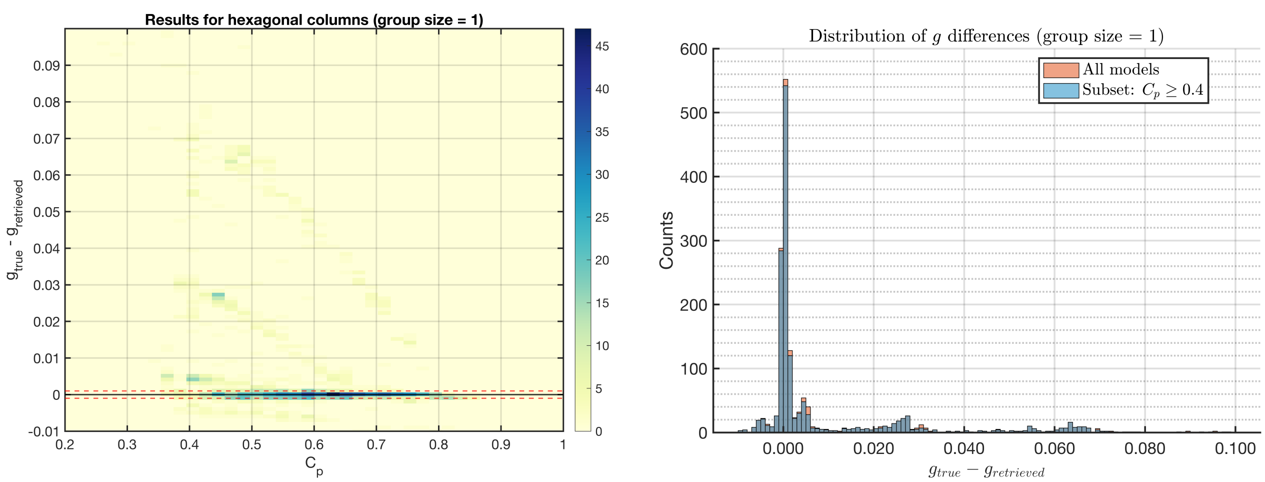
Response to Reviewer #3

We thank the reviewer for raising this important point. A closure study of the type requested has already been presented in Xu et al. (2022, their Fig. 6). That analysis showed that for roughened hexagonal crystals the retrieval error in g is typically below 0.001 when the complexity parameter $C_p > 0.4$. We acknowledge, however, that the range of crystal configurations considered in the original study was limited.

Since then, we have substantially extended our ray-tracing database using the code of Macke et al. (1996). The new simulations cover hexagonal crystals within the size range from 20 to 500 µm and for aspect ratios from 0.68 to 0.85 that reflect the microphysical results from the PHIPS stereo-imaging. Surface complexity was introduced by applying tilted-facet Gaussian roughness with σ between 0 and 0.9, and in some cases additional complexity was included by implementing the mean-free-path model to simulate internal air inclusions. In total, 1612 different orientation-averaged crystal configurations were generated.

For each case, the simulated phase function was truncated to the PHIPS angular range, integrated over the PHIPS detector geometry, and passed through the Xu et al. retrieval algorithm. The retrieved g was then compared against the true value from the Macke code. Results for single-habit simulations (Fig. 1) show that while many cases reproduce g within the ± 0.001 uncertainty reported in Xu et al. (2022), some configurations produce larger deviations, occasionally exceeding 0.05 even for $C_p > 0.4$. The bias is generally positive, confirming earlier reviewer concerns that the method may underestimate g. However, the fraction of simulations that have a bias of larger than 0.02 is around 18%. Further, we stress that such single-habit cloud particle populations are not representative of natural cirrus populations, which consist of mixtures of habits, aspect ratios, and roughness states.

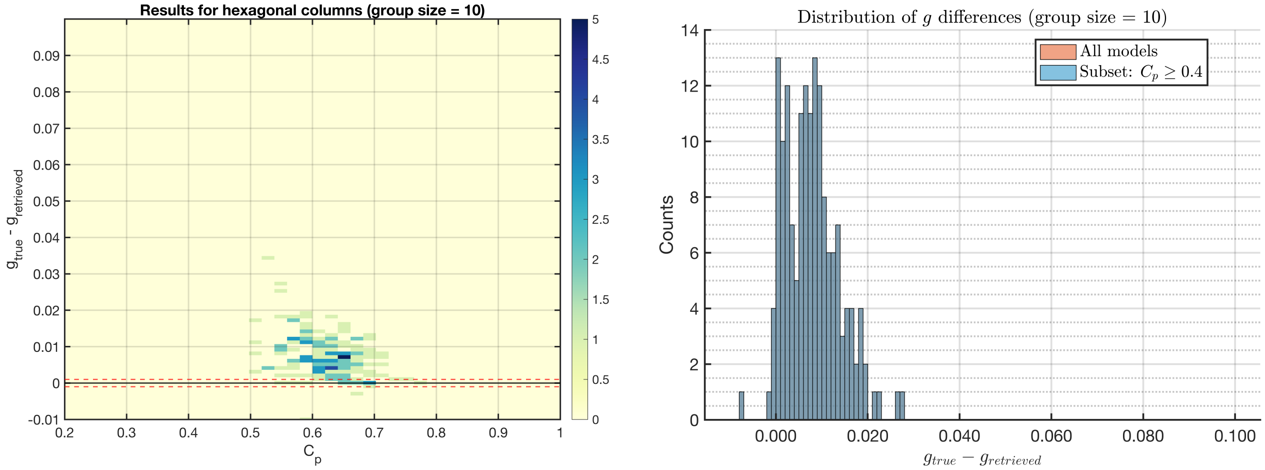


(a) Difference between true and retrieved g vs. retrieved C_p. Red dashed lines indicate ± 0.001.

(b) Histogram of the retrieval error in g for 1612 simulations of single habits.

Figure 1: Closure test of g retrieval using 1612 simulated phase functions of individual crystal habits.

To reflect more realistic cloud conditions, we repeated the closure test using ensembles of 10 randomly selected crystal morphologies. As shown in Fig. 2, the ensemble results converge rapidly, with retrieval errors consistently below 0.02. Increasing the number of morphologies confine the results even further below 0.02. The bias remains predominantly positive, indicating that the method tends to underestimate g, again consistent with the reviewer's expectation.



(a) Difference between true and retrieved g vs. retrieved C_p.

(b) Histogram of retrieval error in g for ensembles of 10 habits.

Figure 2: Closure test of g retrieval using ensembles of 10 randomly selected crystal morphologies.

Based on these expanded closure studies, we adopt a conservative updated uncertainty estimate of about $+0.02$ in g. We will include this revised estimate, together with a clearer and more comprehensive description of the retrieval methodology, in the manuscript, as already indicated in the answers to the other reviewers. Importantly, even with this uncertainty the central result of our study remains unchanged: g in both Arctic and mid-latitude cirrus is systematically lower than the values typically assumed in current ice particle optical models (0.76-0.88) (e.g. Iaquinta et al., 1995; Yang et al., 2008; Um and McFarquhar, 2009).

References

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