

# *Using laboratory and field measurements to constrain a single habit shortwave optical parameterization for cirrus*

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Using laboratory and field measurements to constrain a  
single habit shortwave optical parameterization for  
cirrus

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**Abstract**

A single habit parameterization for the shortwave optical properties of cirrus is presented. The parameterization utilizes a hollow particle geometry, with stepped internal cavities as identified in laboratory and field studies. This particular habit was chosen as both experimental and theoretical results show that the particle exhibits lower asymmetry parameters when compared to solid crystals of the same aspect ratio. The aspect ratio of the particle was varied as a function of maximum dimension,  $D$ , in order to adhere to the same physical relationships assumed in the microphysical scheme in a configuration of the Met Office atmosphere-only global model, concerning particle mass, size and effective density. Single scattering properties were then computed using T-Matrix, Ray Tracing with Diffraction on Facets (RTDF) and Ray Tracing (RT) for small medium and large size parameters respectively. The scattering properties were integrated over 28 Particle Size Distributions

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as used in the microphysical scheme. The fits were then parameterized as simple functions of Ice Water Content (IWC) for 6 shortwave bands. The parameterization was implemented into the GA6 configuration of the Met Office unified model along with the current operational long-wave parameterization. The GA6 configuration is used to simulate the annual twenty-year short-wave (SW) fluxes at top-of-atmosphere (TOA) and also the temperature and humidity structure of the atmosphere. The parameterization presented here is compared against the current operational model and a more recent habit mixture model.

*Keywords:* GCM, cirrus, parameterization, climate, ice crystal

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## 1 **1. Introduction**

2 In 2013, the Intergovernmental Panel on Climate Change (IPCC) con-  
3 cluded that the coupling of clouds with the Earth's atmosphere is the largest  
4 uncertainty faced in predicting climate change today (Intergovernmental  
5 Panel on Climate Change, 2013). One such cloud type that contributes to  
6 this uncertainty is cirrus due to their extensive global coverage of about 30%,  
7 with coverage reaching 60–80% in the tropics (Sassen et al., 2008). Further-  
8 more, cirrus has diverse microphysical properties, containing a multitude of  
9 particle habits which range in size over several orders of magnitude. This  
10 variety in size, shape and complexity poses many difficulties for the accu-  
11 rate representation of ice cloud in climate models. The range in size means  
12 that currently no single method can be used to calculate the single scatter-  
13 ing properties of ice crystals. For smaller sizes, exact solutions can be sought  
14 (Mano, 2000; Havemann and Baran, 2004; Groth et al., 2015), but as the size

15 and complexity of the ice crystal increases, more approximate solutions are  
 16 necessary (Macke et al., 1996b; Hesse et al., 2012). The diversity of particle  
 17 shape also presents many challenges, and it is well established that the par-  
 18 ticle habit significantly impacts upon the single scattering properties of ice  
 19 crystals (Macke et al., 1998; Bacon and Swanson, 2000; Baran, 2012; Baum  
 20 et al., 2014).

21 The representation of single ice particles for scattering calculations has  
 22 improved significantly over the years. Early studies used very simplified  
 23 shapes such as spheres and cylinders, but these were found to be inadequate  
 24 approximations for the treatment of ice crystals (Macke and Mishchenko,  
 25 1996). More realistic representations of particle habits such as bullet rosettes  
 26 and aggregates have been constructed (Um and McFarquhar, 2007; Xie et al.,  
 27 2011; Baran and Labonnote, 2007; Baum et al., 2014; Baran et al., 2014), and  
 28 are commonly used in habit mixture models to represent cirrus. In addition to  
 29 particle habit, small scale features such as surface roughness, inclusions and  
 30 indentations/cavities have gained recognition as potentially important con-  
 31 tributors to the scattering behaviour of ice crystals (Schmitt and Heymsfield,  
 32 2007; Yang et al., 2008; Schnaiter et al., 2011). Ice particles with deep inden-  
 33 tations/cavities (typically on their basal facets) are commonly described as  
 34 ‘hollow’. Hollowness can significantly affect the *asymmetry parameter*, which  
 35 is given by:

$$g = \frac{1}{2} \int_0^{\pi} P_{11}(\theta) \sin \theta \cos \theta d\theta \quad (1)$$

36 where  $\theta$ , is the *scattering angle*, defined as the angle between the incident and  
 37 the scattered beam.  $P_{11}$ , is the *phase function* - a normalised distribution of

38 the intensity of radiation, scattered from a *randomly* oriented particle (van de  
39 Hulst, 1957), given by:

$$\int_0^{\pi} P_{11}(\theta) \sin \theta d\theta = 2 \quad (2)$$

40 .

41 The phase function, and by extension, the asymmetry parameter, hold in-  
42 formation about the angular distribution of the scattered light, and as such,  
43 the asymmetry parameter is commonly used to implement ice crystal optical  
44 properties into a GCM. Theoretical results show that hollow hexagonal crys-  
45 tals exhibit a general increasing trend in the asymmetry parameter, suggest-  
46 ing that hollow crystals reflect less than their solid counterparts (Yang et al.,  
47 2008). On the contrary, it has been shown that rough particles could reflect  
48 up to twice the radiation when compared with pristine crystals (Ulanowski  
49 et al., 2006). The asymmetry parameter is typically over predicted in scat-  
50 tering models compared with results estimated from in-situ measurements  
51 (Gerber et al., 2000; Gayet et al., 2011). However, these in-situ results could  
52 have been affected by particle shattering on the inlets of the microphysi-  
53 cal probes, thereby artificially decreasing the size and asymmetry parameter  
54 (Korolev et al., 2011).

55

56 To mimic naturally occurring surface roughness, many theoretical studies  
57 make use of the distortion parameter, which approximates surface roughness  
58 by tilting the surface normal for an incoming ray. The tilt angle is defined  
59 by a random number from zero up to a maximum, where the maximum  
60 is defined by the distortion parameter (Macke et al., 1996b). This method

61 yields smoother phase functions with lower asymmetry parameters than when  
62 roughness is not accounted for. Another method used is that of particle inclu-  
63 sions: the incorporation of inclusions into the ice crystal model also smooths  
64 peak features such as ‘halos’ and ‘ice bows’, and reduces the asymmetry pa-  
65 rameter, yielding more realistic values (Macke et al., 1996a; Yang and Liou,  
66 1998; Labonnote et al., 2001; Baran and Labonnote, 2007). For optical pa-  
67 rameterizations, many studies make use of a range of particle habits (Baum  
68 et al., 2005; Bozzo et al., 2008; Baran and Labonnote, 2007), although the  
69 distortion parameter is still widely used as a proxy for surface roughness.  
70 Other studies suggest that with the use of distortion, ice clouds can be rep-  
71 resented entirely by hexagonal prisms of varying aspect ratio, negating the  
72 need to represent the full range of crystal habits (Van Diedenhoven et al.,  
73 2014).

74  
75 Whilst the single scattering properties of cirrus ice particles are affected  
76 by micro-scale features, the bulk optical properties of cirrus are also affected  
77 by macro-scale properties such as cloud optical depth, ice mass in the cloud  
78 column and particle size distribution (PSD). As such, the cirrus net radia-  
79 tive effect is sensitive to the various assumptions made in the microphysical  
80 scheme. Typically, in a GCM, the bulk optical properties of clouds are pa-  
81 rameterized in terms of the diagnostic variable *effective dimension*,  $D_e$ , as a  
82 function of the Ice Water Content (IWC) and/or environmental temperature  
83 ( $T$ ) (Bozzo et al., 2008; Fu et al., 1999). Effective dimension of the PSD is  
84 given by (McFarquhar and Heymsfield, 1998):

85



$$D_e = \frac{3}{2} \frac{WC}{\rho \sum_i n_i A_i} \quad (3)$$

86

87

88 where:

89

90  $WC$  = Water Content91  $\rho$  = density of ice or liquid water92  $A_i$  = the mean cross sectional area in bin  $i$ 93  $n_i$  = number concentration in bin  $i$ 

94

95 The use of effective dimension assumes that the bulk-optical properties  
 96 are uniquely defined by  $D_e$  and either  $IWC$  and/or  $T$ , but it has been shown  
 97 that they are also dependent upon the shape of the PSD (Mitchell et al.,  
 98 2011; Baran, 2005). This dependency is not accounted for in  $D_e$  based  
 99 schemes as they tend to be physically inconsistent with the microphysical  
 100 scheme (Baran, 2012), consequently the microphysical and radiative param-  
 101 eterizations may assume different PSDs. Whilst the use of  $D_e$  is generally  
 102 valid for water clouds, the relationship becomes unreliable for ice clouds and  
 103 for more absorbing wavelengths (Mitchell, 2002; Baran, 2005; Mitchell et al.,  
 104 2011; Baran et al., 2014; Baran, 2012). Recent parameterizations have by-  
 105 passed the need for  $D_e$  by coupling the optical parameterization directly to  
 106 the GGM prognostic variable  $IWC$  (Baran et al., 2014). In order to make the  
 107 microphysical and optical schemes physically consistent, it has also been ar-  
 108 gued that particles used in the optical parameterization should adhere to the

109 same mass-dimensional and area ratio-dimensional power laws as assumed in  
110 the microphysical scheme (Baran, 2012; Baran et al., 2014).

111

112 The parameterization presented in this paper (referred to as hex\_cav from  
113 this point forward) tests the theory that ice clouds can be represented en-  
114 tirely by a single particle habit, as long as the mass-dimensional and area  
115 ratio-dimensional relationships are consistent with the those assumed in the  
116 microphysical scheme. As asymmetry parameters are typically over-predicted  
117 by using pristine particle models, the particle chosen for this parameteriza-  
118 tion is a stepped hollow column, as observed in recent laboratory studies  
119 (Smith et al., 2015, 2016). This particle was chosen because it yields lower  
120 asymmetry parameters than it's solid counterpart (Smith et al., 2015). By  
121 varying the aspect ratio (i.e. ratio of length to radius), as a function of  
122 maximum dimension (defined as the distance between opposite corners of  
123 the two basal facets, see figure 2), the hollow column was fitted to observed  
124 ranges of mass and area-ratio relationships. By doing so, the particles sat-  
125 isfy the same power laws that are assumed in the cloud physics scheme of  
126 the Met Office 6.0 configuration. The construction of the particle model  
127 is discussed in section 2.1. The single scattering properties are determined  
128 using various scattering models for 26 particle sizes across 54 wavelengths  
129 (given in Appendix B), in the shortwave only. Single scattering properties  
130 were calculated with and without the use of the distortion parameter (which  
131 is used to simulate particle roughness) and therefore hex\_cav is split into  
132 two parameterizations: hex\_cav1 (without distortion) and hex\_cav2 (with  
133 distortion), this is further discussed in section 2.3. Bulk optical properties

134 were then found by integrating the single scattering properties over 28 Par-  
135 ticle Size Distributions (PSDs) (section 2.4). The bulk properties were used  
136 in the GA6 configuration of the Met Office Unified Model along with the  
137 current operational longwave parameterization (section 2.5). The GCM is  
138 used to simulate the annual twenty year shortwave (SW) fluxes at the top of  
139 the atmosphere (TOA) and the corresponding zonal mean temperatures and  
140 specific humidities. In total, four model runs are completed. Each of these  
141 runs assumes the same microphysics, but a different optical parameteriza-  
142 tion. These optical parameterizations are: the current operational model by  
143 Edwards et al. (2007), henceforth referred to as Edwards2007; a more recent  
144 optical parameterization by Baran et al. (2014), henceforth referred to as  
145 Baran2014; hex\_cav1 and hex\_cav2. Results from the hex\_cav model runs  
146 are compared against results assuming the Edwards2007 & Baran2014 opti-  
147 cal schemes, and further comparison is made to observations from CERES  
148 (Stephens et al., 2012; Loeb et al., 2009). The hex\_cav2 predicted zonal mean  
149 temperatures and specific humidities are compared against the ERA-Interim  
150 re-analysis product (Dee et al., 2011). The parameterizations Edwards2007,  
151 Baran2014, hex\_cav1 and hex\_cav2 are summarised in table 1.

152

## 153 1.1. Summary of parameterizations

Parameterization	Summary
Edwards2007	<ul style="list-style-type: none"> <li>• An effective dimension <math>D_e</math> based scheme, where <math>D_e</math> is a function of environmental temperature</li> <li>• Ice particles are represented by the 8 branched hexagonal aggregate with roughened surfaces (Yang and Liou, 1998)</li> <li>• Uses 54 in-situ derived size distributions, from the observational campaign CEPEX (McFarquhar and Heymsfield, 1996). The shattered ice crystal artifacts are not removed from the PSDs (see section 2.4)</li> </ul>
Baran2014	<ul style="list-style-type: none"> <li>• Coupled directly to the microphysics scheme, assumes the same mass-dimensional and area-dimensional relationships</li> <li>• Ice particles are represented by a weighted habit mixture model, using six elements: simple column, six-branched bullet rosette, and three-, five- eight- and ten-monomer aggregates Baran and Labonnote (2007)</li> <li>• Uses 28 in-situ derived PSDs (from various field campaigns) parameterized by Field et al. (2007), where shattering artifacts have been removed (see section 2.4)</li> <li>• Bulk optical properties are parameterized in terms of IWC and wavelength</li> </ul>
hex_cav1	<ul style="list-style-type: none"> <li>• Coupled directly to the microphysics scheme, assumes the same mass-dimensional and area-dimensional relationships</li> <li>• Ice particles are represented by a single particle habit: A hollow column with stepped internal cavities (Smith et al., 2015).</li> <li>• Uses 28 in-situ derived PSDs (from various field campaigns) parameterized by Field et al. (2007), where shattering artifacts have been removed (see section 2.4)</li> <li>• Bulk optical properties are parameterized in terms of IWC and wavelength</li> </ul>
hex_cav2	<ul style="list-style-type: none"> <li>• This parameterization is the same as hex_cav1 but the hollow particle is treated as ‘rough’ by using distortion in the single scattering calculations</li> </ul>

Table 1: Summary of the main features of the optical parameterizations: Edwards2007 (current operational model) and Baran2014 (recent habit mixture model) and hex\_cav, which is split into hex\_cav1 (no distortion) and hex\_cav2 (with distortion).

154 **2. Methods**

155 *2.1. Particle Model*

156 The hollow column used in this parameterization is based upon parti-  
157 cles observed during laboratory experiments conducted in the Manchester  
158 Ice Cloud Chamber (MICC) (Smith et al., 2015). Hollow ice crystals have  
159 been observed in many lab and field studies (Walden et al., 2003; Heyms-  
160 field et al., 2002; Bailey and Hallett, 2009). Images from these experiments  
161 show that the hollow columns have cavities which are pyramidal in struc-  
162 ture, which have been modelled in theoretical studies (Schmitt et al., 2006;  
163 Yang et al., 2008). When using a rigorous improved geometric approach,  
164 the general effect of these pyramidal cavities was to increase the asymmetry  
165 parameter (Yang et al., 2008). Laboratory experiments in the MICC found  
166 ice crystals grown at  $-30^{\circ}\text{C}$  tended to have stepped hexagonal intrusions as  
167 seen in figure 1. There was little variation in the geometry of the cavities  
168 at this temperature, and no solid columns were observed. Similar structures  
169 can be seen from in-situ studies which catalogued photographs of ice crystals  
170 collected in-situ (Weickmann, 1949).

171

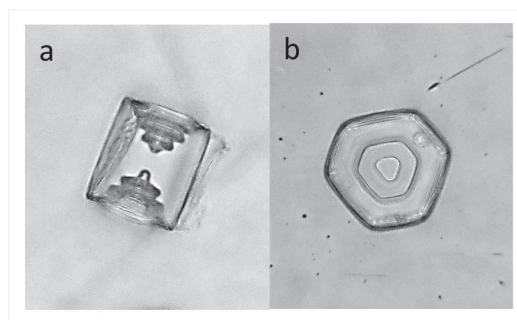


Figure 1: Formvar replicas of typical habits of ice crystals found at  $-30^{\circ}$  in the Manchester Ice Cloud Chamber. Viewed from the prism face (a), and the basal face (b).

172 In order to create a particle model based on formvar replicas, similar to  
173 the one shown in figure 1, an optical microscope was used to take measure-  
174 ments of the crystal facets, averaged values were then used to create a particle  
175 model for use in scattering simulations Smith et al. (2015). The construction  
176 of the particle model is shown in figure 2.

177

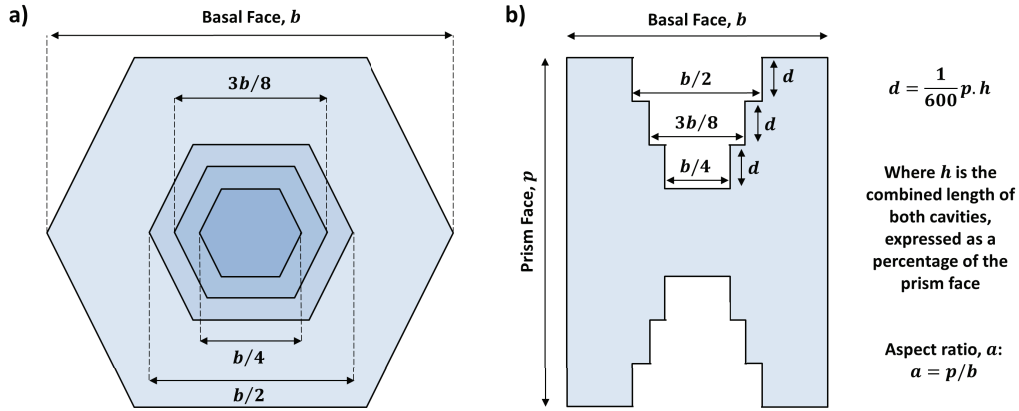


Figure 2: Particle model construction based on average measurements from formvar replicas. Figure a shows a plan view of the particle from the basal facet, and figure b shows a cross sectional view of the particle, taken parallel to the prism facet where  $b$  and  $p$  are the lengths of the basal and prism facets respectively.  $d$  is the depth of each cavity, and  $h$  is the total combined length of both cavities expressed as a percentage of  $p$ . The maximum dimension,  $D$ , is given by  $D = \sqrt{b^2 + p^2}$ .

178 This particular particle model was chosen for the parameterization be-  
 179 cause modelled results show that the stepped hollow column causes a re-  
 180 duction in asymmetry parameter compared with a solid column of the same  
 181 maximum dimension and aspect ratio, in contrast to the pyramidal hollow  
 182 column which causes a general increase (Smith et al., 2015). Therefore, the  
 183 hollow column model offers a way of obtaining smaller asymmetry parameters  
 184 other than the use of the distortion parameter or by embedding air or aerosol  
 185 inclusions within the volume of the ice. Figure 3 shows phase functions and  
 186 asymmetry parameters for the stepped hollow column model, calculated for a  
 187 wavelength of 632 nm, using both Ray Tracing (Macke et al., 1996b) and Ray  
 188 Tracing with Diffraction on Facets (Hesse et al., 2012). This latter model

189 takes into account internal diffraction not accounted for by classical geomet-  
190 ric optics (Hesse et al., 2009). Calculations from Ray Tracing and RTDF  
191 were conducted for a randomly oriented particle, based on  $5 \times 10^4$  particle  
192 orientations, and  $5 \times 10^7$  rays per orientation. 181 angular bins were used  
193 for scattering angles between  $0.25^\circ$  and  $179.75^\circ$ . The hollow particle model  
194 was set up as shown in figure 2, with basal and prism facets measuring 50  
195 and  $100 \mu\text{m}$  respectively, and a hollowness,  $h$ , of 80%. From figure 3 it can  
196 be seen that ray tracing over predicts the halo peaks relative to RTDF but  
197 predicts the same  $g$  values as RTDF. However, in this paper we prefer to  
198 apply the most physically appropriate model, which is RTDF.

199



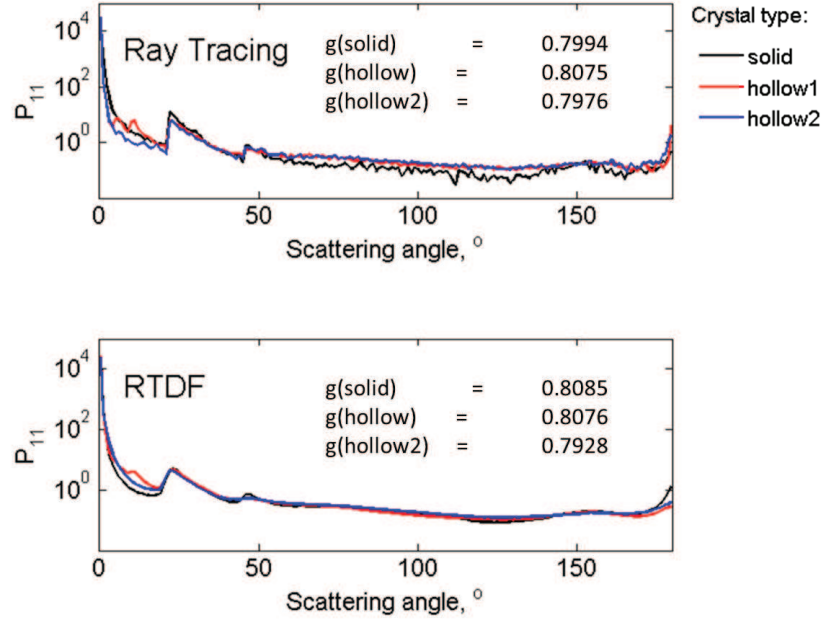


Figure 3: Modelled phase functions of randomly oriented solid and hollow hexagonal columns using Ray Tracing (top) and RTDF (bottom). ‘Hollow 1’ is a particle with a pyramidal cavity, whereas ‘hollow 2’ is a particle with a stepped internal cavity as shown in figure 2.

200 To utilize this model in the optical parameterization, the aspect ratio,  $\alpha$ ,  
 201 is varied as a function of maximum particle dimension in order to fit within  
 202 observed mass-dimensional and area ratio-dimensional relationships. In this  
 203 paper, we define maximum particle dimension,  $D$ , as:

204

$$D = \sqrt{b^2 + p^2} \quad (4)$$

205

206

207 where:

208

209  $D$  = maximum particle dimension210  $p$  = dimension of the prism facet211  $b$  = dimension of the basal facet

212

213 and the aspect ratio  $\alpha$ , is defined as:

214

$$\alpha = p/b \quad (5)$$

215

216

217 *2.1.1. Area Ratio-Dimensional Relationships*

218 The area ratio,  $A_r$ , is defined as the ratio of the particle's projected cross-  
 219 sectional area to the area of a circumscribed circle having a diameter equal  
 220 to the maximum dimension of the particle.

221 *Observed  $A_r(D)$  relationships*

222 Area ratio is a shape sensitive parameter, and is therefore sensitive to par-  
 223 ticle habit. Consequently, observed  $A_r(D)$  laws vary between cloud types.  
 224 Relationships have been found for various cloud types including mixed-habit  
 225 cirrus, mixed phase clouds and tropical anvils (Heymsfield and Miloshevich,  
 226 2003; McFarquhar et al., 2013; Field et al., 2008). For this parameteriza-  
 227 tion, we fit the particles to  $A_r(D)$  relationships observed in mixed habit

228 cirrus (Heymsfield and Miloshevich, 2003). This data represents 10 profiles  
 229 through midlatitude, continental and synoptic cirrus, acquired over 3 field  
 230 experiments. The combined profile follows the relationship:

$$A_r = 0.18 \times D^{-0.271} \quad (6)$$

231 where  $D$  is the maximum particle dimension in cm. This relationship is  
 232 derived from observations in the size range 0.004–0.320 cm, giving area ra-  
 233 tios between 0.8 and 0.25, where the area ratio decreases with respect to  
 234 maximum dimension.

### 235 *2.2. Mass-Dimensional Relationships*

236 In addition to  $A_r(D)$  relationships, the particles used in the parameter-  
 237 ization must also adhere to observed mass-dimensional power laws. Cirrus  
 238 ice crystals are observed to obey the following mass-dimensional relationship  
 239 (Cotton et al., 2013):

$$M(D) = (0.026 \pm 0.012)D^2 \quad (7)$$

240 in the range  $D > 70 \mu\text{m}$

241

242 where:

243

244  $M(D)$  = mass of the ice particle, kg

245  $D$  = maximum dimension, m

246

247 In the size range  $D \leq 70 \mu\text{m}$ , ice particles were found to have a constant  
 248 effective density, given by:

$$\rho_{ICE} = 700 \pm 135 \text{ kgm}^{-3} \quad (8)$$

249 where the effective density of ice,  $\rho_{ICE}$ , is defined as the mass of the ice crys-  
 250 tal, divided by the volume of a sphere with diameter equal to the maximum  
 251 particle dimension  $D$ .

252

253 For the hollow particle model used, equations were derived to characterize  
 254 the relationships between the aspect ratio,  $\alpha$ , area ratio ( $A_r$ ), mass ( $M$ )  
 255 and effective density ( $\rho_{ICE}$ ). These equations were fitted to the observed  
 256 relationships as given in equations 6, 7 and 8. Particles could not be fitted  
 257 exactly to both mass and area ratio relationships, therefore weighted averages  
 258 are taken in order to fit the particle models within observed ranges. A full  
 259 derivation is given in Appendix A.

260 The chosen aspect ratios fit within observed observed area-ratio and ef-  
 261 fective density values in the range  $D > 70 \mu\text{m}$  as shown in figure 4. The  
 262 maximum ice effective density that is achievable with the hollow particle  
 263 model is  $384.9 \text{ kg m}^{-3}$ , which is below the observed range, and subsequently  
 264 particles  $< 70 \mu\text{m}$  cannot be fitted within observed values.

### 265 *2.3. Single Scattering Calculations*

266 The single scattering properties for each of the 26 particles were calcu-  
 267 lated using either T-Matrix, RT or RTDF for 54 wavelengths in the short  
 268 wave between  $0.2 \mu\text{m}$  and  $5 \mu\text{m}$ . The wavelengths and refractive indices can

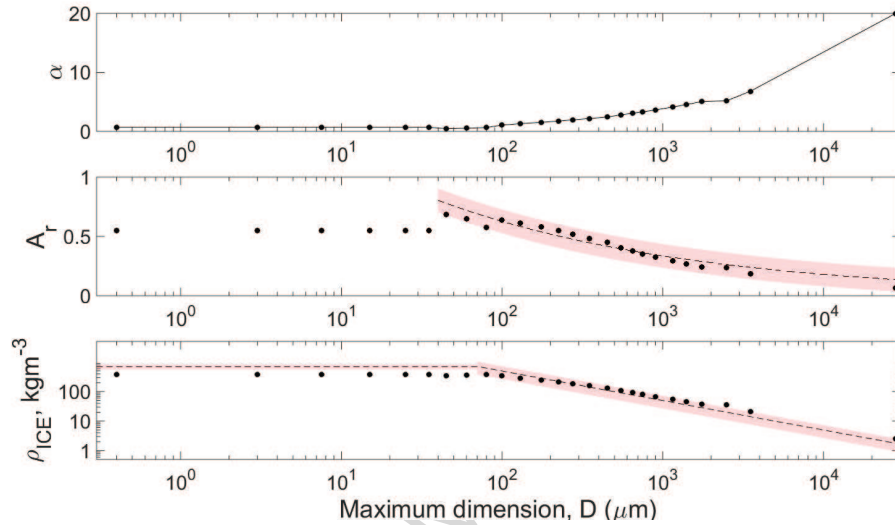


Figure 4: The top graph shows the chosen aspect ratios used for this parameterization. The second graph shows the corresponding area ratios of the chosen particles, and the shaded region shows the observed range. The bottom graph shows the corresponding ice effective density of the chosen particles, and the shaded region shows observed ranges.

269 be found in Appendix B. The choice of scattering model is dependent upon  
 270 the size parameter,  $x$ , defined as  $\pi D/\lambda$ , where  $D$  is the maximum dimension  
 271 of the particle and  $\lambda$  is the wavelength (Hesse et al., 2012). The size param-  
 272 eter can be loosely defined as small ( $x \leq 20$ ), intermediate ( $20 \leq x \leq 60$ ), or  
 273 large ( $x \geq 60$ ) (Baran, 2004). Since no scattering model is applicable across  
 274 the entire range of size parameters found in cirrus, optical parameterization  
 275 make use of a range of models, from exact methods for small size parameters  
 276 (such as T-Matrix), geometric methods for larger size parameters (such as  
 277 ray tracing) and improved geometric methods for intermediate sizes (such as  
 278 RTDF). Since the stepped hollow model contains many small facets, which  
 279 vary in size with aspect ratio, the applicable limits of each scattering model

280 were not well defined. These limits were found by comparing phase func-  
281 tion outputs from the three scattering models. At transitional sizes (sizes  
282 between small, intermediate and large size parameters), the phase functions  
283 were found to be largely similar but below/above these, they were found  
284 to deviate. Therefore the limits were defined where the different scattering  
285 models showed good agreement. By doing so, the scattering model for each  
286 particle size and wavelength was decided on a case by case basis. At smaller  
287 size parameters, the hollow hexagonal model was not used because of the  
288 very small facets, and therefore solid hexagonal prisms were used. In this  
289 case, differences between RT and RTDF were minimal and so RT was used  
290 for the small, solid particles. At even smaller sizes, where RT became none-  
291 applicable, T-Matrix for solid hexagonal columns was used (Havemann and  
292 Baran, 2004). A chart of the chosen models with respect to particle size and  
293 wavelength can be found in Appendix C. For RT and RTDF, each simula-  
294 tion used  $5 \times 10^4$  particle orientations and  $5 \times 10^7$  incident rays. For each of  
295 the 26 particles, the single scattering properties (asymmetry parameter, sin-  
296 gle scattering albedo, extinction cross section and scattering cross section)  
297 were calculated for 54 wavelengths in the short-wave ranging from  $0.2 \mu\text{m}$   
298 to  $5.0 \mu\text{m}$ , using complex refractive indices from Warren and Brandt (2008).  
299 These calculations form the basis of the hex\_cav1 parameterization.

300 In order to diminish the  $22^\circ$  halo, the simulations were also done using the  
301 distortion parameter. Distortion values of 0.1, 0.2, 0.3 and 0.4 were tested for  
302 an example column of maximum dimension  $100 \mu\text{m}$ , aspect ratio 2 and wave-  
303 length  $632 \text{ nm}$  (figure 5). A distortion value of 0.4 was found to completely  
304 remove the halo feature and therefore the single scattering calculations (as

305 done in hex\_cav1) were repeated using a distortion of 0.4, forming the basis of  
 306 the hex\_cav2 parameterization. This distortion value was chosen as the halo  
 307 peak is completely removed, therefore producing a featureless phase function  
 308 similar to those observed in situ (Labonnote et al., 2001). For hex\_cav2, the  
 309 large values of distortion used caused the outgoing ray paths to be signifi-  
 310 cantly deviated. Near the particle edges, this bending of the outgoing ray  
 311 path can cause outgoing rays to re-enter the space occupied by the crystal.  
 312 This can cause errors where the ray is not correctly defined as being either  
 313 in the scattering particle or the host medium, and the particle can no longer  
 314 be considered a closed system. This issue limits the applicable size range of  
 315 RTDF, therefore the applicable size range of RTDF varies between hex\_cav1  
 316 and hex\_cav2 (see Appendix C).

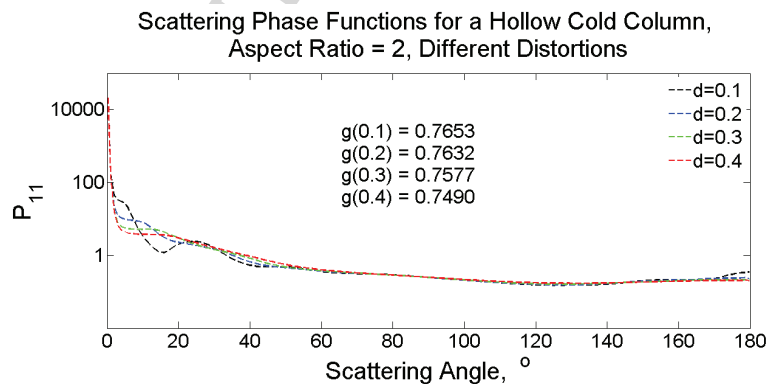


Figure 5: Phase functions of a randomly oriented stepped hollow column, aspect ratio 2, with varying values of distortion. Simulations were run using RTDF, with a wavelength of 635nm. Halo features are evident for distortion values of 0.1, 0.2 and 0.3, but not for 0.4. Therefore a distortion value of 0.4 was used to remove these features.

317 *2.4. Bulk Scattering Properties*

318 In order to calculate the bulk scattering properties, we use 28 PSDs  
319 as parameterized in Field et al. (2007), referred to as Field2007 from this  
320 point forward. The Field2007 parameterization is based on in-situ mea-  
321 surements from the Tropical Rainfall Measuring Mission/Kwajelein Exper-  
322 iment (TRMM/KWAJEX), Cirrus Regional Study of Tropical Anvils and  
323 Cirrus Layers-Florida Area Cirrus Experiment (CRYSTAL-FACE) and the  
324 First International Satellite Cloud Climatology Project Research Experi-  
325 ment(FIRE). Together, these field campaigns include more than 10,000 mea-  
326 sured PSDs for tropical anvils and midlatitude stratiform cloud, covering  
327 temperatures from 0°C to -60°C. Field2007 improves upon earlier parame-  
328 terizations as it covers a larger and therefore more representative tempera-  
329 ture range. Furthermore, the Field2007 parameterization filters out shattered  
330 particles by analysis of ice crystal inter-arrival times, thus reducing the bias  
331 caused by shattering artifacts which is known to have affected historic PSDs  
332 (Field et al., 2006). Generally, bulk optical properties are related to the  
333 microphysical scheme through the use of the diagnosed variable,  $D_e$ , as dis-  
334 cussed in section 1. Instead, we directly couple the bulk optical properties  
335 to the prognostic variable IWC.

336 In order to calculate the bulk scattering properties for each of these PSDs,  
337 firstly, the single scattering properties are interpolated onto size bins in each  
338 PSD, where the number of size bins in each PSD was 500 and these ranged in  
339 size between about 0.4  $\mu\text{m}$  to 28 000  $\mu\text{m}$ . The single scattering properties at  
340 each bin size were then integrated over the PSD, thus finding a weighted av-  
341 erage of each property. The scattering and extinction cross sections ( $\beta_{sca}$  and



342  $\beta_{ext}$ , respectively) are weighted by the mass of cloudy air per unit volume  
343 (in units of  $\text{kg m}^{-3}$ ). This yields the mass scattering and mass extinction  
344 coefficients ( $K_{sca}$  and  $K_{ext}$ , respectively), which describe the scattering and  
345 extinction cross sections per unit mass of cloudy air. The bulk asymmetry  
346 parameter was then found by weighting with respect to scattering cross sec-  
347 tion. These weightings give bulk optical values consistent with the Met Office  
348 Unified Model definitions. In the Met Office global model the bulk scattering  
349 and extinction coefficients are represented by the mass scattering and extinc-  
350 tion coefficients per unit mass of cloudy air, and so the units are  $\text{m}^2 \text{kg}^{-1}$ .  
351 The values of each of the bulk scattering properties are plotted as a function  
352 of wavelength for each of the 28 PSDs, these can be seen in Appendix D.1  
353 and Appendix D.2 for parameterizations hex\_cav1 and hex\_cav2, respectively.  
354 These are used to find parameterized fits for  $g$ ,  $K_{ext}$ ,  $K_{sca}$  and  $\omega_0$  for the 6  
355 short wave bands used in the Met Office configuration 6 atmosphere only  
356 model. A table of these fits can be found in Appendix E.

### 357 2.5. Implementation in the GCM

358 The hex\_cav1 and hex\_cav2 short-wave optical parameterizations are used,  
359 assuming the current Edwards2007 parameterization applied to the long-  
360 wave. In the climate model runs that follow, the Edwards2007 parame-  
361 terization is used as the control model, and comparison is also made with  
362 the more recent Baran2014 parametrization. For all four model runs pre-  
363 sented here (using the optical parameterizations: Edwards2007, Baran2014,  
364 hex\_cav1 & hex\_cav2), the same microphysical scheme is used, based on PSDs  
365 from Field2007, fall speeds parameterized by Furtado et al. (2014) and mass-  
366 dimensional relationships derived by Cotton et al. (2013). This is done so that

367 any changes in the short-wave is entirely attributable to the parameteriza-  
368 tion presented in this paper. The bulk scattering properties are implemented  
369 into the GA6 configuration of the Met Office atmosphere only unified model.  
370 This is used to simulate the annual twenty year short-wave fluxes (fluxes  
371 averaged over 20 one year intervals) at the top of the atmosphere and the  
372 corresponding zonal mean temperatures and specific humidities. Details of  
373 the GA4 configuration can be found in Walters (2016), the subsequent GA5  
374 and GA6 configurations include a new dynamical core, described by Wood  
375 et al. (2014), and the new spectral files for GA6 can be described in section  
376 3 of Manners et al. (2015).

### 377 **3. Results**

#### 378 *3.1. Comparison of Bulk Scattering Properties*

379 In this section, we compare the bulk scattering properties predicted by  
380 the hex\_cav parameterizations with the Edwards2007 parameterization and  
381 the recent Baran2014 parameterization. The Edwards2007 model is an ef-  
382 fective dimension based scheme, with  $D_e$  as a function of temperature. Both  
383 hex\_cav models and Baran2014 have no temperature dependence so instead  
384 we compare bulk scattering properties at set temperatures of 200K, 230K and  
385 270K with respect to ice mass mixing ratio between  $1.0 \times 10^{-7}$  and  $1.0 \times 10^{-3}$   
386  $\text{kg kg}^{-1}$  as these ranges are found in the GA6 model. We compare results for  
387 short-wave band 1 and band 5 (0.2–0.32 $\mu\text{m}$  and 1.19–2.38 $\mu\text{m}$ , respectively).  
388 These particular bands are chosen for comparison due to their contrasting  
389 absorption properties, therefore we expect results to differ largely between  
390 the weakly absorbing band 1 and the strongly absorbing band 5.

391 *Mass Extinction Coefficient*

392 Figures 6, 7 and 8 show the mass extinction coefficient for hex\_cav1, Baran  
 393 2014, and Edwards 2007. From these figures we see that the hex\_cav model  
 394 has the lowest extinction at all fixed values of temperature for short-wave  
 395 band 1. Results from short-wave band 5 and from hex\_cav2 were found to  
 396 be similar, these are not shown for reasons of brevity.

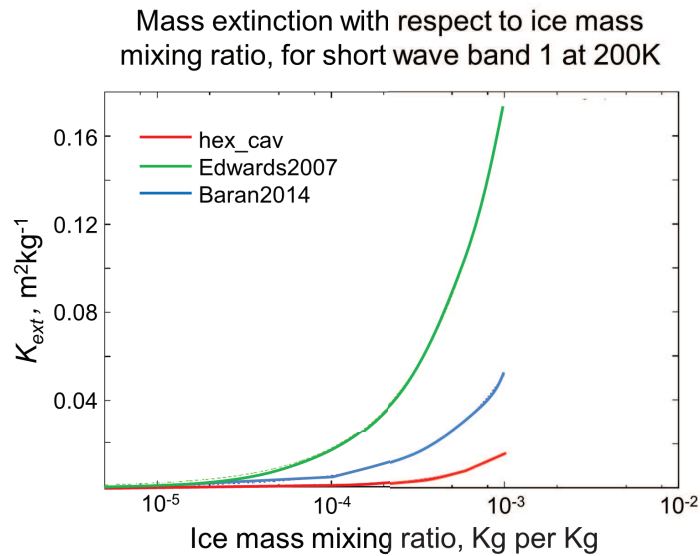


Figure 6: Mass extinction plotted against ice mass mixing ratio as predicted by hex\_cav1, Edwards2007 and Baran2014 at a temperature of 200 K.

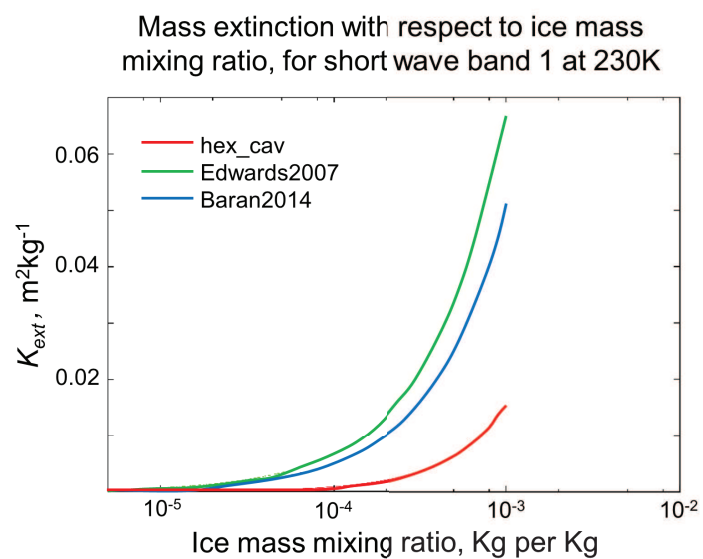


Figure 7: Mass extinction plotted against ice mass mixing ratio as predicted by hex\_cav1, Edwards2007 and Baran2014 at a temperature of 230 K.

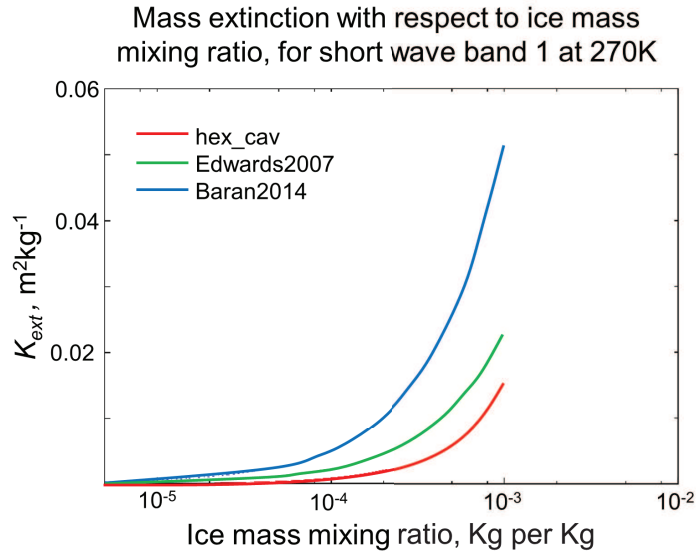


Figure 8: Mass extinction plotted against ice mass mixing ratio as predicted by hex\_cav1, Edwards2007 and Baran2014 at a temperature of 270 K.

397 *Asymmetry Parameter*

398 Figures 9 and 10 show asymmetry parameters for Edwards2007, Baran2014,  
 399 hex\_cav1 and hex\_cav2 at  $T = 200K$  for short-wave bands 1 and 5, respec-  
 400 tively. We see that for the Edwards2007 control model, asymmetry parameter  
 401 is invariant with respect to ice mass mixing ratio as the aspect ratio of the  
 402 particle does not change with particle size. However, the asymmetry values  
 403 for Edwards2007 do vary slightly with temperature, whilst Baran2014 and  
 404 the hex\_cav parameterizations remain constant, as a function of temperature.  
 405 For the more absorbing case (figure 10), we see that the hex\_cav2 parameter-  
 406 ization is closest to the fully randomized Baran2014 model. At this band, the  
 407 asymmetry parameters predicted by Edwards2007 changes significantly as a

408 function of temperature due to the larger (and therefore more absorbing) ice  
409 crystals, but still remain invariant with respect to ice mass mixing ratio.

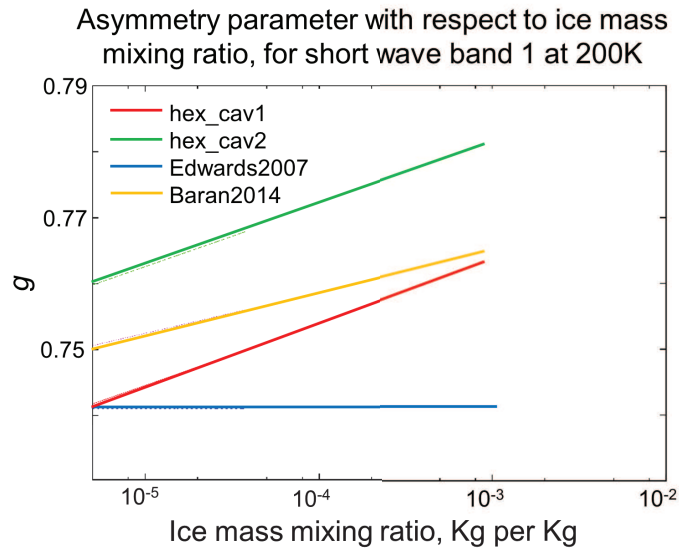


Figure 9: Asymmetry parameter plotted against ice mass mixing ratio for Edwards2007, Baran2014, hex\_cav1 and hex\_cav2, for short wave band 1 at 200K.

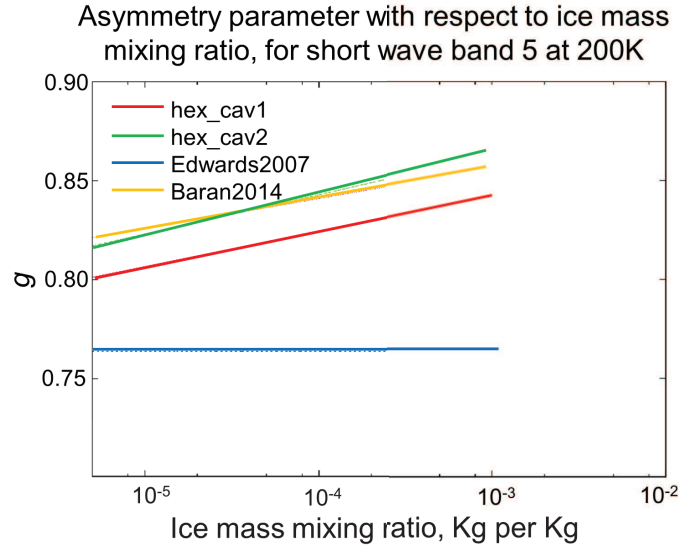


Figure 10: Asymmetry parameter plotted against ice mass mixing ratio for Edwards2007, Baran2014, hex\_cav1 and hex\_cav2, for short wave band 5 at 200K.

410 *Single Scattering Albedo*

411 Figures 11, 12 and 13 show single scattering albedos for Edwards2007,  
 412 Baran2014, hex\_cav1 and hex\_cav2 at temperatures of 200, 230 and 270K  
 413 respectively. At short-wave band 1,  $\omega_0 \approx 1$ , so instead we concentrate on the  
 414 more absorbing short-wave band 5. The Edwards2007  $\omega_0$  values are larger  
 415 than both the Baran2014 and the hex\_cav models. Both hex\_cav values of  $\omega_0$   
 416 increase with ice mass mixing ratio due to the decrease in volume absorption.

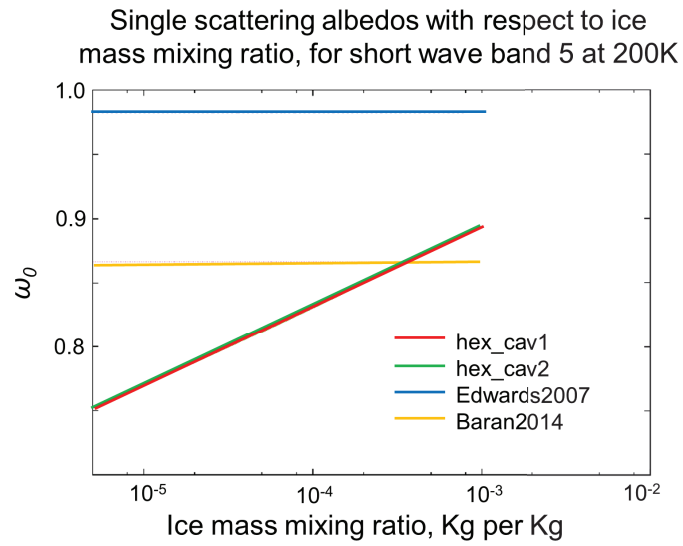


Figure 11: Single scattering albedos plotted against ice mass mixing ratio, as predicted by hex\_cav, Edwards2007 and Baran2014 at  $T = 200\text{K}$ .



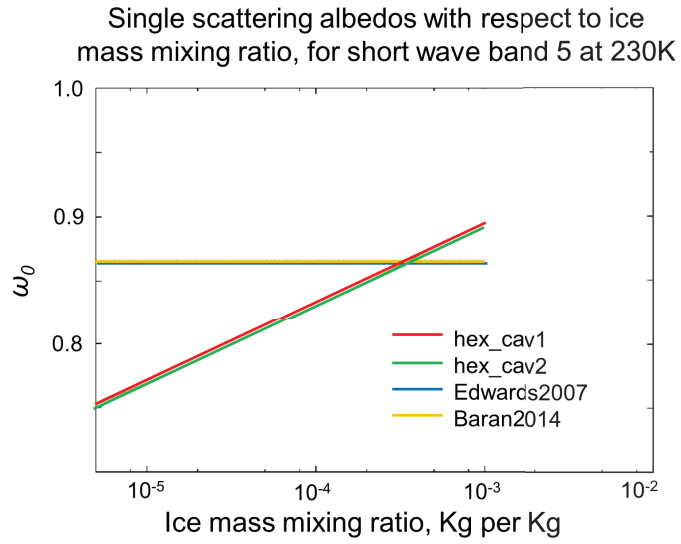


Figure 12: Single scattering albedos plotted against ice mass mixing ratio, as predicted by hex\_cav, Edwards2007 and Baran2014 at  $T = 230\text{K}$ .

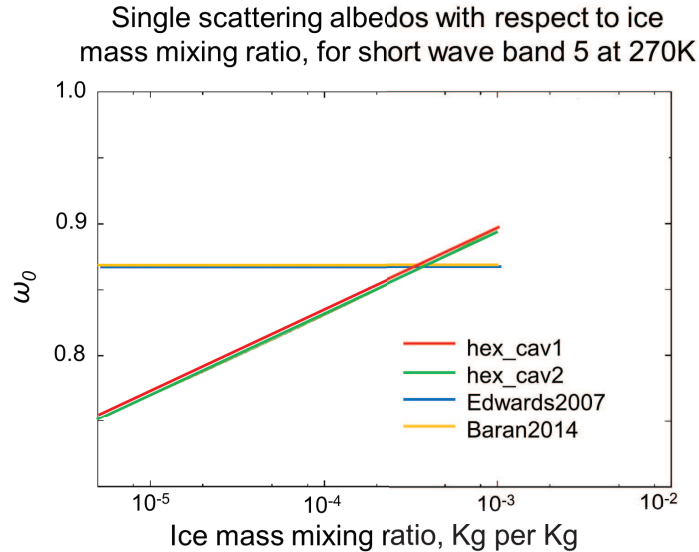


Figure 13: Single scattering albedos plotted against ice mass mixing ratio, as predicted by hex\_cav, Edwards2007 and Baran2014 at  $T = 270\text{K}$ .

### 417 3.2. GCM simulations

418 This section shows results from hex\_cav1 and hex\_cav 2 from the GA6 con-  
419 figuration of the Met Office unified model, compared with the Edwards2007  
420 control model and CERES observations.

421 Figures 14 and 15 show the twenty-year averaged annual down-welling and  
422 up-welling short-wave flux at top-of-atmosphere (TOA) as predicted by the  
423 hex\_cav2 parameterization, respectively. The TOA downwelling short-wave  
424 flux is defined as the short-wave irradiance that reaches the Earths surface  
425 from the model top of atmosphere (80 km). Differences between the two  
426 parameterizations in predicting the downwelling and upwelling fluxes at top-  
427 of-atmosphere can be seen in Figures 14b and 15b, respectively. Results from

428 hex\_cav1 were found to be similar and are therefore not shown for reasons  
429 of brevity. We see differences between the hex\_cav parameterization and  
430 Edwards2007 are highest around the tropics and the southern ocean. When  
431 compared with observations, we see that the control model generally under  
432 predicts down-welling flux, except in the southern ocean where it tends to be  
433 over predicted. On the contrary, the hex\_cav2 parameterization tends to over  
434 predict down-welling flux when compared with observations, particularly in  
435 the tropics and southern ocean. However, there are regional improvements to  
436 be seen in the hex\_cav prediction of TOA fluxes. Improvements can be seen  
437 over the Atlantic, and parts of the Pacific Ocean. Converse to this, figures  
438 15c and 15d show that the Edwards2007 and hex\_cav2 parameterizations  
439 generally over predict and under predict the upwelling short-wave flux at  
440 TOA, respectively.

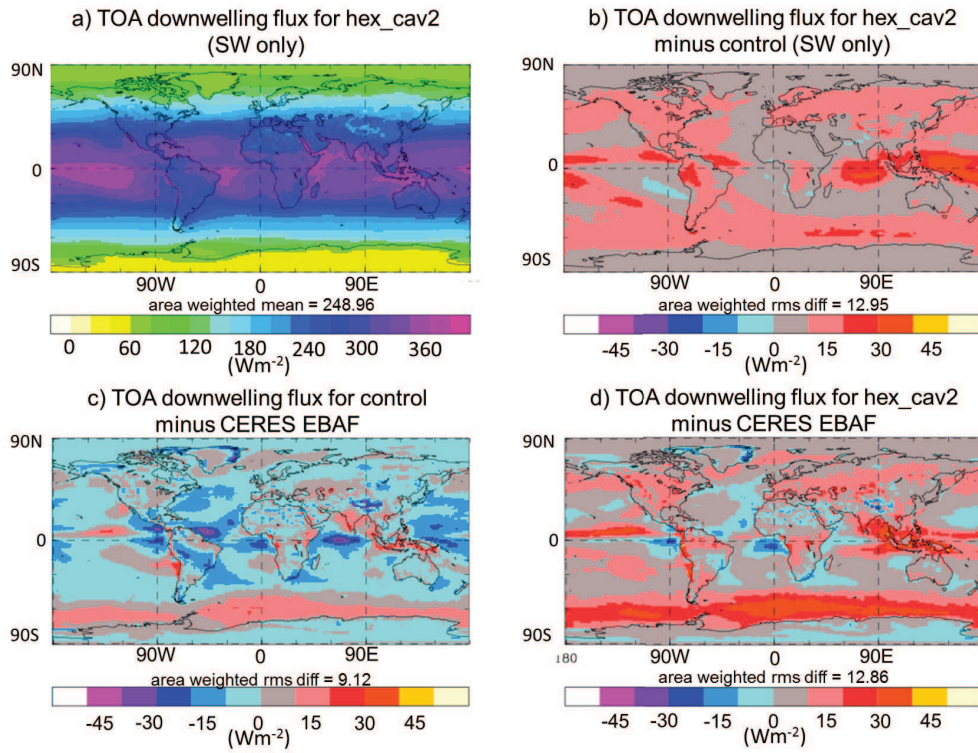


Figure 14: Annual short-wave down-welling flux at top of atmosphere. Clockwise from top left: predictions from hex\_cav2, hex\_cav2 minus control model, hex\_cav2 minus observations, control model minus observations.

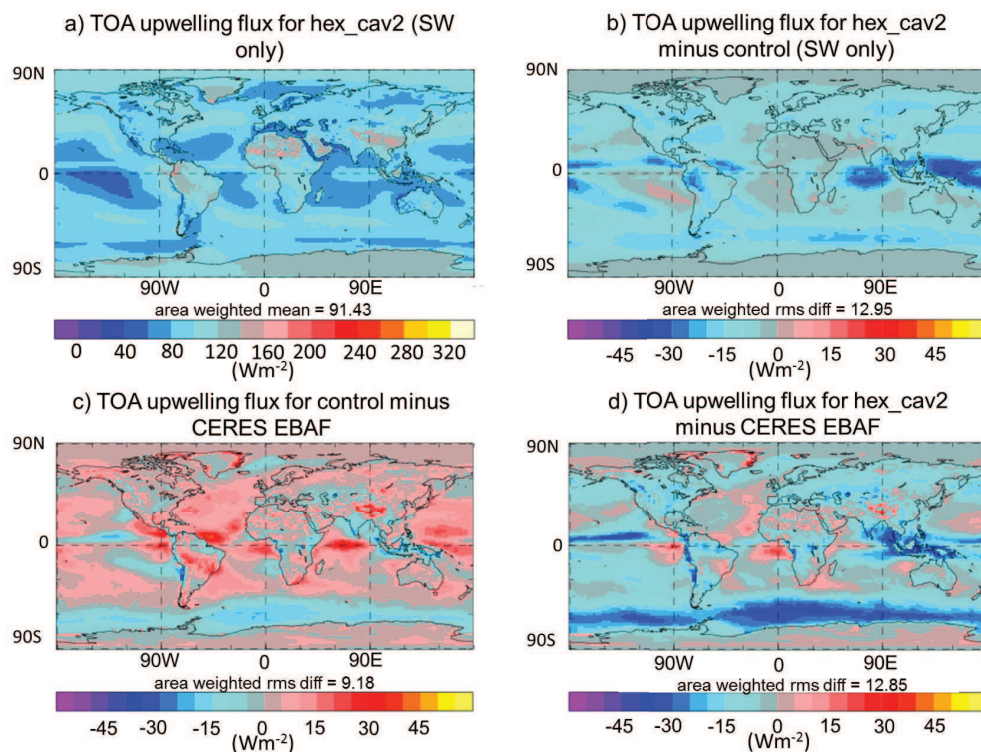


Figure 15: Annual short-wave up-welling flux at top of atmosphere. Clockwise from top left: predictions from hex\_cav2, hex\_cav2 minus control model, hex\_cav2 minus observations, control model minus observations.

441 Figure 16 shows the zonal mean temperatures predicted by by the Ed-  
 442 wards2007 and hex\_cav2 parameterizations. From this it can be seen that  
 443 the under prediction of reflected short-wave flux in the tropics (as seen in  
 444 figures 14 and 15) leads to the warming of the tropical troposphere by about  
 445 1K and cooling of the stratosphere by about 0.5K. Over the North pole this  
 446 results in a significant reduction in the warming relative to the control model,  
 447 and over the South Pole there is a reduction in the cooling relative to the  
 448 control. This warming over the tropics leads to an increase in the specific

449 humidity relative to the control, reducing the dry bias in the upper tropical  
 450 troposphere (shown in figure 17).

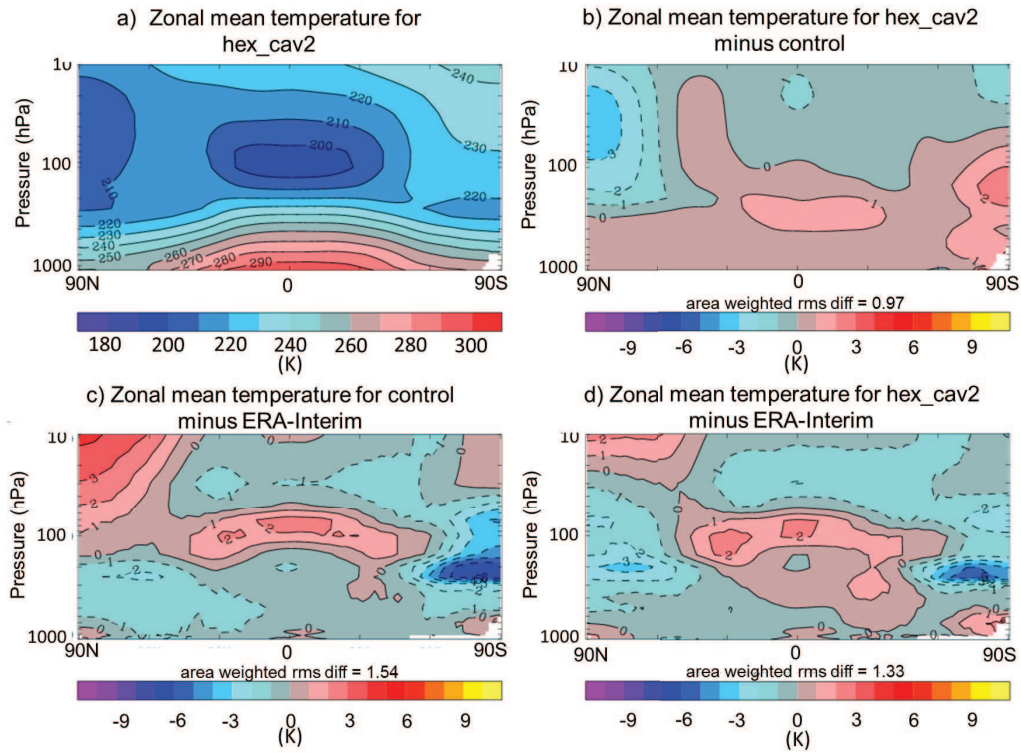


Figure 16: Zonal mean temperatures predicted by the hex\_cav2 parameterization. Clockwise from top left: predictions from hex\_cav2, hex\_cav2 minus control model, hex\_cav2 minus observations, control model minus observations.



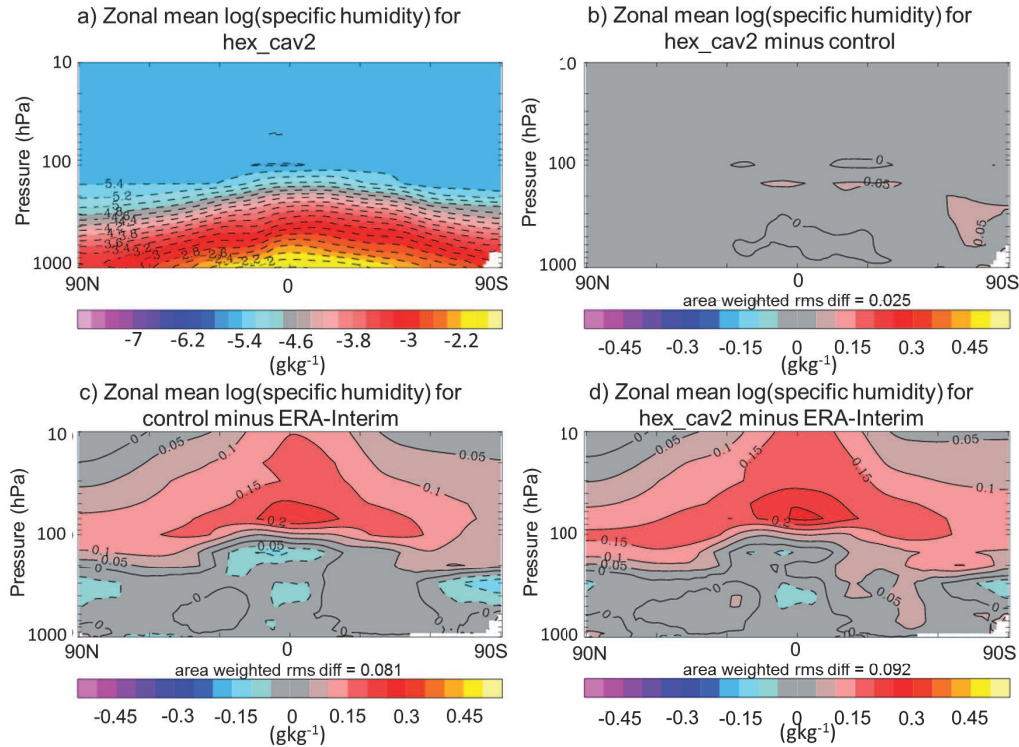


Figure 17: Zonal mean specific humidity predicted by the hex\_cav2 parameterization. Clockwise from top left: predictions from hex\_cav2, hex\_cav2 minus control model, hex\_cav2 minus observations, control model minus observations.

451 Overall, the predictions of TOA short wave flux, zonal mean tempera-  
 452 ture and zonal mean specific humidity differ from observations more so than  
 453 than the current operational model. However, there are regional improve-  
 454 ments that can be seen. For upwelling and downwelling flux, improvements  
 455 on the current model are seen over the North Atlantic, Indian and much of  
 456 the Pacific Ocean. For both the zonal mean temperature and zonal mean  
 457 specific humidity, although biases in the tropical tropopause are increased,  
 458 biases in the polar regions are decreased. Many of these differences may be

459 explained by the largely different mass extinction values predicted by each of  
460 the parameterizations. As seen in figures 6, 7 and 8, the hex\_cav parameter-  
461 izations consistently predicted lower mass extinction values compared with  
462 Edwards2007 and Baran2014 (this is due to large aspect ratios needed to fit  
463 the particle to within observed relationships). These regional improvements  
464 may correspond to areas containing smaller particles, and therefore the larger  
465 particles (with large aspect ratios and low mass extinction) have had little  
466 influence on the region. Alternatively, it is known that the orientation of ice  
467 crystals in the atmosphere is not fully randomized (Yang et al., 2003). Fac-  
468 tors such as gravitational sedimentation can cause preferential orientation of  
469 ice crystals, particularly for  $\alpha \ll 1$  or  $\alpha \gg 1$  (Hashino et al., 2014). In  
470 convective systems, electric fields can also cause preferential alignment (Fos-  
471 ter and Hallett, 2008). In these cases, the projected area, and hence mass  
472 extinction of the ice crystals would be larger than for randomly oriented  
473 particles. Therefore the assumption of random orientation in the GCM may  
474 lead to larger biases in regions where orientation is not negligible. In figures  
475 15 and 14 we see that the largest biases in hex\_cav2 occur in the southern  
476 ocean and over tropical Asia. The derivation of the area-ratio dimensional  
477 relationship is based on data collected in situ via cloud probes. These data  
478 are also orientation dependent, and may be affected by particle orientation  
479 in the sample volume. Data from a variety of cirrus are used to generate a  
480 globally averaged relationship, which may be more representative of certain  
481 regions compared with others.



#### 482 4. Conclusions

483 It has been argued that, to properly model the optical properties of cir-  
484 rus ice clouds, the individual particle models used must adhere to observed  
485 mass-dimensional and area ratio dimensional relationships. By maintaining  
486 these relationships, the optical parameterization not only becomes physically  
487 consistent with the microphysics scheme (in which these relationships are as-  
488 summed), but should ensure that the predicted ice mass and projected areas  
489 are accurate. In this paper, we have investigated the ability of a single par-  
490 ticle geometry (in this case a hollow hexagonal column) to fit within these  
491 constraints.

492 In order to fit a hexagonal prism (whether solid or hollow) to observed  
493 area ratios, preferentially oriented particles had to be assumed, as described  
494 in Appendix A. This resulted in very large aspect ratios of up to 20 being as-  
495 summed. Despite the assumption of preferential orientation for the selection of  
496 particle aspect ratio, single scattering properties were found using randomly  
497 oriented particles, as required by the GCM. In comparison to preferential  
498 orientation, the projected area in random orientation is reduced, which is  
499 particularly significant for larger aspect ratios. Therefore the use of such  
500 large, and unrealistic aspect ratios caused much lower predictions of mass  
501 extinction coefficient compared with other parameterizations, as shown in  
502 figures 6, 7 and 8. Although the use of the hollow particle model reduced the  
503 asymmetry parameter (causing clouds to become brighter) compared with  
504 an equivalent solid model, the effect of reducing the asymmetry parameter  
505 was cancelled out by the very small mass extinction values (causing clouds  
506 to become darker). Therefore, more short-wave radiation will be transmit-

507 ted to Earth, which is evident in figures 14 and 15, where we can see that  
508 hex\_cav2 under-predicts the reflected short-wave radiation at TOA. The ef-  
509 fect of this is to warm the tropical troposphere (figure 16). Generally speak-  
510 ing, the hex\_cav predictions of TOA SW flux, zonal mean temperature and  
511 specific humidity differed from observation moreso than Edwards2007 and  
512 Baran2014, however, some regional improvements were seen. Areas in the  
513 North Atlantic, Indian and much of the Pacific Ocean showed improvements  
514 for upwelling and downwelling flux, and temperature and humidity biases in  
515 polar regions were decreased. This highlights the sensitivity of the climate to  
516 small changes in the microphysical properties of ice clouds and it is therefore  
517 pivotal to construct parameterizations that are microphysically consistent.  
518 Furthermore, it is crucial to evaluate microphysical properties of cirrus and  
519 the single scattering properties of individual ice particles.

520 The results suggest that a single hexagonal prism cannot be used to ap-  
521 proximate ice of all sizes. As seen in figure 4, the particle could not be fitted  
522 to the high values of ice effective density as observed for smaller particles.  
523 In order to conserve the ice mass for such particles, quasi-spherical parti-  
524 cles might be a better approximation (McFarquhar et al., 2002), allowing for  
525 higher area ratios to be achieved. As for large particles, the use of very elon-  
526 gated hexagonal prisms leads to under-predictions in orientation-averaged  
527 projected area. These particles may be better represented by spatial aggre-  
528 gate models, which can achieve the low values of area ratio required, but are  
529 less sensitive to particle orientation. The stepped hollow particle has been  
530 observed in field studies (Weickmann, 1949) and in laboratory studies (Smith  
531 et al., 2015, 2016), where clouds below  $-25^\circ$  were found to contain almost ex-

clusively stepped hollow particles. Therefore, it is likely that such structures occur frequently in cirrus ice cloud, however the internal structures are often unseen with current measurement techniques. Due to their predominance in these studies, in conjunction with their particular optical properties (Smith et al., 2015, 2016), these stepped hollow columns should be incorporated into future habit mixture models.

In current habit mixture models, perturbations from the pristine form are often treated with the use of distortion as a proxy for surface roughness, or by the use of inclusions. Whilst these methods may yield values of scattered intensity close to observations, they may overlook other properties of the scattered light. Measurements from the A-train now provide us with polarization measurements from ice cloud, and it has been shown that particles with similar phase functions may differ significantly with respect to degree of linear polarisation (Mishchenko et al., 2007; Baran and Labonnote, 2006; Stephens et al., 2002). It has also been shown in laboratory studies that hollow particles are more weakly depolarizing compared with solid crystals (Schnaiter et al., 2007; Smith et al., 2016). In this case, roughness proxies may not be representative of various micro-scale features such as cavities, inclusions, and real surface roughness.

## Appendix A. Derivation of aspect ratio equations

*Fitting the model to observed  $A_r(D)$  relationships*

*Appendix A.0.1. Randomly Oriented Particles*

For a solid convex particle, the average projected cross section is given by  $S/4$ . Where  $S$  is the particle surface area. Although the hollow particle

556 is concave, the projected area is not influenced by the concavities, and there-  
 557 fore the same equation can be applied. For a randomly oriented hexagonal  
 558 prism, the average projected area is given by:

$$A_{average} = \frac{D^2(12\alpha + 3\sqrt{3})}{16(1 + \alpha^2)} \quad (\text{A.1})$$

560

561

562 and the area ratio is given by:

563

$$A_{r.average} = \frac{12\alpha + 3\sqrt{3}}{4\pi(1 + \alpha^2)} \quad (\text{A.2})$$

564

565

### 566 *Appendix A.0.2. Preferentially Oriented Particles*

567 In reality, elongated ice particles tend to fall preferentially with their  
 568 largest projection perpendicular to the direction of propagation (Platt, 1978;  
 569 Chepfer et al., 1999), although vertically aligned prism facets have also been  
 570 observed (Westbrook, 2011). As such, columns fall preferentially with their  
 571 prism facet parallel to the ground, whereas plates fall preferentially with their  
 572 basal facet parallel to the ground.

573

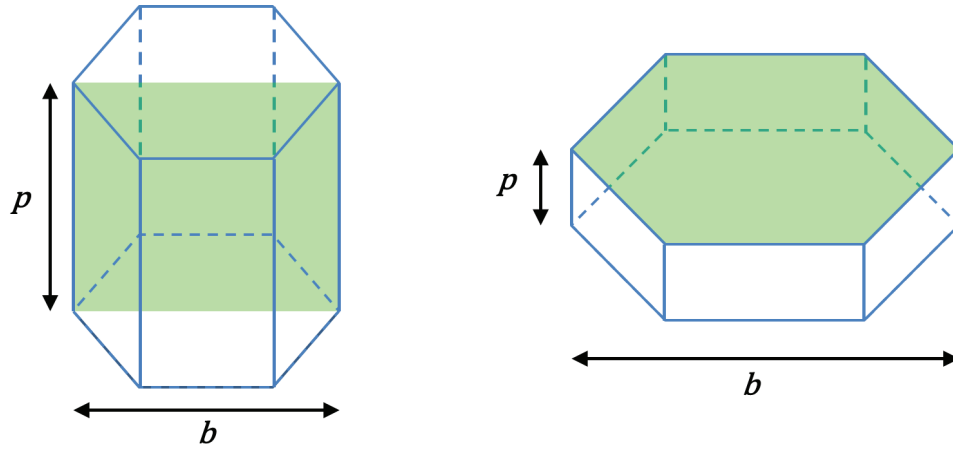


Figure A.18: Projected area of a hexagonal prism when oriented like a column (left) and a plate (right). Green shaded areas represent projected cross sections. ‘Hollowness’, in the form of basal cavities, does not affect the particles projected area, therefore cavities are omitted from the diagram.

574 For column-oriented particles, the projected cross section is given by:

575

$$A_{column} = \frac{D^2 \alpha}{1 + \alpha^2} \quad (\text{A.3})$$

576

577

578 and the area ratio is given by:

579

$$A_{r.column} = \frac{4\alpha}{\pi(1 + \alpha^2)} \quad (\text{A.4})$$

580

581

582 For plate-oriented particles, the projected cross section is given by:

583

$$A_{plate} = \frac{3\sqrt{3}}{8} \times \frac{D^2}{(1 + \alpha^2)} \quad (\text{A.5})$$

584

585

586 and the area ratio is given by:

587

$$A_{r\_plate} = \frac{3\sqrt{3}}{2\pi(1 + \alpha^2)} \quad (\text{A.6})$$

588

589

590 The area ratios for preferential and random orientations are plotted against  
591 aspect ratio in figure A.19.

592

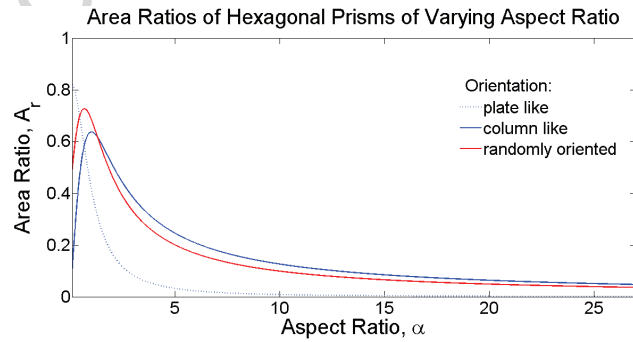


Figure A.19: Area ratio plotted against aspect for randomly oriented and preferentially oriented hexagonal columns.

593 By assuming a randomly oriented particle, the maximum area ratio for a

594 hexagonal column is 0.7271. However, observed  $A_r(D)$  relationships exceed  
 595 this, with a maximum value of 0.8. In order to achieve this value, we must  
 596 assume oriented plates. Therefore the two orientation specific relationships  
 597 are used rather than the randomly oriented one.

598 If we extend the  $A_r(D)$  relation to cover the full size range used in this  
 599 parameterization (0.4-28127 $\mu\text{m}$ ) we get a range of values of  $A_r$  from 2.8–  
 600 0.1360. Physically, the area ratio for a hexagonal column cannot exceed  
 601 0.8270, and therefore this observational relationship cannot be extrapolated  
 602 to smaller particles. As  $D$  tend to infinity,  $A_r$  tends asymptotically towards  
 603 0. So in theory, the relationship can be extrapolated to larger sizes.

604 For plate-oriented prisms, we can equate equations A.6 and 6 to get:

$$\alpha = \sqrt{4.59D^{0.271} - 1} \quad (\text{A.7})$$

606  
 607  
 608 For column-oriented prisms we equate equations A.4 and 6 to get:

$$\alpha = \frac{1 + \sqrt{1 - 4(0.045\pi D^{-0.271})^2}}{0.09\pi D^{-0.271}} \quad (\text{A.8})$$

610  
 611  
 612 Below  $D = 100 \mu\text{m}$ , equation A.8 does not yield real results, and therefore  
 613 all particles  $< 100 \mu\text{m}$  are assumed to be oriented plates.

614 *Appendix A.1. Fitting the particles to  $M(D)$  relationships*

615 For the hollow column used in this parameterization, the mass is given by:

616

$$M(D) = \rho \frac{3\sqrt{3}}{8} \left(1 - \frac{29h}{19200}\right) \alpha (1 + \alpha^2)^{-3/2} D^3 \quad (\text{A.9})$$

617

618

619 where:

620

621  $M$  = particle mass, kg

622  $\rho$  = density of ice,  $\text{kgm}^{-3}$

623  $h$  = hollowness described as the combined length of both cavities, expressed  
624 as a percentage of the length of prism facet,  $p$

625

626 Varying the hollowness caused little difference in the particle mass, and  
627 therefore a constant hollowness of 80% was assumed, as commonly observed  
628 in cloud chamber investigations (Smith et al., 2015). In order to fit the hol-  
629 low particle to observed mass-dimensional relationships, we equate equations  
630 7 and A.9 to get:

631

$$D = 4.91 \times 10^{-5} \times \frac{1}{\alpha} (1 + \alpha^2)^{3/2} \quad (\text{A.10})$$

632

633



634 The relationship between  $\alpha$  and  $D$  is approximated by a 10<sup>th</sup> degree poly-  
 635 mial:

$$\alpha = \sum_{n=0}^{10} c_n D^n \quad (\text{A.11})$$

637

638

639 where  $c_n$  are the polynomial coefficients, given in table A.2.

640

$n$	$c_n$
10	$-2.15 \times 10^{18}$
9	$4.97 \times 10^{17}$
8	$-4.93 \times 10^{16}$
7	$2.75 \times 10^{15}$
6	$-9.45 \times 10^{13}$
5	$2.07 \times 10^{12}$
4	$-2.9 \times 10^{10}$
3	$2.53 \times 10^8$
2	$-1.33 \times 10^6$
1	4820
0	0.45702

Table A.2: Coefficients of  $D^n$  for equation A.11.

641 Equations A.7 and A.8 relate the aspect ratio and the maximum di-  
 642 mension of the hollow column in order to adhere to observed area ratio-

643 dimensional relationships, whilst equation A.11 relates aspect ratio and max-  
644 imum dimension in order to obey observed mass-dimensional power laws.  
645 These equations are not in agreement and therefore the aspect ratio cannot  
646 be fitted exactly to both observed relationships. Instead, we take a weighted  
647 average in order to fit the values within observed ranges. It was found that  
648 a 50:50 weighting gave the best agreement for sizes  $>70\mu\text{m}$ . In the size  
649 range  $40\text{--}70\mu\text{m}$ , a 65:35 weighting was used ( $M(D):A_r(D)$ ). These weight-  
650 ings were chosen as they produced the most amount of crystals within the  
651 observed ranges of  $M(D)$  and  $A_r(D)$ . For particles below  $40\mu\text{m}$ , there is  
652 no established  $A_r(D)$  relationship and so particles are fitted using only the  
653  $M(D)$  relationship.

654 These equations were used to find the aspect ratios of 26 particles ranging  
655 in size from  $0.4$  to  $28\,127\mu\text{m}$ , given in table A.3.

Maximum Dimension, $D / \mu\text{m}$	Aspect Ratio, $\alpha$
0.4	0.7070
3.0	0.7070
7.5	0.7070
15	0.7070
25	0.7070
35	0.7070
45	0.4546
60	0.5294
80	0.6626
100	1.0585
130	1.3235
175	1.5361
225	1.7582
275	1.9540
350	2.1834
450	2.5289
550	2.8103
650	3.0682
750	3.3072
900	3.6362
1150	4.1212
1400	4.5433
1750	5.0525
2500	5.9192
3500	6.7936
28127	20.0000

Table A.3: Aspect ratios and maximum dimensions of the 26 particles used in the hex\_cav parameterizations. For particles  $\leq 80\mu\text{m}$ , plate orientation is assumed, for particles  $\geq 80\mu\text{m}$ , column orientation is assumed.

656 **Appendix B. Wavelengths and Refractive Indices**

657 Calculations were done for 54 wavelengths in the shortwave ranging from  
658  $0.2\ \mu\text{m}$ – $5\ \mu\text{m}$ . The complex refractive indices are taken from Warren and  
659 Brandt (2008), and are given in figure B.20.

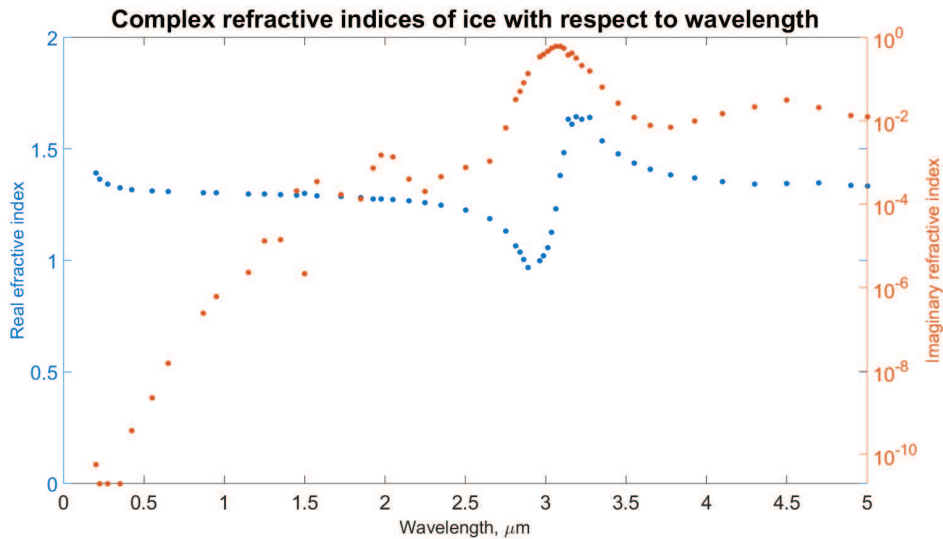
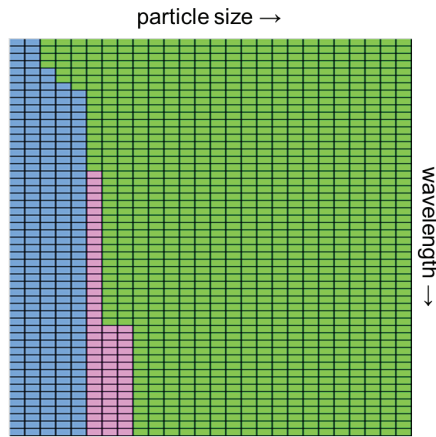


Figure B.20: Complex refractive indices for ice over the range of wavelengths used. The left axis shows the real component of the refractive index and the left axis shows the imaginary component.

## 660 Appendix C. Scattering Models used

a) Scattering Models for hex\_cav1



b) Scattering Models for hex\_cav2

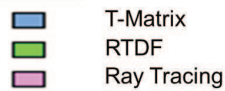
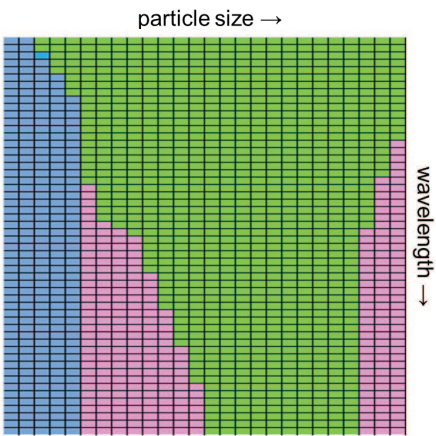


Figure C.21: Scattering models used for differing values of wavelength and particle size, for parameterizations hex\_cav1 and hex\_cav2. Particle size increases from left to right, numeric values can be found in table A.3. Wavelength increases from top to bottom, values can be found in figure B.20.

661 **Appendix D. Bulk optical properties**

662 The bulk optical properties for the 28 PSDs are shown below with respect  
 663 to wavelength. Large differences can be seen in each of the optical  
 664 properties at wavelengths of  $\approx 3 \mu\text{m}$  due to large values of absorption,  
 665 which can be seen in figure B.20.

666 *Appendix D.1. Bulk properties for hex\_cav1*

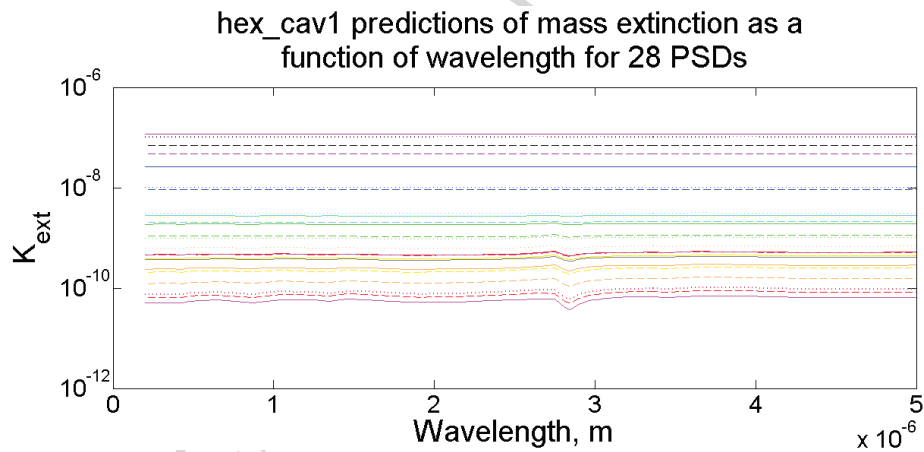


Figure D.22: Bulk  $K_{ext}$  values calculated using the hex\_cav1 parameterization. Each trace represents a different PSD from Field2007.

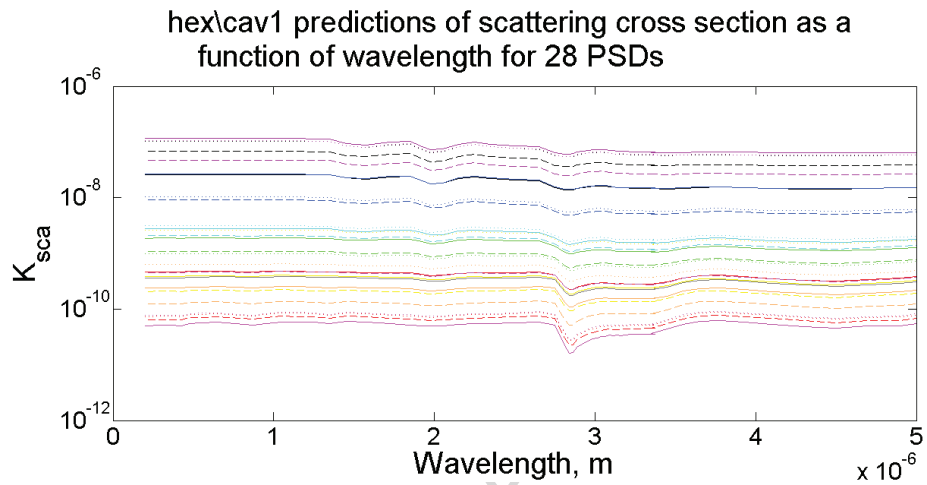


Figure D.23: Bulk  $K_{sca}$  values calculated using the hex\_cav1 parameterization. Each trace represents a different PSD from Field2007.

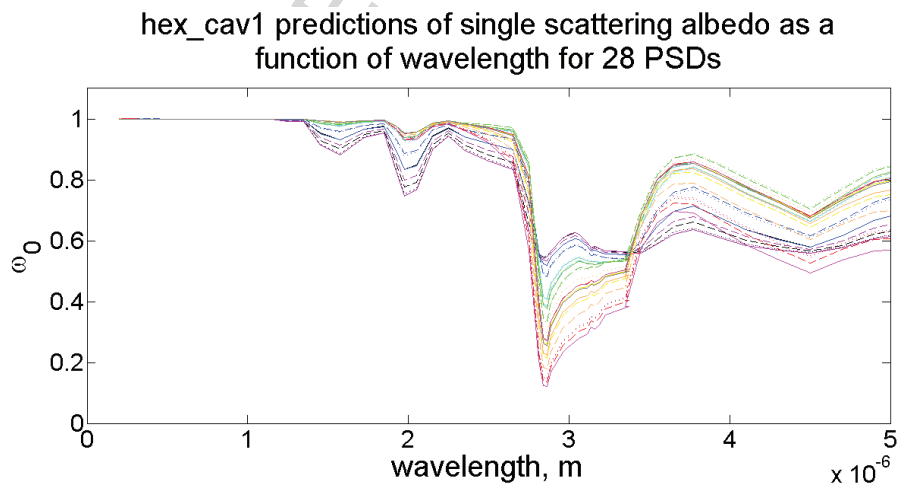


Figure D.24: Bulk  $\omega_0$  values calculated using the hex\_cav1 parameterization. Each trace represents a different PSD from Field2007.

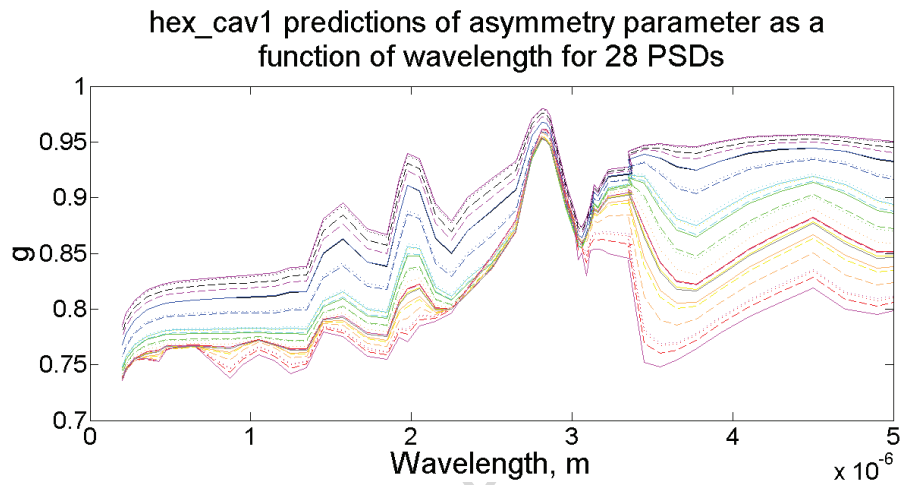


Figure D.25: Bulk  $g$  values calculated using the hex\_cav1 parameterization. Each trace represents a different PSD from Field2007.

667 *Appendix D.2. Bulk properties for hex\_cav2*

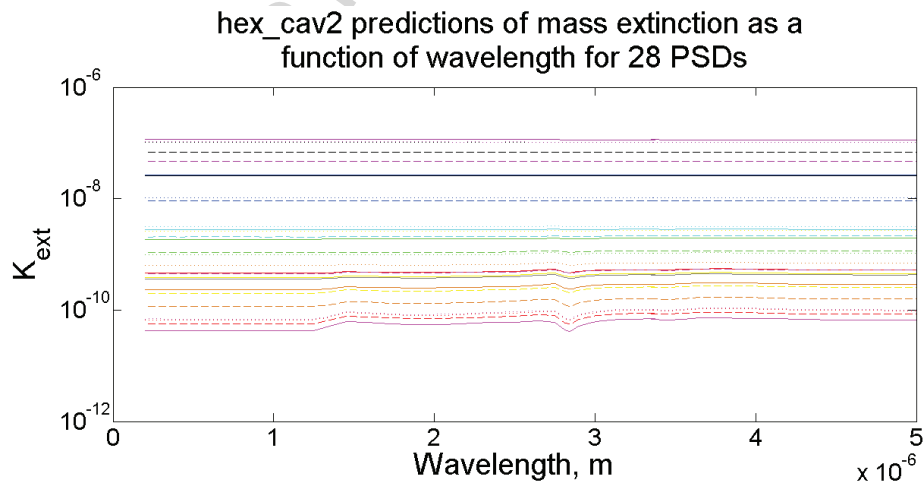


Figure D.26: Bulk  $K_{ext}$  values calculated using the hex\_cav2 parameterization. Each trace represents a different PSD from Field2007.



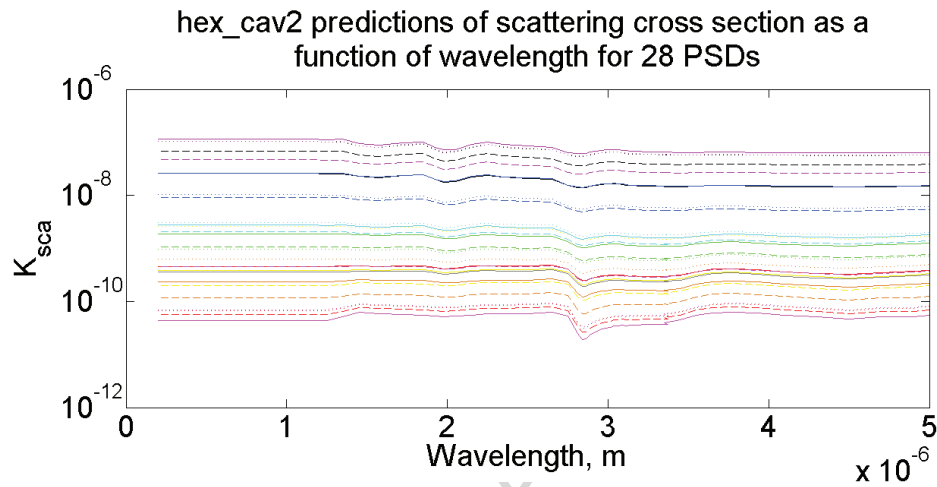


Figure D.27: Bulk  $K_{sca}$  values calculated using the hex\_cav2 parameterization. Each trace represents a different PSD from Field2007.

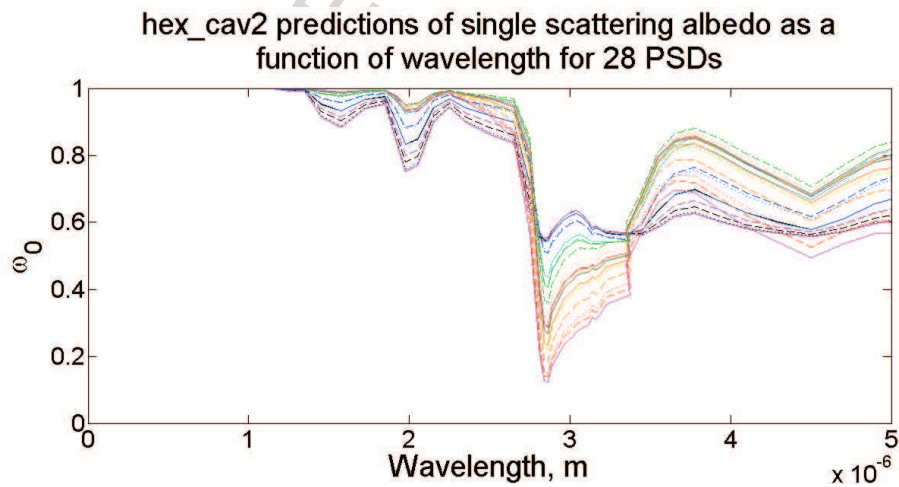


Figure D.28: Bulk  $\omega_0$  values calculated using the hex\_cav2 parameterization. Each trace represents a different PSD from Field2007.

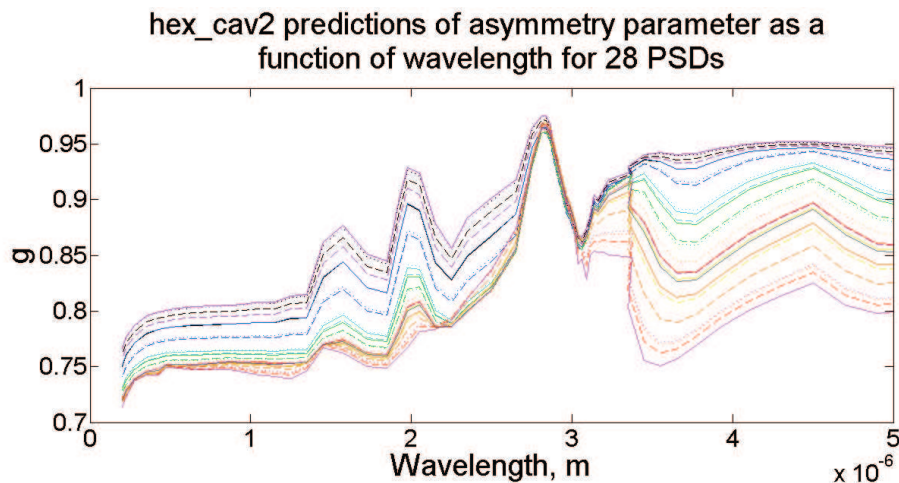


Figure D.29: Bulk  $g$  values calculated using the hex\_cav2 parameterization. Each trace represents a different PSD from Field2007.

## 668 Appendix E. Parameterized fits

Wavelength, m	$K_{ext}$	$K_{sca}$	$g$
$2.0 \times 10^{-07}$ – $3.2 \times 10^{-07}$	$92.4557 \times q_i^{1.25807}$	$92.4557 \times q_i^{1.25807}$	$0.809881 \times q_i^{5.22739 \times 10^{-03}}$
$3.2 \times 10^{-07}$ – $5.05 \times 10^{-07}$	$92.7110 \times q_i^{1.25847}$	$92.7111 \times q_i^{1.25847}$	$0.841690 \times q_i^{6.38061 \times 10^{-03}}$
$5.05 \times 10^{-07}$ – $6.90 \times 10^{-07}$	$92.3745 \times q_i^{1.25793}$	$92.3761 \times q_i^{1.25794}$	$0.844428 \times q_i^{6.14116 \times 10^{-03}}$
$6.9 \times 10^{-07}$ – $1.19 \times 10^{-06}$	$92.5359 \times q_i^{1.25816}$	$92.6756 \times q_i^{1.25852}$	$0.855544 \times q_i^{7.21452 \times 10^{-03}}$
$1.19 \times 10^{-06}$ – $2.38 \times 10^{-06}$	$92.0046 \times q_i^{1.25726}$	$104.484 \times q_i^{1.29188}$	$0.927497 \times q_i^{1.03785 \times 10^{-02}}$
$2.38 \times 10^{-06}$ – $1.00 \times 10^{-05}$	$92.2832 \times q_i^{1.25774}$	$64.4584 \times q_i^{1.27846}$	$0.967942 \times q_i^{6.66089 \times 10^{-03}}$

Table E.4: Parameterized fits of  $K_{ext}$ ,  $K_{sca}$  and  $g$  for 6 short-wave bands for the hex\_cav1 parameterization. Where  $q_i$  is the ice mass mixing ratio in Kg per Kg.

Wavelength, m	$K_{ext}$	$K_{sca}$	$g$
$2.0 \times 10^{-07}$ – $3.2 \times 10^{-07}$	$92.4557 \times q_i^{1.25807}$	$92.4557 \times q_i^{1.25807}$	$0.792337 \times q_i^{5.40227 \times 10^{-03}}$
$3.2 \times 10^{-07}$ – $5.05 \times 10^{-07}$	$92.7110 \times q_i^{1.25847}$	$92.7111 \times q_i^{1.25847}$	$0.815496 \times q_i^{5.57400 \times 10^{-03}}$
$5.05 \times 10^{-07}$ – $6.90 \times 10^{-07}$	$92.3745 \times q_i^{1.25793}$	$92.3761 \times q_i^{1.25794}$	$0.819914 \times q_i^{5.62200 \times 10^{-03}}$
$6.9 \times 10^{-07}$ – $1.19 \times 10^{-06}$	$92.5359 \times q_i^{1.25816}$	$92.6756 \times q_i^{1.25852}$	$0.824879 \times q_i^{5.99128 \times 10^{-03}}$
$1.19 \times 10^{-06}$ – $2.38 \times 10^{-06}$	$92.0046 \times q_i^{1.25726}$	$104.484 \times q_i^{1.29188}$	$0.901148 \times q_i^{9.62755 \times 10^{-03}}$
$2.38 \times 10^{-06}$ – $1.00 \times 10^{-05}$	$92.2832 \times q_i^{1.25774}$	$64.4584 \times q_i^{1.27846}$	$0.958268 \times q_i^{5.73484 \times 10^{-03}}$

Table E.5: Parameterized fits of  $K_{ext}$ ,  $K_{sca}$  and  $g$  for 6 short-wave bands for the hex\_cav2 parameterization. Where  $q_i$  is the ice mass mixing ratio in Kg per Kg.

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## Highlights –

- A short-wave parametrization for cirrus is presented
- A single habit is chosen to test its applicability
- A hollow column structure is chosen based on laboratory experiments
- The particle is fit to observations of mass, area-ratio, size
- Predictions of short-wave fluxes, temperature and humidity are discussed