Answer to reviewer #1

General comments

RC1: 'Comment on egusphere-2025-5329', Anonymous Referee #1, 23 Jan 2026

This study presents a systematic framework for tuning and modifying the cold-pool parameterization in LMDZ using the High-Tune-Explorer (HTE), with large-eddy simulations (LES) serving as the physical reference. Motivated by insights from LES, several key parameter assumptions are revised, and the use of HTE to optimize free parameters leads to a substantial reduction of biases in single-column model (SCM) simulations.

A major strength of the manuscript lies in its clear and well-structured description of the LMDZ convective parameterization associated with cold-pool processes. The results demonstrate clear benefits for representing cold-pool effects and are potentially valuable for future LMDZ CMIP7 simulations. Overall, this is a solid and well-executed study.

I recommend publication after the following points are addressed or discussed.

Thanks a lot for these very positive comments and for all your suggestions. We answered them all and tried to use them to improve the text.

1.LES cases used for tuning
The LES cases employed in this study include radiative-convective equilibrium (RCE) simulations and a diurnal cycle over land (AMMA) case. While these configurations are appropriate for examining cold-pool impacts on convection initiation and diurnal timing, cold-pool dynamics are also closely linked to the organization of mesoscale convective systems through mechanisms such as those described by RKW theory. It would be helpful for the authors to discuss whether incorporating LES cases of squall lines or other organized mesoscale convective systems could further constrain or refine the parameterization, or whether such regimes lie beyond the intended scope or intrinsic limits of the current cold-pool formulation.

Thanks for the suggestion. Wind shear could indeed modify the dynamics of cold pools within organized convective systems. However, the effect of wind shear on cold pools is not yet explicitely taken into account in LMDZ. Once this effect is integrated into the model, it would be interesting to recalibrate the cold pool parameterization using LES of squall lines or mesoscale convective systems. Following your suggestions, we added a paragraph discussing this issue in the conclusions (L725-731):

▷ The LES of the AMMA case is characterized by a significant wind shear resulting in relatively organized convection. Although the interaction between wind shear and cold pools is not yet explicitly taken into account in LMDZ, the results indicate that the cold pool model already represents quite well regimes with moderate wind shear. Accounting for wind shear in the parameterization of both convection and cold pools is under consideration in the LMDZ team. Once such effects taken into account, it may be relevant to recalibrate the cold pool model using, in addition to the RCE and AMMA cases, LES of strongly organized convection such as squall lines or Mesoscale Convective Systems (MCS), for which the influence of wind shear is more pronounced.

2.Remaining bias in diurnal cycle timing
The simulated diurnal cycle remains delayed by approximately three hours. Previous studies (e.g., Khairdinov and Randall 2009) have suggested that cold-pool processes may play an important role in regulating convective timing. It would be useful to clarify whether this timing bias could potentially be reduced through further tuning of the cold-pool parameters, or whether it reflects a more fundamental limitation of the parameterization in capturing timing as opposed to intensity or spatial structure.

Yes, cold pools can play a role in regulating the onset of convection. The introduction of the cold pool model together with a mass flux scheme of the boundary layer through ALE and ALP closure, indeed significantly delayed already the diurnal cycle of convective precipitation in LMDZ, both in 1D (Rio et al., 2009) and 3D (Hourdin et al., 2020). We do not have however a specific parameter in the cold-pool model that could correct the remaining bias, and we are not sure in fact that this remaining bias is related to the cold-pool model itself. There is, however, a parameter in the convection scheme that can slightly shift the timing of convection onset in the AMMA case: the threshold size at which a cumulus evolves into a cumulonimbus, which is currently *prescribed in the model. We consider that this lag more likely reflects a physical limitation of LMDZ, that we are working on, trying to improve more generally the transition between shallow and deep convection. We have added sentences in the revised version to better clarify this point. (L717-724):*

▷ For the AMMA case, the analysis of the diurnal cycle also shows that the adjusted model reproduces well the intensity and updraft power of cold pools at the time of their maximum development, but with a lead of about 3 hours in the diurnal timing of this maximum. While this single case is not statistically significant it is worth mentioning that early convective initiation is a known limitation of LMDZ, even though the representation of the diurnal cycle of continental precipitation has significantly improved thanks to the inclusion of cold pool effects (Rio et al., 2009). The remaining lead in convective onset cannot be modified by the cold pool model itself, since the cold pool model is by essence not active before convective initiation. It is most probably a question of transition between shallow and deep convection and specific work are ongoing in the LMDZ team to better represent this transition.

3.From SCM tuning to coupled simulations

The SCM experiments provide a clean and controlled framework for evaluating the impact of the revised parameterization. However, it is well known that parameterizations optimized in SCM settings may degrade performance once fully coupled to a three-dimensional model. Before proceeding to fully coupled CMIP-style simulations, it would be valuable to consider an intermediate hindcast-type evaluation (e.g., following Ma et al. 2015). The authors are encouraged to comment on whether such an approach is planned or feasible within the scope of this work.

We are well aware as well that parameters calibrated in a 1D framework may degrade the results of 3D global simulations, which justifies the need for intermediate testing before full integration into the global model. In our case however, we performed 3D tests and found a behavior overall similar to that observed in 1D. This suggests that the calibrations carried out in 1D remain valid in the 3D, here. This aspect was not discussed in the initial version of the manuscript, but it is indeed worth including. We have therefore added new sentences in the revised version to address this point. The added sentences are as follows (L732-739):

▷ Calibration performed in SCM is not a general guarantee of improvement in 3D mode. It could even degrade the results if the cases used in SCM mode are not enough representative, or if coupling with the large scale (not accounted for in SCM) matters more than the details of the scheme, which could motivate tuning in intermediate configurations before full 3D implementation (Ma et al., 2015). In the present case, however, preliminary 3D test runs (not shown) of the most recent versions of the LMDZ climate model show a behavior that is overall similar to that obtained in SCM. The new numerical scheme proposed for the computation of p_{wk} also proved to be more robust, significantly reducing crashes during 3D simulations.

4.Effectiveness and physical interpretation of the tuning framework

The manuscript would benefit from a more explicit discussion of the effectiveness of the HTE tuning framework itself. In particular, further elaboration on how the adjusted parameters relate to the underlying physics of cold pool processes-such as their fundamental structure, triggering mechanisms, and interaction with convection would strengthen the physical interpretation of the tuning results and improve the broader applicability of the methodology

Thank you for the suggestion. We have tried to add more explanation to the text. We hope that these sentences, added below to the text at the section 5.4, bring more clarity.

▷ The `htexplo` tool retrieves automatically cold pool model parameter values close to those issued from direct analysis of LES. This highlights both the power of using such a tool for model development, avoiding a long phase of trial error in a multi-dimensional space, and the relevance of the model physics. Likewise, the range of values selected for σ_{int} leads to cold pool heights of about 600 m in the RCE case and 2 km in the AMMA case, in agreement with the expected orders of magnitude over ocean and over land, respectively. One goal of the tuning is to intensify cold pools, particularly in the RCE case. The increase of σ_{desc} is primarily responsible for strengthening cold pools in this case, through stronger evaporation.This increases confidence in the validity of the physics implemented in the cold pool model. In the AMMA case, the opposite effect (less colder cold pools) is explained by the rather large increase in C_* (from 3 to 5 m/s), induced by the adjustment of k. This increase in C_* accelerates the increase of the cold pools fractional area σ_{wk}, reducing the efficiency of evaporative cooling, which can no longer compensate for the dilution due to their rapid evolution. Although this mechanism is also present in the RCE case (with an increase in C_* from about 1 to 2 m/s), it remains much less pronounced there, allowing the evaporation obtained with these σ_{desc} values to effectively strengthen the cold pools. We also consider that the increase of 1-EP_{max} and σ_{desc} played an important role in the improvement of the specific humidity profiles for the RCE and AMMA cases, although other parameters may also play a role. The increase of the difference 1-EP_{max} increases the amount of condensed water released at the top of the convective columns, thereby moistening the upper layers of the atmosphere. The value of EP_{max} was set to 0.999 in the control configuration. The increase in σ_{desc} may both enhance humidity through enhanced evaporation and dry the boundary layer, for the AMMA case in particular, due to increased entrainment and downward advection of dry air from the free troposphere.

My suggestion would be replacing Figure 1 with more coherent parameters of cold pools

Excellent suggestion. We did provide a totally new version of Figure 1, giving more insight to the cold pool parameterization and of its coupling with parametrizations of shallow and deep convection

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