Reply to comments by referee #1

We thank the referee for taking the time to carefully review the manuscript. We appreciate the positive feedback and the valuable suggestions and comments, which are addressed below. The referee's comments are highlighted in blue.

1) Ice crystals in cirrus clouds are not monodisperse. Moreover, various ice crystal habits/shapes may coexist in a given cirrus cloud. In the revised manuscript, could the authors please elaborate on the impacts of the ice crystal size and shape distributions on the results?

We appreciate this suggestion and addressed it by adding the following statements to the manuscript starting on page 5, line 26:

> "Note that the retrieved ice crystal effective radius, shape and SCF will depend on assumptions about the underlying particle distribution, since the bulk optical properties, as e.g. the extinction coefficient β_{ext}, are obtained by integrating the single scattering properties over Eq. 1."
>
> "Ice crystals in cirrus clouds are known to follow multi-modal rather than monomodal size, shape, and surface roughness distributions. Therefore matching ice crystal properties could be retrieved for mixtures of arbitrary complexity. However, this study aims at finding the simplest ice crystal model with the minimum degrees of freedom that matches the observations within the measurement uncertainty. Inspired by Schmitt and Heymsfield (2014) and Liu et al. (2014), who separate the huge variety of ice crystal shapes into simple and complex crystals, we employ this two-habit approach for smooth and rough crystals to represent the "halo-producing" and "non-halo-producing" category of ice particles. "

2) In Eqs. (1) and (2), the extinction coefficient is involved, which is a bulk radiative quantity. But the particle size distribution is not specified.

We added information about the particle size distribution starting on page 5, line 17:

"The resulting ice crystal properties assumed here represent a single ice crystal shape, two levels of surface roughness, and follow a particle size distribution n according to:

$$n(D) = D^{\nu} \exp(-\lambda D), \tag{1}$$

with maximum crystal dimension D and $\nu = 1$ fixed. For a given effective radius r_{eff}, the optical properties provided for a range of maximum dimensions D in YG13 were integrated over the size distribution. During integration, λ was determined iteratively to match the computed with the prescribed effective radius. The smooth crystal fraction

$$\mathrm{SCF} = \beta_{\mathrm{ext,smooth}} / \beta_{\mathrm{ext,total}}\,, \tag{2}$$

with $\beta_{\mathrm{ext,total}} = \beta_{\mathrm{ext,smooth}} + \beta_{\mathrm{ext,rough}}$ ranges between $0 \leq \mathrm{SCF} \leq 1$, resulting in a rough crystal fraction of

$$\mathrm{RCF} = 1 - \mathrm{SCF} = \beta_{\mathrm{ext,rough}} / \beta_{\mathrm{ext,total}}\,. \tag{3}$$

Note that the retrieved ice crystal effective radius, shape and SCF will depend on assumptions about the underlying particle distribution, since the bulk optical properties, as e.g. the extinction coefficient β_{ext}, are obtained by integrating the single scattering properties over Eq. 1."

3) As stated in the second paragraph on page 3, the authors' previous findings confirm that 25% of cirrus clouds produce 22-deg halos. However, spaceborne observations seem to suggest that ice crystals in cirrus clouds are roughened, for example, as demonstrated by one year of POLDER/PARASOL observations (see, Fig. 15 in Yang, P., S. Hioki, M. Saito, C.-P. Kuo, B. A. Baum, K.-N. Liou, 2018: A review of ice cloud optical property models for satellite remote sensing, Atmosphere 2018, 9, 499; doi:10.3390/atmos9120499). It will be valuable if this manuscript provides insight to coincide the finding based on spaceborne observations with that based on ground-based observations.

Our finding that a small fraction of smooth ice crystals mixed with severely roughened ice crystals is sufficient to produce a visible halo is not in contradiction to findings from spaceborne observations suggesting that ice crystals in cirrus clouds are roughened in general. We address this question in the discussion section of this manuscript starting on page 21 line 13, where we added the above mentioned publication:

> "Our finding that columnar ice crystal shapes best represent the HaloCam observations further implies that a majority of rough ice crystals mixed with a smaller fraction of smooth crystals is sufficient to produce a visible 22° halo. Finding predominantly rough and complex ice crystals to best match the observations is in agreement with the results of several studies based on satellite retrievals. Using multi-angle reflectance measurements, Baran et al. (1998, 1999) and McFarlane and Marchand (2008) found polycrystals and complex crystals to better represent the observations than pristine single crystals. Studies based on multi-angular polarized reflectances from POLDER (Polarization and Directionality of Earth Reflectance) also report that featureless phase functions, which correspond to roughened or complex crystals, better represent the measurements than phase functions of a single ice crystal habit (Descloitres et al., 1998; Chepfer et al., 2001; Baran et al., 2001; Baran and Labonnote, 2006; Sun et al., 2006; Yang et al., 2018). Holz et al. (2016) and Wang et al. (2014) confirmed that rough and complex crystals better match the observations than smooth single crystals for optically thin clouds ($\mathrm{COT} < 3$) using retrievals based on lidar observations and reflectances in the infrared spectrum."

Optional minor editorial revisions:

a) Lines 2-3 on page 1: change "making use of" to "using"

Changed.

b) Line 4 on page 1: Change " ... the retrieval of size and shape of randomly oriented crystals" to " ... the retrieval of the sizes and shapes of randomly oriented ice crystals"

Changed.

c) Line 12 on page 1: change "forward scattering part of the ice crystal optical properties" to "forward portion of the light scattered by ice crystals"

Changed.

d) Line 13 on page 3: change "...retrieve ice crystal shape and surface roughness" to "...retrieve ice crystal shape and the degree of surface roughness".

Changed.

e) Line 12 on page 4: change "To the authors' knowledge" to "To the best of the authors' knowledge".

Changed.

f) Line 32 on page 4: change "Look-up tables (LUT)" to "Look-up tables (LUTs)".

Changed.

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