We sincerely thank the editor and reviewers for the time and effort dedicated to the revised version of our manuscript, “Introducing aerosol-cloud interactions in the ECMWF model reveals new constraints on aerosol representation”. We are particularly grateful to Anonymous Reviewer #1 for the constructive suggestions that helped us improve the presentation and discussion of the results. We agree with their comments and have integrated all proposed changes, while also adding improvements to the language and figures throughout the manuscript.

Reviewer #1 **Suggestions for revision or reasons for rejection**

Comment:

The revised manuscript is substantially improved. The authors have clarified the model configuration, the distinction between online and offline calculations, and the diagnostic nature of the aerosol activation scheme. Most of my previous comments have been addressed satisfactorily.

Two concerns remain partially addressed. First, the evaluation of aerosol mass fields remains limited. The added AOD, Angstrom exponent, AERONET size spectra, and TOA shortwave flux comparisons are useful, but they do not fully demonstrate that the aerosol mass fields, speciation, or vertical distributions are reliable in the exact cloudy regimes used for the (Nd) optimization. The optimized PSDs should therefore be described as effective parameters conditional on the model aerosol fields and diagnostic sampling method, rather than as physically unique aerosol size-distribution corrections. Second, the cloud-top activation issue remains only partly resolved. The revision now acknowledges that activation occurs near cloud base and includes useful InCloud, InCloudNoBC, and ClBase3 sensitivity tests. However, the main optimization still relies on aerosol sampled near cloud top. This is acceptable as a diagnostic approach, but the manuscript should frame it more cautiously and avoid implying that the InCloud-optimized PSDs represent a unique physical solution, as indicated by words like “physically informed representation”, “keeping the setup physically consistent”, and “interpreted as physically plausible”.

Some minor changes can help resolve the issue. For example:

Abstract:
“We optimise aerosol size distributions” could be revised to “we infer effective aerosol size-distribution parameters”. This better reflects that the optimized PSDs are conditional on the aerosol fields, vertical sampling, and cloud-regime selection.

"After optimisation, CAMS aerosols produce overall realistic Nd" could be revised to "After optimisation, CAMS aerosols produce more realistic large-scale Nd patterns". This wording is safer given the remaining regional biases.
"Representing ACI in a weather model enables Nd to constrain aerosol processes globally" could be revised to "Representing ACI in a weather model enables Nd to provide additional global constraints on aerosol number and related processes…" This leaves room for the fact that AOD/AE/AERONET comparisons help but do not fully prove that aerosol mass fields and vertical distributions are correct in the exact cloudy regimes used for optimization.

Response:

Abstract. Realistic cloud droplet number concentrations (N_d) are critical for simulating the Earth's radiative budget, yet remain challenging to represent in global models. One reason is that aerosol optical depth (AOD), commonly used for aerosol validation and assimilation, only weakly constrains aerosol number concentrations relevant for cloud formation. We introduce a ~~physically informed~~ representation of aerosol-cloud interactions (ACI) into the ECMWF Integrated Forecasting System (IFS), restricted to aerosol activation and the first indirect effect, and use it as a diagnostic tool to relate aerosol properties to cloud observations in the Copernicus Atmosphere Monitoring System (CAMS). Using 18 years of MODIS N_d retrievals, we ~~optimise aerosol size distributions and validate~~ infer effective aerosol size distribution parameters and evaluate results using independent observations of AOD, Angstrom exponent, size spectra, and top-of-atmosphere shortwave fluxes. After optimisation, CAMS aerosols produce ~~overall realistic~~ more realistic large-scale N_d patterns, but exhibit regional biases: overestimation over sub-Saharan Africa and underestimation at high latitudes. The African bias is consistent with carbonaceous aerosol~~s~~emissions from wildfires and can be partially mitigated through optimisation, while the high-latitude bias is likely linked to excessive aerosol scavenging in mixed-phase clouds and cannot be resolved by size adjustments alone. We show that introducing phase-dependent aerosol scavenging substantially improves all-sky shortwave fluxes over the Southern Ocean compared to the ACI implementation in the standard CAMS system. This highlights a direct link between radiative biases and aerosol wet removal processes. Representing ACI in a weather model enables N_d to ~~constrain aerosol~~ provide additional constraints on aerosol numbers and related processes globally, revealing limitations in how ageing, vertical transport and wet removal are represented, as these processes are only weakly constrained by standard AOD evaluation.

Comment:

Conclusion:
"we showed that Nd can constrains aerosol number concentrations" should be revised to "we showed that Nd can provide additional constraints on aerosol number concentrations". This is more accurate because Nd constrains aerosol number only conditionally through the model aerosol fields, activation scheme, and sampling assumptions.
"bulk aerosol scheme can reproduce realistic Nd" could be revised to "a bulk aerosol scheme can reproduce broad large-scale patterns of Nd, within limits imposed by…". The term "realistic" should be qualified because the manuscript shows persistent regional biases and sensitivity to the sampling setup.
"The resulting PSDs substantially improve simulated Nd" could be revised to "The resulting effective PSD parameters substantially improve simulated Nd within this diagnostic framework…" More evidence needs to be provided if framed as physically unique aerosol size-distribution corrections.

Response:

8 Summary, outlook and conclusions

In this study, we introduced an explicit representation of aerosol-cloud interactions (ACI), limited to aerosol activation and the first indirect effect, in the ECMWF Integrated Forecasting System (IFS), enabling cloud droplet number concentrations (N_d) to be used as an additional aerosol diagnostic. By combining a physically informed aerosol activation scheme with 18 years of satellite N_d retrievals from MODIS, we showed that N_d can ~~constrains~~ provide additional constraints on aerosol number concentrations for the Copernicus Atmosphere Monitoring Service (CAMS). Using this framework, we illustrated that a bulk aerosol scheme can reproduce ~~realistic~~ broad large-scale patterns of N_d, within limits imposed by the ~~modelled aerosol particle~~ aerosol size distributions (PSDs), vertical transport and wet removal processes.

We optimised the PSDs of CCN-providing aerosols using an offline diagnostic method, adjusting a small set of five free parameters using MODIS N_d observations. This method accounts for the co-location of aerosol and cloud profiles by combining stored output of prognostic aerosol simulations with reanalysis data, and consistently filters the same cloud regimes as in the N_d observations. The resulting ~~PSDs~~ effective PSD parameters substantially improve simulated N_d within the diagnostic framework used here, while having only a limited impact on aerosol optical properties. The optimised PSDs were further evaluated against independent observations of optical properties from AERONET and satellites.

Comment:

I still see some grammar errors and typos in the revised manuscript, but I believe these issues can be resolved during copyediting.

Overall, I recommend acceptance after minor revision, provided that the authors more explicitly state the conditional and diagnostic nature of the optimized PSDs and retain aerosol mass/vertical-distribution uncertainties as a clear limitation.

Response:

While we believe that the conditional nature of the optimisation was already present in the previous version, we agree that it is important to state this aspect more explicitly. We have introduced several punctual changes that should help and make this point even more visible and consistently reflected in the Methods, Discussions and Conclusions. In addition to all the changes integrated above, we added these:

Methods section:

As a result, a collection of optimised median radii for each species x and year y is obtained, $r_{\text{med},x,y}$. We finally define the optimal PSD as ~~the one using the optimal~~ those using the effective median radius $\overline{r_{\text{med},x}} \equiv \text{med}_y(r_{\text{med},x,y})$, i.e. the median across the 18 years of the optimised median radii. Within this framework, the resulting optimised aerosol PSDs are constrained by the cloud-top N_d observations and represent an effective description of aerosol number consistent with these observations; their realism is conditioned by non-represented processes (e.g. diagnostic representation of N_d and absence of prognostic droplet microphysics) and aerosol biases (e.g. speciation and vertical structure), and is therefore evaluated *a posteriori* through independent observations of aerosol optical properties.

Discussion section:

deals with the systematically low N_d at mid- and higher latitudes in the Southern hemisphere, where the optimisation is unable to bring improvement, and how the outcome of the sensitivity tests compare with the optimisation results. In both cases, results from the different setups (InCloud, InCloudNoBC, ClBase3), combined with independent observations, are used to clarify to what extent ~~each optimal PSD can be interpreted as physically plausible~~the optimal PSDs are consistent with independent observational constraints, and when ~~it compensates~~ they compensate for non-tuned aspects such as speciation, ageing or poor ~~mass concentration representation~~ representation of aerosol mass concentrations.