Authors' Response to Anonymous Referee's Comment RC#2

on Manuscript "CLEO: The Numerical Methods of a New Superdroplet Model including a Droplet Breakup Algorithm" , now renamed "Cleo: The Numerical Methods of a New Superdroplet Model including a Droplet Breakup Algorithm (v0.52.0)" by Clara J.A. Bayley et al. (2026)

Original Title	CLEO: The Numerical Methods of a New Superdroplet Model including a Droplet Breakup Algorithm
New Title	Cleo: The Numerical Methods of a New Superdroplet Model including a Droplet Breakup Algorithm (v0.52.0)
Author(s)	Clara J.A. Bayley et al.
MS No.	egusphere-2025-4399
MS type	Model description paper

We thank Referee #2 very much for taking the time to review our manuscript and suggest improvements. We found the comments thought provoking and helpful to making our manuscript appeal to a wider audience. In the following we address each of their comments as well as some additional revisions.

Please note the updates to the dataset for this paper (https://doi.org/doi:10.17617/3.SDN0NX) are currently viewable from this link whilst they await publishing:
https://edmond.mpg.de/previewurl.xhtml?token=6ed04ec0-fd10-4ce4-a508-09280f4f2a14.

Additional Revisions

These additional revisions were made based on comments by RC#2 on the companion to this manuscript (https://doi.org/10.5194/egusphere-2025-4398) which were also applicable to this one:

- **Renamed "CLEO" to "Cleo":** We think the acronym we gave Cleo in the original companion manuscript was not only unhelpful but also restrictive for Cleo's future development. We've therefore reverted to using Cleo as a proper noun, as it was originally intended to be, in tribute to the real-life "super-women", Cleopatra and the anonymous mathematician whose pseudonym was Cleo.
- **Corrected the acronym "Super-Droplet Model" to "Super-Droplet Method":** to align with the definition of SDM as in Shima et al. 2009. This occurs in the abstract (P1 L2) and includes minor re-wording of the sentences introducing SDM in the introduction (P2 L41-42): "The Super-Droplet Method (SDM; Shima et al., 2009) is a Lagrangian particle method for modelling cloud microphysics where the condensate population is represented by "superdroplets"".
- **The Edmond dataset metadata keywords were replaced:** we removed keywords which were not befitting of this dataset and replaced them with "Superdroplet Model, SDM, Cloud Microphysics Modelling, HPC" and "Cleo".
- **Using raster graphics:** we've replotted all the figures in this manuscript as .pdf files instead of .png. Except for Fig.10 because the .pdf file was too large (120MB!).
- **Updated References:** we've updated the references to the pre-prints for Bayley et al. 2025 (this manuscript's companion manuscript; egusphere-2025-4398) and for Niebaum et al. 2025 (egusphere-2025-5551). We've also updated the references to the final accepted versions of de Jong et al. (2023a) and Matsushima et al. (2023).
- **Merge the "Code availability" and "Code and data availability":** we have combined these two sections and written them following the guidelines from the GMD data policy (https://www.geoscientific-model-development.net/policies/code_and_data_policy.html).

These additional revisions were made as well:

- **Figure 6**: We corrected the citation for "Pruppacher and Klett (1978)", from "Pruppacher and Klett (1997)" and we've added citations for the terminal velocity parametrisations in the figure caption.
- **Additional acknowledgements**: we've added an acknowledgement to both referees of this manuscript (P22 L576-577).

Major Comments

In the following we address each of the Referee's major comments, however we have re-ordered some of the points by moving the ones related to model assumptions/limitations to the end to aid readability.

- *The general use of term Eulerian feels potentially confusing as a reader given the paper discusses Eulerian in both the sense of space and also in the sense of sectional microphysics. The presented model relies on a Eulerian model for solving wind field (and water vapor) but is Lagrangian in both particle position and in terms of microphysics.*

  We agree this was potentially confusing and we now specify "Eulerian, bulk and bin, models", "Eulerian models for cloud microphysics", "Eulerian microphysics models", or "Eulerian cloud microphysics models" whenever we use the word "Eulerian" in referring to bulk or bin models for cloud microphysics.

- *The authors could briefly discuss how CLEO can interface with other models, especially since it is presented here in a simplified 2D setup. Even if the companion paper covers this in detail, a short explanation would help readers understand its applicability, particularly regarding particle motion (see Section 4).*

  We have added a Section (Section 5; P15 L355- P16 L374), which provides details of the coupling with other models. (See also our response to Emily de Jong's Major Comment #4.). In light of the comment above, we've also been careful here to point out what is Eulerian and what is not. The following extract is the new Section 5:

  "Cleo is designed to run SDM microphysics concurrently to any host dynamical driver which it couples to (for the computational implementation see Bayley et al., 2025). For a certain simulation, there are therefore two distinct grids composing the domain at play: Cleo's Eulerian grid and the Eulerian grid of the driver, and these are completely independent except during coupling when information is sent between the two. Cleo's grid can be any kind of Arakawa C-grid and is composed of grid-boxes which define the volumes of the domain and the necessary Eulerian thermodynamic and wind fields so that the Lagrangian superdroplets can enact microphysics and move around. These are: the temperature, pressure, water vapour mass mixing ratio, and liquid water mass mixing ratio defined at the centre of each of Cleo's grid-boxes, as well as the wind velocity defined on the faces of each grid-box. (The meridional wind component is defined at the centre of the faces perpendicular to north-south, and analogously for the zonal and vertical wind components.)

  Cleo can be one-way or two-way coupled to a host dynamical driver. In both cases, at the start of each coupling time-step the host dynamical driver, via the coupler, communicates each of the necessary thermodynamic and wind fields to Cleo's grid-boxes. Cleo then enacts SDM microphysics and droplet motion, which potentially alters the temperature, water vapour and liquid water in each grid-box but not the pressure nor winds (e.g. condensation increases temperature and converts water vapour to liquid). In a two-way coupling Cleo then communicates the thermodynamic fields back to host dynamical driver, whereas in a one-way coupling it does not. As long as it can provide the required fields for Cleo, the host dynamical driver can be anything, from analytical formulae, to reading data from files, all the way to a fully-fledged numerical weather or climate model. Any potential advection of thermodynamic fields, momentum feedbacks, radiation or turbulence schemes are the responsibility of the particular host dynamical driver which Cleo is coupled to. For further details of Cleo's time-stepping, coupling or domain composition, readers should refer to Bayley et al. (2025).".

- *In general, it is not really clear to me what CLEO is and is not. It is not 100% clear how it relates to the original SDM or PySDM, if it is merely an extension of a model or brand new model.*

  Cleo is a novel computational implementation of a typical/ordinary SDM for warm-cloud microphysics. It models warm-cloud microphysics almost-entirely like other SDMs (condensation/evaporation, droplet collisions and droplet motion) except for some small but noteworthy differences. We have added some text in both the introduction and conclusion to make this clearer, as well as outline our motivation for making Cleo in the first place. With regard to addressing what Cleo is not, we've added three sections on this and a summary paragraph in the conclusion, as explained in response to the points on Cleo's assumptions/limitations below.

  To better address what Cleo is in the introduction, we now state in P3 L74-77: "We have created a novel computational implementation of SDM, Cleo. Our goal is to make a simplistic, ordinary representation of warm-cloud microphysics according to SDM which is well-suited to high-performance computers. Consequently we hope to make SDM feasible for large-enough-domain LES to resolve the interactions between warm-cloud microphysics and shallow mesoscale cloud organisation $\mathcal{O}(100\,\mathrm{km})$.". We also think that the following paragraph further explains what Cleo is ("Cleo models all the major microphysical processes of warm-clouds: condensation/evaporation, collisions between droplets and droplet motion. Most of the methods are already found in the literature, but in addition to documenting which of those Cleo adopts, we highlight particular novelties of our approaches and explain how the flexibility we incorporated reflects the uncertainties in our current understanding of warm-cloud microphysics. More specifically [...]"), but we've now also added to that (P3 L87-88) "For collision between droplets, Cleo can use the original collision-coalescence algorithm according to Shima et al. (2009), however Cleo also facilitates various definitions for the collision kernel and the outcome of collisions between droplets." to make it explicit how Cleo's representation of collisions relates to existing SDMs here as well.

And in the conclusion we now state in P20 L503-508: "Cleo is a concise and fully-functioning novel implementation of SDM for warm-cloud microphysics. Our primary motivation for creating Cleo is to provide a computationally efficient, "standard" SDM, which we could use in large-enough-domain LES to decipher the interactions between warm-cloud microphysics and shallow mesoscale cloud organisation. Cleo models collisions between droplets and condensation/evaporation, including (de-/re-)activation, similarly to existing SDM implementations albeit with some differences as summarised below. Cleo models Lagrangian particle motion following the SDM of Grabowski et al. (2018) but with the ability to switch between different terminal velocity calculations.". And in the subsequent paragraph in P20 L512-520 "Our numerical methods for condensation/evaporation and collisions between droplets have subtle but noteworthy differences to existing SDM implementations. For condensation/evaporation we solve the Köhler theory ODE explicitly with a number of cost-saving measures including adaptive sub-time-stepping. Our method for condensation/evaporation is thus purposefully very similar to Shima et al. (2009) and Matsushima et al. (2023), except that we additionally incorporate ventilation effects into the ODE we solve. For collisions between droplets, Cleo can use the original collision-coalescence algorithm according to Shima et al. (2009), however Cleo also has various other options, which reflect the uncertainty in the current knowledge about collision probabilities and their outcomes. Therefore Cleo can easily switch between different formulations of the collision kernel and, motivated by a need to investigate the possible influence of collisional breakup on rain evaporation and downdraughts, Cleo includes a framework to model collisional breakup and rebound.".

- *Section 5 is entitled "Validations" while it appears to contain, at least mostly, model verification. The authors should clarify whether or not certain aspects are for model verification or model validation. Dividing up this section of four tests into subsections may also be of benefit, such as one section for three individual proceses and another section that puts everything together.*

  We did not appreciate the difference between a validation and a verification and we thank the Referee for helping educate us on this. Accordingly, we have changed all mentioning of validations/validate to verifications/verify. We've also taken on the suggestion to seperate the verifications Section into sub-sections, and we have also split the paragraphs within these sub-sections into smaller ones to aid readability.

- *I suggest that the authors find a way to possibly present the convergence of the particle field of Figure 9 in a more meaningful way rather than relying on visual inspection.*

  We've added three extra sub-plots to the figure (now Figure 11) showing the number of superdroplets in each grid-box during the simulation. Accordingly we have replaced "(not shown)" with "(Figure 11d,e,f)" in P19 L472-473; the full sentence now reads: "As expected, Cleo's particle motion does indeed follow the flow field and respect its divergence-free properties, as confirmed by the conservation of particle number in each grid-box throughout the simulations (Figure 11d,e,f)." and amended the figure caption of Figure 11 to include: "Panels d, e, and f show the number of superdroplets in each grid-box over time, as well as the mean across all the grid-boxes (black; solid) and the standard deviation (black; dashed). The variance is caused by superdroplets leaving/entering different grid-boxes.".

The following three points all relate to model assumptions/limitations:

- *This paper has been submitted as a Model description paper. I would suggest that the following is considered: The scope and limitations of the approach adopted for CLEO could be expanded as the authors deem applicable. The manuscript may benefit from a paragraph or brief subsection regarding a discussion of scope of applicability and limitations. This is helpful for people to evaluate the applicability of CLEO and be aware of its weaknesses or aspects that are currently omitted. Example of which, how effects of sub-grid scale turbulence were noted to be neglected in Section 4..*

Thank you for your feedback and suggestion. We realise we made an error by omitting a discussion of Cleo's scope and limitations in the previous version of the manuscript (see next point for our explanation). We have therefore added three new sub-sections, which detail all of Cleo's major assumptions and limitations (see next point). Additionally in the conclusion we've added a new paragraph which summarises these sections and, at the same time, makes it clearer what Cleo is and is not suitable for ("it's scope of applicability"). The new paragraph reads (P20 L523-530): "Cleo's numerical methods have some limitations in comparison to some existing SDMs. Regarding condensation/evaporation, perhaps the most significant is that Cleo's method for condensation/evaporation currently does not account for multiple aerosol types. Regarding collisions, we have not incorporated any sub-time-stepping algorithm. Whilst Cleo's simple predictor-corrector method for droplet motion is less expensive than higher-order methods and still preserves the flow-field, is non-diffusive, and has increasing accuracy with increasing grid resolution, it does not yet incorporate turbulent effects and is less precise than a higher order method. All Cleo's limitations and assumptions make it poorly applicable to highly detailed microphysics studies requiring more complex processes, but make it well-designed, as intended, as a simplistic, ordinary representation of warm-cloud microphysics according to SDM.". (Please also see our reply above to the reviewer's third major comment, starting "In general, it is not really clear to me what CLEO is and is not. [...]", which explains the changes we have made to make it clearer what Cleo is, rather than is not.)

- *Beyond the noted parameterizations and particle motion, were there other significant assumptions in the model process design? Listing these briefly would help potential users or those comparing CLEO with their own models understand it's key assumptions.*

  As with any model of course we have to make assumptions, but whether or not they are significant/key depends on the application Cleo is used for. We thought that by stating what Cleo does, anyone interested in a particular aspect would be able to understand what assumptions Cleo makes and determine for themselves if they are significant for their particular application (e.g. someone studying the effect of sub-grid-scale supersaturation fluctuations vs. someone studying the effect of different collision kernels). Clearly, based on the feedback of both reviewers, this was not satisfactory enough. We have therefore added three new sub-sections in which we've tried to include an explicit and comprehensive list of all the model assumptions for condensation/evaporation, collisions, and droplet motion which we think warm-cloud microphysics modellers may view as "significant", also in comparison to other SDMs. The following extracts are the three new sections we have added:

  - (P6 L150-166) Sub-Section on "Condensation/Evaporation: Limitations":

    "In attempting to be computationally efficient and relatively concise, Cleo's representation of condensation/evaporation is less easily modified than it's representation of collisions and droplet motion. Whilst Cleo provides multiple options for the choice of terminal velocity (Section 4) and collision outcomes and probability calculations, as well as the ability to easily incorporate new ones (Section 3), Cleo's condensation/evaporation algorithm is comparatively inflexible. This reflects the greater consensus in modelling condensation/evaporation in contrast to the large uncertainty in droplet collisions and the multitude of acceptable droplet terminal velocity parametrisations in the literature. However, this means that unlike for example PySDM, Cleo has a fixed definition of its ventilation coefficient, arguably the most uncertain aspect of the ODE for condensation/evaporation. It also currently does not support a parametrised version of CCN activation, for example Twomey CCN activation as done by Grabowski et al. (2018), or a different numerical method for solving the condensation/evaporation ODE (e.g. as in Dziekan et al., 2019). Again in comparison to PySDM, Cleo does not provide between different parametrisations of thermodynamic formulae, for example for calculating supersaturation, conductivity or diffusion factors, or specific/latent heat capacities. (Nonetheless, if it were desired, a user could always change these fixed formulae or algorithms directly in the source code.)

    Additionally we do not account for any local perturbation in the environment around each superdroplet; they all experience the same grid-box values of thermodynamics and winds (Section 5), and Cleo's current representation of aerosols is crude, following Shima et al. (2009), unlike some SDMs which have since incorporated multiple aerosols and aerosol chemistry (Jaruga and Pawlowska, 2018; Bartman et al., 2022b).".

  - (P13 L310-315) Sub-Section on "Collisions: Limitations":

    "Cleo also has certain limitations related to its representation of collisions. Our decision to follow the original collision algorithm of Shima et al. (2009) means we are restricted to using a linear sampling for superdroplet pairs (although this is unlikely to be an issue; Dziekan and Pawlowska, 2017), and we do not implement any sub-time-stepping during collisions—for example as done in the latest version of PySDM (de Jong et al., 2023b). Terminating the simulation if superdroplet multiplicities reach zero during coalescence also makes Cleo currently unsuitable for modelling superdroplets with O(1) multiplicities.".

- (P14 L343- P15 L354) Sub-Section on "Droplet Motion: Limitations":

  "As already mentioned, Cleo uses a simple second-order method for droplet motion and does not yet incorporate any stochastic element to represent sub-grid scale turbulent effects on droplet motion. For simulations with increasingly high resolution and low superdroplet multiplicities, it may become more desirable to use a higher order method or one with adaptive sub-time-stepping, as done by some other SDMs (e.g. Naumann and Seifert, 2015; de Jong et al., 2023b), because in such simulations the superdroplet positions more precisely correspond to the real droplets' positions. Especially in coarse resolution simulations, neglecting sub-grid scale turbulence in droplet motion is idealistic, and so in a later version of Cleo our method should be extended to include a stochastic component, e.g. following Dziekan et al. (2019). During superdroplet motion we also make two more minor assumptions, first, we neglect any momentum exchange between the air and droplets (unlike Shima et al., 2020), and second, we assume each particle reaches their terminal velocity instantaneously, since this is unlikely to be noticeable in LES (Naumann and Seifert, 2015). Our method for superdroplet motion is therefore most similar to the other SDMs described by Arabas et al. (2015); Jaruga and Pawlowska (2018), Chandrakar et al. (2021), and Matsushima et al. (2023)".

- *Section 4 does not include any stochastic component for turbulence. While this is an intentional choice, if may be unclear to readers why this decision was made, whether or not there are justifications to this or if this is a possibly a typical assumption in these types of models.*

  This choice was made because Cleo's algorithms for droplet motion are intended to be as simplistic and computationally efficient as possible, as now stated (P20 L528-530) "All Cleo's limitations and assumptions make it poorly applicable to highly detailed microphysics studies requiring more complex processes, but make it well-designed, as intended, as a simplistic, ordinary representation of warm-cloud microphysics according to SDM.". However, neglecting turbulence is indeed a gross assumption and we now include this in our discussion of the limitations of Cleo's representation of droplet motion, and we make clear it's an area for Cleo's future development: (P15 L348-350) "Especially in coarse resolution simulations, neglecting sub-grid scale turbulence in droplet motion is idealistic, and so in a later version of Cleo our method should be extended to include a stochastic component, e.g. following Dziekan et al. (2019).". Also in the conclusion we state (P20 L525-528) "Whilst Cleo's simple predictor-corrector method for droplet motion is less expensive than higher-order methods and still preserves the flow-field, is non-diffusive, and has increasing accuracy with increasing grid resolution, is does not yet incorporate turbulent effects and is less precise than a higher order method.".

Minor Comments

- *I believe that the title, per journal guidelines, should include information regarding the version number. This number appears to be v0.52.0 in the code availability section of this manuscript. However, this may be complicated by the fact that the companion paper regarding performance appears to have used a different version of CLEO.*

  We've now corrected the title to include the version number, "(v0.52.0)". (And also re-name "CLEO" to "Cleo" as already discussed; see first point in section on additional revisions above.) It is true that the companion paper uses an older version of Cleo (v0.39.0), however since the changes between v0.39.0 and v0.52.0 do not impact the results nor discussion in the companion paper, we did not find it necessary to re-run the analysis in that paper with this later version of Cleo. The changes were predominately refactoring, including python bindings, new examples and documentation, and minor bug fixes to the microphysics. This is all detailed in Cleo's release history (https://github.com/yoctoyotta1024/CLEO/releases).

- *I believe Equations 12 and 13 should use S_S and S_L rather than R_S and R_L, since the latter are not defined in the text. Please verify or correct accordingly. Also check the consistency of the defintion of S_c since it uses R_S and R_L, and it isn't clear why it would not just use R_j and R_k.*

  We've now defined R_S and R_L in the text (P8 L208-209): "Let the pair of droplets j and k be re-labelled small, S, and large, L, based on their radii, R_S and R_L respectively.", as well as keeping their definitions in Equations (10) and (11). Although both $S_c = 4\pi\sigma_l(R_S^3 + R_L^3)^{2/3}$ and $S_c = 4\pi\sigma_l(R_j^3 + R_k^3)^{2/3}$ can be used in this context interchangeably, we've now switched to using j and k indexing to aid readability.

- *Line 334: "...and a log standard deviation of 1.4" appears to be incorrect. I believe this should be standard deviation and not the log of the standard deviation. Please verify and correct if necessary.*

  We follow the terminology of Hill et al. (2023) who stated they used a "prescribed single-mode lognormal aerosol size distribution with a lognormal geometric mean diameter of 0.08 μm and a log standard deviation of 1.4.". We have however corrected a typo so that our manuscript now states (P19 L483): "geometric mean diameter of 0.08 μm" not "geometric mean diameter of 0.08 mm".

Technical Corrections

- *Line 176: should σ actually be σ_l?*: Yes, corrected (P9 L224).
- *Figure 8 introduces N as number of superdroplets when ns was introduced earlier.*: We have corrected N to n_s (now Figure 9).
- *In the reference section, many of the DOIs appear to be mangled with repeated doi.org.*: We apologise that we overlooked that. We have now corrected the formatting of all the references.