

Responses to the Reviewer 2 comments.

We greatly appreciate the Reviewer's effort in providing us with the annotated manuscript. This is very efficient way to communicate the comments. However, this also makes our job more difficult to communicate back our responses. We decided to pull out all comments marked as "major" from the annotated manuscript and respond to them in this document. The minor comments were either addressed by appropriate changes to the manuscript or are copied below together with our responses if no changes to the manuscript were done.

In the text below, the Reviewer's comments are in italics, our responses in regular font.

Major comments:

P. 5: To avoid confusion, the definition and time dependence of your multiplicity parameter has to be clarified.

Yes, we agree that the formulation in the Twomey activation formulation was in error. This was a mistake by the lead author that is now corrected. The code now uses multiplicity expressed as the number (i.e., the number of real droplets each super-droplet represents), not the number mixing ratio, in agreement with previous applications of the Lagrangian thermodynamics. After modifying the Twomey approach code the results are in a better agreement with the UWLCM. This is very much appreciated!

P. 12: Please clarify at which timing the Twomey activation performed. Perhaps just after the transport of SDs? Please also clarify when and how the cloud droplet deactivation (removal of SDs) is calculated. Perhaps when solving the droplet growth eq. (4)? And remove those SDs that have negative radius?

Activation takes place when the local supersaturation exceeds the "activation supersaturation", where the "activation supersaturation" is given by Twomey relationship applying the number mixing ratio for all droplets present in a given grid cell. This check is performed at every model time step applying updated thermodynamic Eulerian and Lagrangian variables, that is, as the final element of the time stepping algorithm (or the first element of the next time step). This allows additional temperature and moisture tendencies due to activation to be added to other forces that are derived at the same time and then used in the time-stepping procedure as given by Eq. 6 in the manuscript. At the same time, SDs are removed from the SD list when their radius becomes zero.

P. 13: Please clarify the following points.

1) At which timing is this spurious supersaturation mitigation performed? Perhaps just after the transport of SDs, but before the Twomey activation?

2) In GM08, under sub-saturated condition, a limitation $\epsilon \leq 0$ is imposed. Is this the same for Twomey SDs?

3) As explained in eq.6b of GM08, another limitation $\epsilon \geq -q_c$ is imposed for the bulk model because available cloud water is limited. In the same manner, is the limitation $\epsilon_i \geq -N_i m_i / dV$ imposed for Twomey SDs? If this condition is met, do you deactivate and remove the i -th SD from the list?

1) Since the model applies the Euler forward time integration scheme for thermodynamic fields (as explained in the manuscript, see Eq. 6), the adjustment takes place after calculations of new time level temperature and moisture variables are completed. Subsequently, the activation is calculated as it requires the final (i.e., adjusted so no spurious supersaturation values are present) thermodynamic variables within the grid cell.

2) Yes, an increase of the cloud water due to adjustment within a cell is not allowed if the air is sub-saturated. Please note that the sub-saturated air does not cause any harm in terms of droplet activation.

3) In the code, ϵ is first limited by the total liquid water as in the case of the bulk model. Then ϵ is “distributed” into ϵ_i for each SD and adjustment of each SD takes place. In the adjustment, the radius is changed and multiplicity is preserved as explained in the manuscript. And yes, the adjustment is allowed to remove all water from a given SD (such SD is later removed from the SD list). That said, we expect that complete elimination of a SD seldom happens as the amount of water substance involved in the adjustment is typically a small fraction of available water. This is our experience from 1D tests described in Grabowski and Morrison MWR manuscript and some limited testing we performed with the rising thermal simulations.

P. 14: *Let me confirm. Not in a per-grid manner, but in a per-particle manner? Does this mean that each SD does not feel the influence of other SDs in the same grid for 1sec? I suppose it is too long, at least to calculate activation/deactivation by solving the kappa-Kohler based growth equation.*

No, the “per-particle” term is confusing as thermodynamic fields are updated during the sub-stepping procedure. We revised the text removing the “per-particle” term and we refer to Arabas et al. (GMD 2015) that provides more detail.

Minor comments that did not lead to significant changes and require an explanation:

Abstract, L. 5-7: *Naumann and Seifert (2015, JAMES) applied the Lagrangian framework only to rain droplets. I think their work should be cited somewhere in the paper.*

We feel this is a very peculiar (but insightful as far as science is concerned) application of the Lagrangian methodology. We decided not to cite this paper. We removed the word “all” from the abstract.

P. 4, Eq. 4 and line 14: *Not the mass diffusivity D_v , but the thermal diffusivity α should be used here. α is about 15% smaller than D_v . See, e.g., table 2 of Montgomery (1947). Please update eq (4) or justify the use of D_v here.*

As explained in the manuscript, the simplified formulation (4) (except for the r_0 factor, i.e., $dr/dt = AS/r$) can be derived from the more accurate textbook formulation of the droplet growth equation that involves the sum of heat conduction and vapor diffusion factors (e.g., p. 73 in Rogers “Short course in cloud physics” book or the reference to Grabowski et al. 2011 paper given in the text). The derivation – again, as explained in the text – involves assuming that the thermal diffusivity is close to water diffusivity and using the latter in the thermal conductivity, $K=c_p \rho_a D_v$. The reviewer is correct, there is a 10-15% difference between the two that is neglected in the approximate formulation. Such a simplified formulation is used in the double-moment warm-rain scheme described in the appendix of Morrison and Grabowski (JAS 2008) referred to in the manuscript. We modified slightly the text to explicitly state the above.