Again, we see very clearly that the ice cloud particles with the largest optical depth [model (B)] have the strongest impact on the cloud radiative forcing. The different magnitudes of the forcings obtained from models (A), (C), and (D), which have comparable optical depth profiles, reflect the differences in asymmetry parameters between these models. Model (D), which has the lowest asymmetry parameter, has the strongest impact on the cloud radiative forcing. Model (A), which has the largest asymmetry parameter, has the smallest magnitude of the radiative forcing. At TOA, models (B) and (D) yield comparable results, thus indicating that the high optical depth in model (B) and the low asymmetry parameter in model (D) have a comparable impact on the TOA radiative forcing.

5. Ice-cloud optical and radiative properties based on a fixed ice water content

So far we have simulated optical and radiative properties of an ice cloud with a given particle number density as a function of altitude (see right panel in Fig. 4). However, climate models usually have IWC as input
rather than the particle number density. As mentioned earlier, a significant part of the discrepancies in radiative quantities obtained with the four different particle models arises from their different mass–dimension ratios. It is therefore important to clarify how these differences change when radiative transfer simulations are based on particle mass rather than particle number density as a principal input parameter. In this section we therefore present simulations of optical and radiative properties of ice clouds based on assuming a fixed IWC altitude distribution or IWC vertical profile for all four particle models.

The IWC is defined as the ice mass per volume of air, i.e.

\[
IWC = \rho_{\text{ice}} \int_0^\infty n(r) V(r) \, dr,
\]

where the density of ice is \(\rho_{\text{ice}} = 0.91 \text{ g/cm}^3\) [36], and where \(V(r)\) denotes the particle volume as a function of its size \(r\), which is different for the four different particle models. Thus, if we were to use the same size distribution \(n(r)\) given in Section 3 for all four particle models, we would obtain different IWC vertical profiles, as illustrated in Fig. 11.

By comparing the IWC vertical profiles in the left and right panels in Fig. 11, we see that the circles make a small contribution to the total IWC. The four particle models used to represent the irregulars predict IWC vertical profiles that differ considerably in magnitude although they have a similar dependence on altitude. As expected, the compact Koch fractals [model (B)] yield the largest IWC values. Corresponding results for inhomogeneous hexagonal plates [model (C)] are about a factor of 5 smaller. The other two models (A) and (D) yield almost identical results that lie in between those obtained with models (B) and (D).

The quantitative differences between the four different particle models also become apparent by comparing the total ice mass column, which is obtained by integrating the IWC vertical profile over altitude. For the circles we obtained 0.7 kg/m², and for the irregulars we computed 23 kg/m² [model (A)], 62 kg/m² [model (B)], 14 kg/m² [model (C)], and 24 kg/m² [model (D)].

![Fig. 11. IWC vertical profiles for circles (left) assuming particle model (C), and for irregulars (right) computed for particle models (A) (solid line), (B) (dashed line), (C) (dash-dotted line), and (D) (dotted line).](image-url)
We noted earlier that comparison of the right panel in Fig. 4 with Fig. 6 illustrates the poor correlation between particle number density and extinction. In contrast, comparison of Figs. 6 and 11 reveals that the IWC vertical profiles are strongly correlated to the extinction. This correlation might lead one to believe that knowledge of the IWC vertical profile should enable one to accurately predict the cloud optical depth. But we shall see below that such a belief would be incorrect.

In the following simulations we assumed the IWC vertical profile for the ice cloud under study to be given for both circles and irregulars by the results obtained with model (C) (corresponding to the left panel in Fig. 11 and to the dash-dotted line in the right panel of Fig. 11). In the computation of the ensemble-averaged ice-cloud optical properties the particle number size distribution of model (C) remained unchanged. The particle number size distributions of the other three particle models were scaled at each altitude to make the IWC vertical profiles of all four particle models coincide.

Figure 12 shows the extinction profiles obtained with the four particle models by assuming a fixed IWC profile, as explained above. The result obtained for model (C) is, of course, the same as that in Fig. 6. The Koch fractals [model (B)] yield extinction values that are almost a factor of 3 lower than those obtained for model (C). Due to the high mass–dimension ratio of the Koch fractals, their particle number density must be scaled down considerably in order for their IWC vertical profile to coincide with that of the much less compact hexagonal plates [model (C)]. Models (A) and (D) yield extinction results that are roughly a factor of 2 lower than those obtained for model (C).

These results illustrate that, even when the IWC vertical profile is assumed to be given, the predicted extinction, and hence the cloud optical depth, can vary considerably depending on the employed ice cloud particle model. In fact, the extinction results in Fig. 12 differ by larger amounts than those obtained in Fig. 6, even though there is a much better correlation between the vertical profiles of the IWC and the extinction than between the vertical profiles of the particle number density and the extinction.

In Fig. 13 we see that the differences in optical depth obtained with the four particle models lead to significant differences in the SW cloud radiative forcing. This finding shows that knowledge of the IWC vertical profile is not sufficient to obtain an accurate estimate of the cloud radiative forcing. The reason is that the cloud optical depth depends on the extinction cross section of the particles, which in turn depends on the average geometrical cross section of the particles. In contrast, the IWC depends on the particle mass, and

![Graph](image-url)
hence on the particle volume. The ratio between the geometrical cross section and the volume can differ considerably between different particle shapes. For instance, the Koch fractals [model (B)] are rather compact and have a low ratio of geometrical cross section to particle volume. Hexagonal plates [model (C)] are less compact and have a larger ratio of orientationally averaged geometrical cross section to particle volume. Consequently, when comparing two particle size distributions with equal IWC, model (C) will yield a larger average geometrical cross section, a larger average extinction cross section, and hence a larger cloud optical depth than model (B), resulting in a larger negative cloud radiative forcing. To be able to accurately predict the cloud radiative forcing based on knowledge of the IWC, one needs to use a particle model that accurately mimics the cross-section-to-volume ratio of the ice particles. This idea goes back to Grenfell and Warren [37], who proposed to model scattering by non-spherical ice particles by an ensemble of spheres with an equivalent surface area-to-volume ratio. However, as pointed out in the previous section, an accurate estimate of the cloud optical depth is not sufficient for accurate simulations of the SW cloud radiative forcing. In addition, an accurate estimate of the asymmetry parameter is required.

In Fig. 12 we see that the extinction obtained from model (D) is generally comparable to and only slightly lower than that obtained from model (A). Thus, considering extinction or optical depth alone, one would expect model (D) to yield only a slightly lower negative SW radiative forcing than model (A). In contrast, Fig. 13 shows that model (D) yields a considerably larger negative forcing than model (A). At BOA, the SW cloud radiative forcing of models (A) and (D) differ by 6 W/m², and at TOA by 12 W/m². This discrepancy is caused by the low asymmetry parameter obtained from model (D) compared to that obtained from model (A) (see Fig. 7).

Comparison of radiative flux and cloud forcing estimates obtained with different particle models allows us to assess the uncertainty in such estimates due to different assumptions about particle shape. We need to gauge the significance of these uncertainty estimates by comparing them to uncertainties due to variations in other input parameters. In the previous section we did such a comparison by varying the surface albedo. Now we will do another comparison by varying the IWC, which is an essential parameter in climate models.
The dotted line in the right panel of Fig. 11 shows the IWC vertical profile according to model (D) computed by assuming the fixed number density profile shown by the dashed line in the right panel of Fig. 4. Fig. 10 shows the SW cloud radiative forcing computed based on this assumption. As explained above, we scaled down the particle number density vertical profile in model (D) in order to make its IWC vertical profile coincide with that of model (C) (dash-dotted line in Fig. 11). Comparing the dotted and dash-dotted lines in Fig. 11, we see that this amounts to a reduction of the IWC by roughly a factor of 2. A comparison of the model (D) results in Figs. 10 and 13 (dotted lines) shows that this reduction in the IWC causes a change in the SW cloud radiative forcing by almost 20 W/m². In Table 1 we see that the cloud radiative forcing rates computed with different particle modes can differ by as much as 23 W/m² at TOA and 26 W/m² at BOA [compare models (A) and (B)]. Thus, as a rough uncertainty estimate, we conclude that the use of different ice particle models can result in a variation in the simulated SW cloud radiative forcing that is comparable to the variation in radiative forcing caused by changes in the IWC by a factor of 2.

6. Discussion and conclusions

One goal of this study is to make a quantitative assessment of the impact of different ice cloud particle models on radiative forcing and flux simulations. One important finding is that differences in cloud forcing, downward flux at the surface, and absorbed flux in the atmosphere associated with the use of different ice cloud particle models are comparable to those resulting from a doubling of the surface albedo from 0.4 to 0.8. Another important result is that the variation in the cloud radiative forcing due to the use of different particle models is comparable to the variation in the radiative forcing resulting from a doubling of the IWC. These observations demonstrate that the use of suitable models for ice cloud particle shapes is very important for a realistic assessment of the radiative impact of arctic ice clouds.

The differences in radiative broadband fluxes predicted by different ice cloud particle models were found to be caused mainly by differences in (i) the extinction optical depth and (ii) the asymmetry parameter. An interesting and important observation is that these two single-scattering parameters were found to have a comparable impact on the predicted cloud radiative forcing, in particular at the TOA. Similar findings have recently been reported for the climate forcing by mineral aerosol particles [38–40], which are much smaller than ice and have higher imaginary parts of the refractive index over a broad range of the solar spectrum. It was found that particle shape and its effect on the asymmetry parameter are of primary importance for accurately estimating the direct climate forcing effect of dust aerosols [38–40].

When comparing results obtained by assuming equal IWC vertical profiles for all particle models with corresponding results based on assuming equal number density profiles, we found that the variability of the cloud radiative forcing results computed with different particle models is roughly comparable in both cases. This finding indicates that neither knowledge of particle number nor precise information about particle mass is sufficient for accurate prediction of the cloud optical depth and the cloud radiative forcing. It is of crucial importance to employ a particle model that accurately mimics the cross-section-to-volume-ratio and the asymmetry parameter of the ice particles. In contrast, an accurate estimate of the cloud SSA is far less important for SW radiative transfer computations, since for ice it is close to unity over a large range of UV and visible wavelengths.

Another goal of this study is to contribute to the development of an intuitive and physical understanding of the relation between ice cloud particle models and the predicted climate impact of arctic ice clouds. It is well known from studies of the climate impact of mineral aerosols that it is desirable to use particle models with a high degree of flexibility without introducing too many free parameters [41]. For instance, it has been found that simple spheroidal particle models are capable of producing a broad range of asymmetry parameters and phase functions by just varying one parameter, namely, the spheroids’ aspect ratio [41]. The use of such a model allows one to reproduce realistic aerosol optical properties [41] and radiative fluxes [38] by employing a suitable size-shape distribution of spheroids. Analogously, we may interpret our results in terms of simplicity and flexibility of our ice cloud particle models for simulating the radiative forcing of arctic ice clouds. Clearly, a precise quantification of the effect of different model shape parameters, such as randomization, surface roughness, and inhomogeneity, would require extensive broadband computations in which the particle-model parameters would have to be systematically varied. Due to the high computational
costs of broadband calculations based on geometrical optics simulations and accurate radiative transfer computations, this task would be formidable. However, the results of our study allow us to discuss some key issues.

For a given particle number density, an increase in the optical depth of the ice cloud can be obtained by choosing more “compact” ice cloud particles, i.e. particles having a small average projected surface area compared to average volume. Conversely, for a given IWC the most compact particles yield the lowest optical depth. The randomized Koch fractals are the most compact particles among the four different models used in our study. A hexagonal particle model is more flexible, since it can be made more or less compact by varying its aspect ratio.

The dependence of the asymmetry parameter $g$ on the choice of ice cloud particle model is more complex. According to the third row of Fig. 3, bullet rosettes yield a relatively large asymmetry parameter, even for a rather high degree of surface roughness (40%). This finding indicates that we may not get much variation in $g$ by changing the surface roughness. Thus, rough-surface bullet rosettes will yield relatively large asymmetry parameters, and hence, relatively large TOA net fluxes and correspondingly small negative cloud radiative forcings. This is precisely what we found using ice cloud particle model (A), which mainly consists of bullet rosettes, so that the third row of Fig. 3 applies. Note, however, that the relatively strong forward-scattering of our bullet rosettes is likely to be related to the way in which we simulated surface roughness. The GOA does not lend itself easily to the incorporation of small, sub-wavelength scale features of the particle surface. The method adopted in our study, which was based on randomizing the tilt angle of the surface for each incident ray in the Monte Carlo computations, may have its limitations. A more promising approach may be to replace the Fresnel reflection at the surface by a Lambertian-type reflection.

For a given wavelength, the increase of $g$ with particle size observed for model (A) particles in the third row of Fig. 3 can be partly explained by reduced radiative interactions between the bullet branches as the particle gets larger. For a given particle size, the large values of $g$ for long wavelengths, especially in the NIR, are a consequence of the strong absorption inside the particle, which results in quenching of multiple internal reflections, and thus in stronger forward-scattering.

Inhomogeneous hexagonal particles and, even more so, columns, which have air-bubble inclusions, show a pronounced reduction of $g$ as the particle size increases. This reduction can be explained by the fact that the number of inclusions increases with the particle size. However, for a particle of fixed size one can vary the number of air-bubbles by changing the average separation between them. Thus, ice cloud model particles with air-bubble inclusions having a variable separation can be expected to give a convenient way of varying $g$, and hence, to provide a relatively high flexibility in simulating the radiative impact of ice clouds.

In conclusion, inhomogeneous hexagonal crystals with air-bubble inclusions seem to be a good candidate for further investigations. Variation of the aspect ratio allows one to vary the cross-section-to-volume-ratio, while variation of the mean separation of the inclusions will yield different values of the asymmetry parameter. Another approach to obtain a certain degree of flexibility in varying the optical depth and the asymmetry parameter of ice cloud model particles would be to combine different model shapes.

To validate the performance of different cloud particle models against observations required to provide realistic recommendations for parameterizations in large-scale climate models, it would be desirable to have access to high-quality measurements for comparison. In situ measurements of the direct downward, diffuse downward, and diffuse upward fluxes are available from the data set (Flight #16), but those observations were found to be reliable only as long as the aircraft was at a constant altitude. Thus, we were left with a 14-min record of data, which we considered to be too short for a meaningful evaluation. Also, the size range covered by the CPI measurements was not large enough to simulate the optical depth of the actual ice cloud with sufficiently high accuracy.

For further work on arctic clouds and their influence on radiation and climate feedback, it is crucial to increase the number of high-quality in situ measurements of both microphysical properties and radiative fluxes. During the IPY (International Polar Year) Thorpex project, we plan to deploy a tethered balloon platform at Ny-Ålesund, Svalbard equipped with a miniature cloud particle imager (CPI) and a 4-$\pi$ radiometer to collect data suitable for this purpose. Future high-quality in situ measurements and additional insights from cloud particle model studies should be used to develop improved microphysical and radiative parameterizations for use in GCMs.
Acknowledgements

This work was supported by the Norwegian Research Council, project number 108278 and 175992/S30. The observational data used in this study were collected as part of the First International Satellite Cloud Climatology Project (ISCCP) Regional Experiment-Arctic Cloud Experiment (FIRE-ACE). We thank two anonymous reviewers for their helpful comments.

References