

Dear topic editor and reviewers,

Thank you for taking the time to review the revised manuscript. We appreciate your feedback and have implemented the minor revisions as suggested by Reviewer #3. We are pleased to submit this revised version of our manuscript 'Assessment of an updated polar stratospheric cloud parameterisation for the UK Earth System Model (UKESM1.1) within the UK Met Office Unified Model (v13.9) using CALIOP and MLS observations'.

Please find the point-by-point response to Reviewer #3 comments. Our responses are in blue and new text in the manuscript are **bold** and *italicised* text.

Sincerely,

Isabelle Sangha, on behalf of all the coauthors

Referee #3

There are a few remaining items the authors should consider prior to publication. Here they are by line number.

1. Line 60: Using Hanson and Maurersberger as a reference for 1 μm NAT particles is odd. Do the authors mean H&M reference to apply to the NAT? If so, the sentence should be fixed.

Reply: Thank you for this comment. We have changed line 60 to read as follows:

'NAT particles are nucleated assuming thermodynamic equilibrium based on Hanson and Maurersberger (1988) and are assumed to have a fixed radius of 1.0 μm .'

2. Lines 199-200: and Table 1 The boundaries for $R_{\text{nat/ice}}$ is not explained well. The authors claim "The R_{532} boundary separating enhNAT and NATmix from ice, $R_{\text{NAT|ice}}$, is calculated dynamically from coincident cloud-free MLS gas-phase HNO_3 and H_2O data and theoretical R_{532} values for fully developed STS." But this is ambiguous. Is there a maximum for R_{sts} ? If so what is it? How the gas phase concentrations are used in the calculation is not explained. Then some numbers are added to the criteria, 50, 2 in R , and $2.5 \times 10^{-5} \text{ km}^{-2} \text{ sr}^{-1}$ for backscatter, with units that are not backscatter. The source of these numbers is also not explained.

Reply: Thank you for highlighting the ambiguities in the description of the CALIOP classifications. We would like to clarify the following:

- There is no maximum for R_{STS} based on the CALIOP v2 Classification Algorithm documented in Pitts et al. (2018).
- $R_{\text{ice|NAT}}$ is based on a parameterisation of theoretical calculations of R_{532} for fully developed STS over a range of atmospheric pressures and H_2O and HNO_3 concentrations. Therefore, to determine the daily $R_{\text{ice|NAT}}$ values for the CALIOP measurements, daily 'cloud-free' MLS HNO_3 and H_2O concentrations are used.
- The $R > 2$ and $\beta_{\perp} > 2.5 \times 10^{-5} \text{ km}^{-1} \text{ sr}^{-1}$ boundaries for enhNAT are determined from empirical comparisons between CALIOP and MIPAS observations of NAT formed with and without the heterogeneous formation on wave ice.
- The wave ice boundary of $R > 50$ is from the composition classification laid out in Pitts et al. (2011).

To address these ambiguities in the boundaries, we have included the following text in the CALIOP classification description and have corrected the units in the table from $\text{km}^{-2} \text{ sr}^{-1}$ to $\text{km}^{-1} \text{ sr}^{-1}$.

*'... PSCs with $\beta_{\perp}$ exceeding the background threshold are assumed to contain non-spherical (i.e., solid) particles. **The solid-containing PSCs are further classified as either liquid-NAT mixtures (NATmix), enhanced NAT mixtures with $r_{\text{NAT}} \lesssim 3 \mu\text{m}$ and NAT volume density $\gtrsim 1.0 \mu\text{m}^3 \text{ cm}^{-3}$ (enhNAT), ice, or high-number-density ice that forms in mountain waves (wave ice). enhNAT is separated from NATmix using boundaries of $R_{532} > 2$ and $\beta_{\perp} > 2.5 \times 10^{-5} \text{ km}^{-1} \text{ sr}^{-1}$, determined from empirical comparisons between CALIOP and MIPAS observations with and without the NAT band formed heterogeneously from wave ice (Höpfner et al., 2006). The R_{532} boundary separating enhNAT and NATmix from ice, $R_{\text{NAT|ice}}$, is based on a parameterisation of theoretical calculations of R_{532} for fully developed STS over a range of atmospheric pressures and H_2O and HNO_3 concentrations. Coincident cloud-free MLS gas-phase HNO_3 and H_2O data are then used to determine the daily $R_{\text{ice|NAT}}$ value for CALIOP measurements. The***

wave ice boundary, $R > 50$, is from the composition classification laid out in Pitts et al. (2011). PSCs below $\beta_{\perp, \text{threshold}}$, but above $R_{\text{threshold}}$ are classified as STS, with no maximum for R_{532} . These classification boundaries are summarised in Table 1, though it is important to note that they are not all-inclusive, i.e., enhNAT might not capture all NAT mixture PSCs that are heterogeneously nucleated downstream of wave ice PSCs. For more details on the CALIOP v2 PSC Classification Algorithm, see Pitts et al. (2018).

3. Lines 208-209: "... with a vertical resolution of HNO₃ data is 3–4 km in the region of interest. ...” Something is wrong with this sentence.

Reply: Thank you for catching this. The sentence has been amended to read:

‘... with a vertical resolution of 3–4 km in the region of interest.

4. Lines 270-272 and Table 2: Why are these numbers three significant figures. That is very exact for an assumed number that can vary by three orders of magnitude.

Reply: Thank you for your comment. We chose three significant figures as this is what has been done in other published work using the same NAT scheme (van den Broek et al. 2004, Kirner et al. 2011, Weimer et al. 2021).

5. Lines 291-293: The authors should briefly explain why the counts of observations cannot be directly compared?

Reply: Thanks for raising this point. We cannot compare the counts of observations with the grid-cells for the simulations because they are on different spatial scales. CALIOP’s counts are based on data at a horizontal resolution of 5 km, whereas the model simulation’s output are at a coarser resolution of ~130 km in the latitudinal direction. We have included the following to clarify this:

*‘Note that while the values of the counts of observations for CALIOP and grid-cells for the simulations in the 2D histograms cannot be directly compared due to **their different spatial resolutions, their relative abundance is comparable.**’*

6. Lines 297: Since no ice particles appear in the Control run, how can they produce an STS signal?

Reply: Thank you for this clarification. The CONTROL does produce ice, but due to the low number density and surface area density of these ice particles, there are no points that classify as ice using the CALIOP classification based on optical parameters. We have clarified this in line 297 which is now:

*‘(Note that since CONTROL includes no STS particles, the STS optical signal likely arises from NAT and ice particles **with low $\beta_{\perp}$ signals.**)’*

7. Line 314: The STS particles are between 50 – 100 counts which hardly implies “a few”.

Reply: We agree with the reviewer that ‘a few’ is not the correct way to describe the abundance of STS particle counts. We have changed the line to read:

‘Most remaining PSCs are NATmix or STS, with only a few ice particles.’

8. Lines 290..., Figs. 1 and 2: The authors should remind the readers that the boundaries between the various PSC types are controlled by Eqs. 14 and 15 which are likewise dependent on the median values plus one median deviation in $\beta_{\perp}$ and scattering ratio. Thus, the boundaries will shift based on the measured and modeled median values. While this characteristic adds to the complications of the measurement to model comparison, it is also an indication of the agreement/disagreement of model with measurement. This latter point perhaps should be mentioned in the panel to panel discussion.

Reply: Thank you for highlighting this. We agree this is important to address and have included the following two sentences near the end of Section 3.1 (Lines 332 – 335):

‘Note that the mean $\beta_{\perp}$ and R_{532} thresholds (including measurement uncertainty) are determined by Eqns. 14 and 15 and therefore shift based on the measured and modelled values. In Fig. 2, the mean $\beta_{\perp}$ line is lower across all periods and simulations compared to CALIOP, indicating the generally lower $\beta_{\perp}$ values in the distribution of model optical values compared to CALIOP.’

9. Line 314: ...with only a few STS particles ... That is not true. The STS density is quite comparable across all three observational periods in the CALIOP data from 31 Dec. to 28 Jan.

Reply: This comment seems to be the same as comment #7, please see response above.

10. Figs. 8, 9: Somewhere on the figures or in the caption, the level being presented, 68 hPa, should be added.

Reply: Thank you for this comment. The Figs. 8, and 9 captions have been amended to include 68 hPa:

‘Figure 8. As Fig. 6, but for zonal mean gas-phase H₂O (ppmv) at 68 hPa. Note that there is complete overlap of all model runs (CONTROL and sensitivity simulations).’

‘Figure 9. As Fig. 6, but for zonal mean O₃ (ppmv) at 68 hPa. Note that there is almost complete overlap of RUN_{HH} and RUN_{HL}, and RUN_{LL} and RUN_{LH}, resulting in only RUN_{HH} and RUN_{LL} being visible in the plot.’

References:

- Höpfner, M., Larsen, N., Spang, R., Luo, B. P., Ma, J., Svendsen, S. H., Eckermann, S. D., Knudsen, B., Massoli, P., Cairo, F., Stiller, G., v. Clarmann, T., and Fischer, H.: MIPAS detects Antarctic stratospheric belt of NAT PSCs caused by mountain waves, *Atmospheric Chemistry and Physics*, 6, 1221–1230, <https://doi.org/10.5194/acp-6-1221-2006>, 2006
- Kirner, O., Ruhnke, R., Buchholz-Dietsch, J., Jöckel, P., Brühl, C., and Steil, B.: Simulation of polar stratospheric clouds in the chemistry-climate-model EMAC via the submodel PSC, *Geoscientific Model Development*, 4, 169–182, <https://doi.org/10.5194/gmd-4-169-2011>, 2011.

van den Broek, M. M. P., Williams, J. E., and Bregman, A.: Implementing growth and sedimentation of NAT particles in a global Eulerian model, *Atmospheric Chemistry and Physics*, 4, 1869–1883, <https://doi.org/10.5194/acp-4-1869-2004>, 2004.

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