Reply to comments by referee #2

We thank the referee for carefully reviewing the manuscript and for the valuable suggestions and comments.

Remark: The referee's comments are highlighted in blue. Figure numbers in the authors' reply refer to the figures in the original manuscript. New/changed figures are included at the end of the document. Snippets included in the revised manuscript are highlighted by an additional indent and quotation marks.

1. A visual inspection of the halo images is presented on page 5. Please indicate whether partial 22-degree halos are also counted in the statistics. Also, in my experience sundogs often appear much brighter than 22 halos, and therefor may be more easily detected. Could that have skewed the statistics?

> The 22° halo observations include both complete and partial halos, the latter occurring more often than the complete 22° halo similar to the observations of Sassen et al. (2003). We added this information for clarification. We agree that bright and colorful sundogs could be more easily detected by eye than a faint 22° halo. However, the 22° halo covers a larger area on the HaloCam images and might therefore compensate for this. Also, looking at a sequence of images helps to detect stationary features within moving clouds even if the brightness contrast is low. In general, a visual halo detection (on images or in the sky) is never unbiased and might vary between different observers.

2. The automated detection algorithm focuses on 22-degree halos. Could you please discuss whether and how the algorithm might be biased by the presence of other optical phenomena such as sundogs and tangent arcs? I can imagine that in case of a 22-degree additional sundogs present halo change the angular width of features seen in segments 3 and 5, which might lead to a false negative detection. On the other hand, the presence of a sundog without a 22-degree halo might lead to a false positive detection of a 22-degree halo.

> You are raising an interesting question. We added a paragraph to the paper to discuss possible mis-classifications due to other halo types (see also comment of referee #3):
>
> > "The current version of HaloForest discriminates only between the two classes "22° halo" and "no 22° halo". Thus, interference with other halo types as sundogs or upper/lower tangent arcs and circumscribed halos might occur at certain solar elevations. The position of sundogs relative to the sun depends on the solar zenith angle (SZA) and can be calculated analytically as described in Wegener (1925); Tricker (1970); Minnaert (1993); Liou and Yang (2016). The sundogs are located at scattering angles close to the 22° halo for large SZAs and occur at larger scattering angles for small SZAs, i.e. high solar elevations. Fig. 1 (now Fig. 9 in the manuscript) shows the same HaloCam image with the azimuth segments as Fig. 4b. In addition, the minimum scattering angle of the sundogs are calculated as a function of the SZA and represented by the red and green squares. The SZAs range between 90° and 35° with a resolution of 1°. The two white circles centered around the sun at scattering angles of 21.0° and 23.5° indicate the mask which is used to find the scattering angle of the 22° halo peak. For SZA $\leq$ 67° the sundog positions are located outside this mask and cannot be mis-classified as 22° halo (green squares). The red squares represent sundog positions which are located within this mask and might therefore be mis-classified. This is the case for SZAs between 90° and 67°. To obtain an estimate of the fraction of sundogs which are mis-classified as 22° halo 1000 randomly selected HaloCam images were counter-checked visually. It revealed that only 6 images showing sundogs without 22° halo in the segments (3–5) were mis-classified as 22° halo, which is $< 1\%$. Upper tangent arcs could be detected by the uppermost image segment (no. 4) and might be mis-classified as 22° halo. For very small SZAs (high solar elevations) the tangent arcs merge to form the circumscribed halo which could be detected in the segments 3 and 5 as well. The same procedure was repeated for these halo types: 1000 randomly selected images were checked for the presence of tangent arcs and circumscribed halos without 22° halo yielding 28 images or 2.8%. However, if only a fragment of a halo is visible in the uppermost segment, it is generally difficult to discriminate between an upper tangent arc or circumscribed halo and a 22° halo."

3. Related to the discussion of influence of optical thickness of the visibility of halos, it would be good to include the follow paper: Kokhanovsky, A.: The contrast and brightness of halos in crystalline clouds, Atm. Res., 89, 110-112, doi:10.1016/j.atmosres.2007.12.006, 2008.

Thank you for this hint, we included the reference together with Gedzelman and Vollmer (2008); Gedzelman (2008), suggested by referee #3, and briefly described their results.

> "The effect of varying cloud optical thickness on the visibility of halo displays was already investigated by Kokhanovsky (2008); Gedzelman and Vollmer (2008); Gedzelman (2008) using radiative transfer simulations. Kokhanovsky (2008) performed simulations of the brightness contrast of the 22° halo as a function of the cirrus optical thickness using the radiative transfer model SCIATRAN neglecting molecular and aerosol scattering. The results show a linear decrease of the halo contrast with increasing optical thickness. Gedzelman (2008) and Gedzelman and Vollmer (2008) used the model HALOSKY for radiative transfer simulations of halos with varying cloud optical thickness. HALOSKY considers single scattering by air molecules, aerosol particles and cloud particles assuming homogeneous, plane-parallel atmospheric layers. Multiple scattering is calculated only within the cloud by a Monte Carlo subroutine. Gedzelman and Vollmer (2008) show results for radiance simulations of the 22° halo in the principal plane below and above the sun. They found that the radiance at the bottom of the halo reaches a maximum value for smaller COT (≈ 0.25) than the radiance at the top of the cloud (≈ 0.63)."

4. On page 17, percentages of the fraction of rough particles are estimated. Since these are based on the minimum percentage of smooth crystals needed for halo features, it seems to me that the deduced fraction of rough particles are maximum values. That is, a lower percentage of rough particles would of course also produce a halo, and probably a brighter one.

Thank you for pointing this out. This is exactly what we aimed to conclude from the observations. We adapted this paragraph to highlight that the derived percentages for rough ice crystals are a maximum value.

> "By analyzing ice crystal single scattering properties van Diedenhoven (2014) showed that a minimum fraction of 10% smooth hexagonal ice crystal columns is sufficient to produce a 22° halo. In case of ice crystal plates the minimum fraction of smooth crystals for a visible halo is much larger with about 40%. Thus, if the exact ice crystal habits of the cirrus cloud are unknown, which is typically the case, the minimum amount of smooth ice crystals probably lies in a range of 10% to 40%. This implies that even for a large fraction of irregular or small ice crystals a halo might still be visible. A larger fraction of smooth ice crystals, however, could well be possible for halos with larger HR, i.e. increased brightness contrast. Multiple scattering of the cirrus cloud or atmosphere was not considered by van Diedenhoven (2014). This study revealed that during the ∼2.5 years of HaloCam observations in Munich about 75% of the cirrus clouds did not produce a 22° halo. For favorable atmospheric conditions, i.e. COT∼1 and negligible aerosol scattering, the maximum fraction of rough ice crystals ranges between 60% and 90%. Thus, it is possible that the majority of cirrus clouds during the observation period in Munich contain a large fraction of rough ice crystals. This would support the hypothesis of e.g. Knap et al. (2005); Baran and Labonnote (2006); Baran et al. (2015) who found that on average rough ice crystals better reproduce remote sensing radiance measurements than assuming crystals with smooth surface. However, if multiple scattering by cirrus clouds or aerosol is accounted for, the minimum fraction of smooth crystals could be much larger in the case of "halo-producing" cirrus clouds."

Minor corrections:
Line 13, page 15: Remove "are" from the final sentence.
Line 1, page 15: I suggest to refer to section 2.1 here

We corrected/changed the respective sentences.

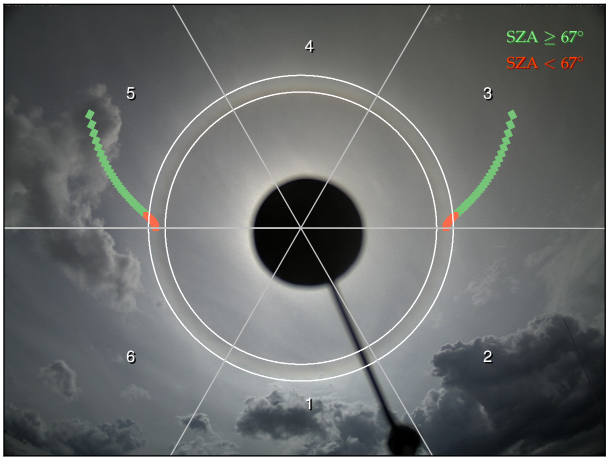

Figure 1. HaloCam image as in Fig. 4b. The red and green squares indicate the position of the sundogs as a function of the solar zenith angle (SZA). The SZA ranges between 90° and 35° with 1° resolution. The mask used to search for the 22° halo peak is displayed by the two white circles and covers scattering angles between 21.0° and 23.5°. Sundog positions located within this mask might be mis-classified as 22° halo and are marked as red. These positions correspond with SZAs between 90° and 67°. For smaller SZAs (higher solar elevations) the sundogs are located outside the mask and cannot be mis-classified as 22° halo by the algorithm.

References

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