Evaluation and improvement of ~~a~~ the cold pool parameterization in the LMDZ climate model against Large Eddy Simulations

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Abstract. Cold pools, formed under clouds by the evaporation of precipitation, play a central role in maintaining and organizing atmospheric convection. It is suspected that their absence in climate models may lead to significant errors in the representation of convection, such as the premature convection extinction after sunset. The introduction of a cold pool parameterization into the LMDZ climate model has significantly improved the representation of convection, in particular its diurnal cycle. ~~However, this parameterization had not yet been accurately evaluated in terms of representing the cold pool properties.~~ This work provides for the first time such an evaluation of this parameterization based on Large Eddy Simulation (LES), relying in particular on a radiative–convective equilibrium case that allows the study of convective processes in a well-controlled framework, without the influence of large-scale dynamics, as well as on a continental case AMMA (African Monsoon Multidisciplinary Analysis), representative of a typical Sahelian convective system. First, we evaluate the physical relationships underlying the cold pool model in the LES, then, in a second step, its behavior when coupled with the deep convection scheme in the single-column version of LMDZ. The analyses carried out demonstrate the relevance of the assumptions underlying the parameterization. The initial version actually captures the main characteristics of LES cold pools but also exhibits some biases. We show how substantial modifications to the cold pool scheme and a readjustment of certain free parameters helped reduce those biases significantly. The remaining flaws could be corrected by adding convective mixing through thermal plumes within the cold pools and by modeling the evolution of cold pools number density rather than imposing it.

1 Introduction

During thunderstorms, ~~a significant amount of~~ precipitation forms within convective clouds. When the air beneath these clouds is not saturated with water vapor, part of the precipitation evaporates before reaching the ~~ground, generating cold air masses in the layers below the clouds. This cooled air~~ surface. This evaporation cools the air beneath the cloud base, making it denser, ~~denser than its surroundings, collapses and then spreads horizontally across~~ giving it negative buoyancy, and causing it to descend toward the ground. When reaching the surface, ~~forming so-called cold pools. These~~ this descending cold air spreads

horizontally. These expanding cold air masses are generally referred to as cold pools. The cold pool, that spreads horizontally because its air is warmer than its environment, can be seen as a density current (Charba, 1974; Droegemeier and Wilhelmson, 1987)

25   . Cold pools are often associated with a gust front, capable of lifting the surrounding warm air and thus promoting the development of new convective cells. In organized propagative systems such as squall lines, convective columns are permanently generated by cold pool fronts at the front of the system (Rotunno et al., 1988; Weisman and Rotunno, 2004). ~~When the cold pool is accompanied by a gust front, it is called a density current. These density currents are fueled by precipitating downdrafts, which is their main dynamic driver.~~ Present over both continents and oceans, ~~density currents~~ cold pools are generally deeper,

30   colder, and propagate more rapidly over continents. They play a key role in the self-aggregation of tropical convection (Jeevanjee and Romps, 2013), as well as in the transition between shallow and deep convection (Khairoutdinov and Randall, 2006; Böing et al., 2012).

In atmospheric Global Circulation Models (GCMs), as those used for climate change studies, convection has to be parameterized due to the coarse horizontal resolution (30 to 300 km). Simulating convective rainfall with parameterized physics is chal-

35   lenging (Randall et al., 2003). GCMs often underestimate rainfall rates ~~(Kendon et al., 2012; Pantillon et al., 2015; Tan et al., 2018)~~ (Kendon et al., 2012; Pantillon et al., 2015; Tan et al., 2018; Rooney et al., 2022) and produce peak precipitation at noon, in phase with insolation, while the maximum precipitation is generally observed in late afternoon or during night (Randall et al., 2003; Guichard et al., 2004; Stephens et al., 2010; Dirmeyer et al., 2012). ~~Density currents~~ Cold pools probably play a key role in this timing, by self-maintaining convection (Pantillon et al., 2015; Grant et al., 2018). One of the first attempts to pa-

40   rameterize ~~density currents~~ cold pools was proposed by Qian et al. (1998). Later on, Grandpeix and Lafore (2010) proposed a parameterization based on a population of identical circular ~~density currents~~ cold pools that are cooled by convective precipitation. ~~The~~ In this parameterization, cold pools do not propagate from one grid cell to another, unlike more recents works of Rooney et al. (2022) and Freitas et al. (2024). This propagation is important for representing their impact on convective organization (Freitas et al., 2024). Nevertheless, the coupling of the Emanuel (1991) parameterization of deep convection with

45   ~~this~~ cold pool parameterization (Grandpeix and Lafore, 2010) and with the thermal plume model of Rio and Hourdin (2008) in the LMDZ climate model significantly improved the simulation of the diurnal cycle of precipitation in the tropics (Rio et al., 2009), shifting its maximum from noon to mid afternoon. A further improvement was brought by the introduction of the stochastic triggering of deep convection (Rochetin et al., 2014) which made the simulated convection more intermittent. Despite this success, and the use of the cold pool model in the standard version of the LMDZ atmospheric and IPSL (Institut

50   Pierre Simon Laplace) coupled models (Hourdin et al., 2020; Boucher et al., 2020), it was not evaluated in details so far. ~~At the same time, other parameterizations have been develop to include the impact of cold pools on convection, but without necessarily evaluating in details simulated cold pool characteristics and properties (Park, 2014; Del Genio et al., 2015)~~The same applies for the other existing cold pools parameterizations (Park, 2014; Del Genio et al., 2015; Rooney et al., 2022; Freitas et al., 2024), which have not been evaluated in detail for their ability to simulate the cold pools themselves, but rather in terms of their effect

55   on convection. This is explained not only by a lack of observational data but also by the fact that the internal variables of parameterizations are not directly accessible from observations.

Large Eddy Simulations (LES) are a useful complement to observations. Their fine horizontal resolution enables them to simulate explicitly turbulent and convective motions in the boundary layer (Brown et al., 2002; Siebesma et al., 2003). One advantage of LES compared to observations is that they provide full three-dimensional information. They have been used ~~extensively~~

60 to develop and evaluate boundary layer and convection parameterizations ~~(?Dorrestijn et al., 2013; Strauss et al., 2019; Legay et al., 2025)~~ (Rio et al., 2009; Dorrestijn et al., 2013; Strauss et al., 2019; Suselj et al., 2019; Legay et al., 2025). LES have been used to simulate and understand cold pools (Feng et al., 2015; Meyer and Haerter, 2020; Lochbihler et al., 2021), as well as to develop parameterizations of cold pools (Kurowski et al., 2018). However, their use for a cold pool parameterization assessment remains unexplored.

65 Here we propose to use LES to evaluate in details the parameterization of cold pools of LMDZ (Grandpeix and Lafore, 2010; Grandpeix et al., 2010). We first use LES to evaluate some of the fundamental relationships between large scale state variables (for LES, the horizontal average over the domain) and internal variables which are at the basis of the parameterization. We then propose improvements which are further assessed in simulations with a Single-Column-Model (SCM) version of LMDZ against LES. In such simulations, the parameterization interacts with all the other parameterizations and depend on the

70 values of a number of free parameters. To explore the sensitivity of the results to those free parameters and retune the model after improvement of its physical content, we use a tool for automatic calibration, High-Tune-Explorer, developed recently (Couvreux et al., 2021; Hourdin et al., 2021). This tool, based on history matching, can be used to characterize the subspace of parameter values for which the model is in agreement with LES, given a series of target metrics and associated tolerance to error (Couvreux et al., 2021). It is used here to explore the sensitivity of the agreement between SCM simulations and LES to

75 the model free parameters.

The paper starts by presenting in section 1 the tools used: the LMDZ model, the cold pool parameterization by Grandpeix and Lafore (2010) (referred to as the GL10 hereafter), and the LES used for evaluation. The presentation of the tuning tool (largely published) and the setup of its use is let to an appendix to concentrate on model physics and improvement in the core of the paper. In section 2, we detail the cold pool sampling in LES, designed to assess the physical laws internal to the

80 cold pool parameterization and its coupling with deep convection. Section 3 is devoted to a comparison of cold pool model variables simulated by LMDZ in SCM mode and those calculated in LES, in order to identify the model's limitations. These results will then be discussed, and proposed improvements will be detailed in section 4. Finally, we conclude with a synthesis and discussion of prospects in section 5.

2 Tools and methods

85 ### 2.1 LMDZ and its single-column version

LMDZ is the General Circulation Model (GCM) used in this work. Developed in the 1970s at Laboratoire de Meteorologie Dynamique (Sadourny, 1984; Hourdin et al., 2006). It is based on simplified Navier-Stokes equations for fluid mechanics, as well as transport equations. It represents the second generation (Hourdin et al., 2013) of a climate model initially described by Sadourny and Laval (1984). LMDZ is the atmospheric component of the IPSL coupled model. The latter is one of around

twenty coupled models taking part in major international model intercomparison exercises, such as those of the CMIP (Coupled Model Intercomparison Project), the results of which are used in IPCC (Intergovernmental Panel on Climate Change) reports. We use here the LMDZ6A configuration of LMDZ designed for CMIP6 and described by Hourdin et al. (2020).

LMDZ consists of two main parts, from a physical, mathematical and computational point of view. The first part, called "the dynamics", concerns the numerical resolution of the atmospheric general circulation equations. This component manages horizontal exchanges between the model's grid cells. The second part, called "physics", calculates the impact of radiation, small-scale processes (subgrid) and phase changes of water on dynamic variables via "physical parameterizations". This "physical" part is made up of juxtaposed atmospheric columns, which do not interact with each other. Within each column, the variables are assumed to be statistically homogeneous in the horizontal plane.

The SCM version of LMDZ is built by extracting an atmospheric column from the GCM, incorporating all subgrid-scale parameterizations, and running it in a large-scale constrained environment. This approach has become central in the development and tuning of parameterizations of convection and associated clouds in several climate modeling groups (Zhang et al., 2016; Gettelman et al., 2019). Parameterizations are often developed and evaluated within this single-column framework by comparing them with LES of the same atmospheric column. The SCM/LES approach was promoted in particular by GCSS (GEWEX Cloud Systems Study), a program aimed at improving the parameterization of cloud systems in climate models (Krueger et al., 2016). A major advantage of the SCM is its low computational cost, which allows a large number of simulations, even on a laptop, making it particularly useful in the development phase, where extensive testing is required.

2.2 Convective parameterizations in LMDZ

The role of convective parameterizations is to provide sources of heating Q_1 and moistening Q_2 to the conservation equations of potential temperature θ and specific humidity q_v :

$$C_p \frac{D\theta}{Dt} = Q_R + (+)(c-e)\frac{\theta}{T}[Q_R + (L_v + f_g L_f)(c-e)] - C_p \frac{1}{\rho}\frac{\partial \overline{\rho w'\theta'}}{\partial z} \quad = Q_R + \frac{\theta}{T}[Q_R + Q_1], \tag{1}$$

$$\frac{Dq_v}{Dt} = e - c - \frac{1}{\rho}\frac{\partial \overline{\rho w'q_v'}}{\partial z} \quad = -Q_2/L_v, \tag{2}$$

where C_p is the heat capacity of dry air, Q_R is the radiative heating, c and e are condensation and evaporation rates, f_g is the condensate ice fraction, L_v is the latent heat of vaporization and L_f the latent heat of fusion. For any state variable ϕ, the source term should include the vertical convergence of the Reynolds turbulent flux of the quantity $-\partial_z \overline{\rho w'\phi'}/\rho$, representing the effect of subgrid-scale turbulent or convective motions on the explicitly resolved large scale flow Note that the θ/T factor on the right hand side of the first equation was missing in the equation of Grandpeix and Lafore (2010) but not in the code of the parametrization. The convective parameterizations also often provide a source term Q_3 for momentum but it is not involved in the coupling with cold pools described here.

Note that the equations above are simplified assuming that the ice fraction f_g is unchanged by evaporation and condensation. Note also that Q_2 is a sink of humidity expressed conventionally as a heating term with constant L_v.

The parameterization of turbulence, convection and clouds in LMDZ is based on a multi-scale, or object view.

2.2.1 The small scale turbulence~~,~~

The small scale turbulence, mainly active near the surface, is accounted for following Yamada (1983) scheme, with an eddy diffusive approach in which the eddy diffusivity relies on a prognostic equation for the turbulent kinetic energy.

125 ### 2.2.2 The thermal plume model

The thermal plume model was developed specifically to account for the vertical transport by organised thermal plumes, cells or rolls in the convective boundary layer~~(Hourdin et al., 2002; Rio and Hourdin, 2008)~~, initially to describe turbulent transport in the dry boundary layer (Hourdin et al., 2002), and later extended to cloud processes, particularly shallow convection (Rio and Hourdin, 2008). The population of convective structures within a grid cell are summarized into a mean ascending plume, with a unique as-
130 cending mass flux $f_{th} = \rho \alpha_{th} w_{th}$, compensated by a mass flux $-f_{th}$ in a fraction $1 - \alpha_{th}$ of the grid cell. This is a bulk-plume approach applied to the subcloud layer. The sources $Q_1{}^{\text{th}}$ and $Q_2{}^{\text{th}}$ only contain the vertical convergence of the mass flux transport $(\overline{\rho w' \phi'} = f_{th}(\phi_{th} - \phi)$ where ϕ_{th} is the value of variable ϕ within the thermal plume), the part coming from the condensation or evaporation being treated in the so-called large-scale condensation scheme.

2.2.3 The large-scale condensation scheme

135 The large-scale condensation scheme is used to predict the cloud fraction except for deep convection, based on a probability distribution function (PDF) of the total water within the horizontal grid cell (giving the cloud fraction as the part of the grid cell with humidity above saturation). This statistical cloud scheme provides to first order: $Q_1{}^{\text{lsc}} = (L_v + f_g L_f)(c - e)$ and $Q_2{}^{\text{lsc}} = -L_v(c - e)$. For shallow cumulus or strato-cumulus, cloud condensation is thus treated outside the thermal plume scheme. Both schemes are however coupled together when the thermal plume is active within a grid cell. In this case, the
140 subgrid water PDF is prescribed as a bimodal function, with one mode corresponding to the thermal plume and the other one to its environment. This coupling led to a strong improvement in the representation of cumulus and stratocumulus clouds (Jam et al., 2013; Hourdin et al., 2019).

2.2.4 Deep convection

Deep convection is represented with a modified version of the Emanuel (1991) scheme ~~. As for shallow convection, the~~
145 ~~parameterization of deep convection represents~~ (Grandpeix et al., 2004). Its fundamental principles are retained, with a representation of a population of cumulonimbus clouds that would occur in the grid cell as an effective cumulonimbus cloud ~~. However, for~~ ~~deep convection, the~~ (bulk scheme). This parameterization simultaneously represents transport, condensation, cloud forma-tion~~and rainfall are treated within the same scheme~~, and precipitation.
    Convective transport in these cumulonimbus clouds is represented by mass fluxes and an air exchange matrix. Several
150 "compartments" can be distinguished. An undiluted updraft that does not entrain air laterally above the base of the cloud, but is gradually "shed" or "eroded" while rising. It is assumed to be fast enough to carry the liquid or solid water condensed within it. Following the Episodic Mixing and Buoyancy Sorting approach, a population of diluted ascending or descending air masses,

saturated, created by mixing a fraction of air shed from the adiabatic ascent with ambient air according to an imposed PDF. It is divided into bins defining a population of air parcels that are lofted to their neutral buoyancy level (layer), thus creating a matrix in which each term is an exchange of air between two layers of the model. Before forming these mixtures, the water in excess in the air shed from the adiabatic updraft is precipitated, and then again, the excess water is precipitated before the diluted updraft is detrained into the environment (there is no further precipitation from diluted downdrafts). Finally, the unsaturated downdrafts receive all the rain formed during shedding or detraining in the environment. Some of these descents take place outside the clouds, in air that is not saturated with moisture, allowing them to evaporate. ~~This evaporation of very large quantities of rain forces strong downdrafts.~~ Below the base of the clouds, all of the precipitation is outside the clouds. ~~Their re-evaporation is the source of density currents, or cold pools , created under cumulonimbus clouds~~ The evaporation of very large amounts of rain beneath the cloud base intensifies the downdrafts, which give rise to cold pools once they reach the surface.

In practice, the convective tendencies Q_1 and Q_2 are separated into two parts, "saturated" and "unsaturated". The saturated tendencies $Q_1{}^{\text{sat}}$ and $Q_2{}^{\text{sat}}$ take into account adiabatic updraft, diluted updrafts and downdrafts, and a downward flux in the environment compensating all these mass fluxes. The unsaturated tendencies $Q_1{}^{\text{unsat}}$ and $Q_2{}^{\text{unsat}}$ take into account unsaturated downdraft as well as compensating ascent.

The main modification of the ~~deep convection scheme~~ concerns the mixing formulation ~~(Grandpeix et al., 2004) and the triggering and closure~~ formulations ~~(Rio et al., 2009; Rochetin et al., 2014) modified~~ Emanuel (1991) scheme, introduced by Grandpeix et al. (2004), concerns the triggering conditions of deep convection as well as the control of its intensity, defined by the closure. These formulations have been adapted so that deep convection is controlled by sub-cloud processes: boundary-layer thermals ~~(?)~~ (Rio et al., 2009; Rochetin et al., 2014) and cold pools ~~(Grandpeix and Lafore, 2010)~~ (Grandpeix et al., 2010). The cold pool scheme and the control of convection by sub-cloud processes, particularly the role of cold pools, will be detailed in the following sections.

2.3 The cold pool model

The cold pool model has been entirely described in GL10. Here, we introduce the main equations and internal variables of the parameterization relevant for the rest of the paper. The cold pool model represents a population of identical circular cold pools (or wakes) over an infinite plane containing the grid cell. Considering an infinite plane is an assumption of the parameterization: only the atmospheric column (1D) is treated, while the surface is assumed to be homogeneous and infinitely extended. All the wakes have the same height, radius, and vertical profiles of thermodynamic variables. The assumption that all cold pools have the same geometric and thermodynamic characteristics is a simplifying choice of the model, although it is a crude approximation. Their centers are statistically distributed with a uniform density D_{wk} ~~. Cold pools~~ (number of cold pools per grid cell). Given that their positions are randomly drawn, the distance between the centers of the cold pools can vary.

The model divide the space into two parts: (i) the interior of cold pools (w) is where convective precipitating downdrafts fall; ~~in these downdrafts, the re- evaporation of precipitation generates intense cooling and strong negative buoyancy;~~ (ii) the exterior of cold pools (x) contains the warm air that fuels the saturated convective currents (Fig. 1). Each cold pool have an
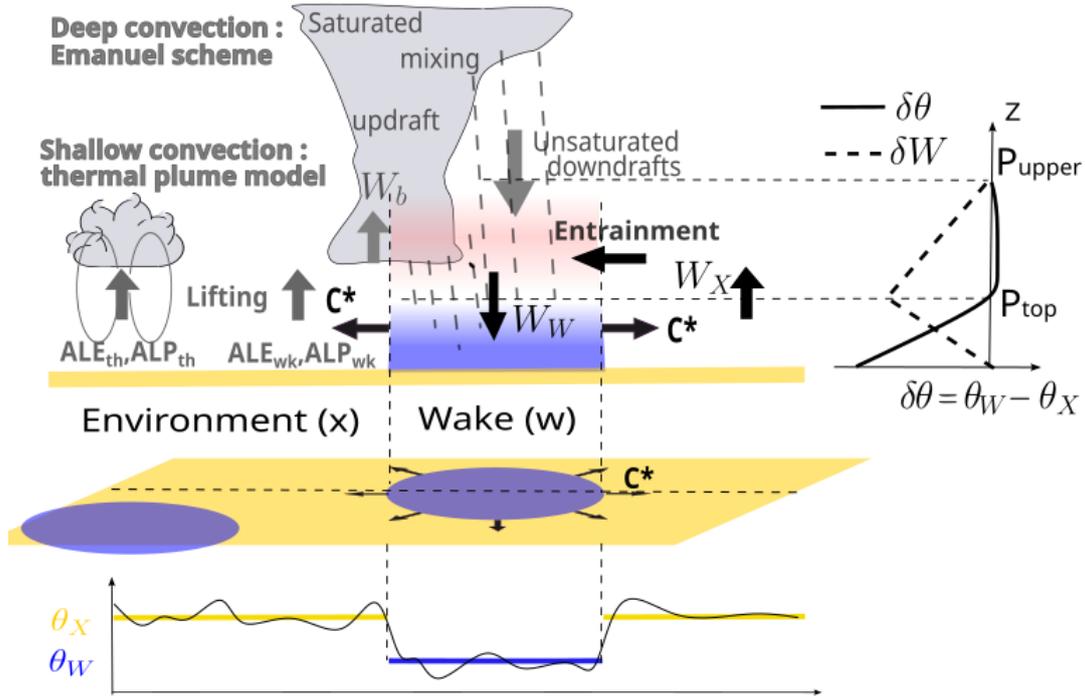
Figure 1. Conceptual diagram of the cold pool model and its coupling with convection in LMDZ climate model. (w) denotes the cold-pool regions, characterized by a ~~density current (Grandpeix and Lafore, 2010)~~ lower temperature (θ_W), while (x) represents the environment of cold pools, with a higher temperature (θ_X). W_W and W_X denote the vertical velocities in (w) and (x), respectively. $\delta\theta$ and δW represent the differences in potential temperature and vertical velocity between regions (w) and (x). p_{wk} represents the pressure corresponding to the height of the top of cold pool, defined as the altitude where θ_W becomes equal to θ_X ($\delta\theta = 0$). p_{upper} represents the level at which all cold-pool model variables vanish. C_* represents the spreading speed of cold pool. W_b corresponds to the vertical velocity at cloud base. Finally, ALE and ALP represent, respectively, the lifting energies and powers provided by thermals (ALE_{th}, ALP_{th}) and cold pools (ALE_{wk}, ALP_{wk}).

associated downdraft. The top height of the cold pool is defined as the altitude h_{wk} (and associated pressure p_{wk}) where the temperature difference between (w) and (x) becomes zero. Below this level cold pools are cooler than their exterior~~: they collapse and spread out as they are denser than the surrounding air~~. The boundary between the cold pool and the environment

190   is considered to be infinitely thin, and at each point on this boundary, the cold pool spreads at a rate C. C is considered to be a random variable whose mean C_* will give the rate at which the cold pool spreads. In the GL10 model, C_* scales with the square root of the potential energy available in the cold pools, i.e the ~~cold pool's collapse energy~~ energy associated with the collapse of the downdrafts, $WAPE$ (Wake Available Potential Energy), given by:

$$WAPE = g \int \frac{\delta\rho}{\overline{\rho}} = -g \int_{0}^{h_{wk}} \frac{\delta\theta_v}{\overline{\theta_v}} dz. \tag{3}$$

~~so~~ So that:

$$C_* = k\sqrt{2WAPE}, \tag{4}$$

where ρ is the air density; θ_v is the virtual potential temperature.

For any variable X, $\delta X = X_{\mathrm{wk}} - X_{\mathrm{ex}}$ is the difference of its mean values in the two subdomains and $\overline{X}$ the average over the horizontal domain.

Coefficient k in equation (4) should take a value between 0 and 1. This coefficient should ~~probably~~ depend on the structure of cold pools. Based on 3D CRM (Cloud Resolving Models) simulations, Lafore (2000) estimated this coefficient to 0.33 in the case of a linear structure such as squall line. This is the value retained in LMDZ6A.

The ~~spread rate of cold pools C_* is deduced from the following relationship:~~ evolution of the surface fraction covered by cold pools is then determined from C_* using the following relation.

$$\partial_t \sigma_{\mathrm{wk}} = 2\pi r C_* D_{\mathrm{wk}} = 2C_*\sqrt{\pi D_{\mathrm{wk}}\sigma_{\mathrm{wk}}}, \tag{5}$$

where σ_{wk} is the surface fraction covered by cold pools (initialized at 2%).

Lamine et Fred, 27 mars : On ne peut pas initialiser à la fois le rayon et σ. Vérification faite, on est cependant dans les bons ordres de grandeur. 2% avec une densité de 10^{-10} donn un rayone de 10 km In the model, cold pool appears when deep convection is triggered with a radius $r = 5\ km$, corresponding to a surface area S_{wk} ($S_{\mathrm{wk}} = \pi r^2$). To account for all the cold pools within a grid cell, S_{wk} is multiplied by D_{wk}, giving the total surface fraction σ_{wk} ~~$= D_{\mathrm{wk}}\pi r^2$).~~ covered by cold pools in the cell ($\sigma_{\mathrm{wk}} = D_{\mathrm{wk}}S_{\mathrm{wk}} = D_{\mathrm{wk}}\pi r^2$). The surface area of each cold pool increases over time as long as the convection that feeds it persists. Nevertheless, the evolution of σ_{wk} is limited to 40% of the grid cell. When this threshold is exceeded, cold pools that are no longer sufficiently fed by the re-evaporation of precipitation, i.e those with a low $WAPE$ ($WAPE < 1$, arbitrarily set), are removed.

Due to the complex life cycle of cold pools (including birth, death, collisions and ~~mergers~~merging), calculating their number density requires an other parameterization. So far, the value of the cold pool number density is thus imposed. In LMDZ6A, this density is fixed to a different value over ocean (10 cold pools over 100 km$\times$100 km) and over the continent (8 cold pools over 1000 km$\times$1000 km). ~~In the GL10 model, cold pools initially appear with a surface fraction of 2% and evolve over time according to equation 5. The evolution of σ_{wk} is arbitrarily limited to a maximum of 40% ($\sigma_{\mathrm{wk}} \leq 0.4$). Those thresholds are one limitation of the scheme that we hope to remove in the future.~~

It is assumed that below the top of cold pool (p_{wk}), the vertical velocity profile associated with ~~the subsidence of the~~ cold pool results solely from the spreading at the surface, without lateral entrainment ($e_{\mathrm{wk}} = 0$) or detrainment ($d_{\mathrm{wk}} = 0$) between the cold pool and its environment. Above this level, the subsidence induces a lateral convergence of air feeding the cold pool which can be reinforced by additional reevaporation of rainfall below stratiform clouds. The shape of the vertical profile of the velocity difference $\delta\omega$ between the cold pool region and its environment is imposed as a piecewise linear function of pressure: $\delta\omega$ increases linearly from zero at the surface up to a maximum value at p_{wk} and then decreases linearly between p_{wk} and

a minimum pressure p_{upper} corresponding to the upper bound of the cold pool model. The vertical subsidence which thus increases downward between p_{upper} and p_{wk} is fed by lateral entrainment

$$e_{\text{wk}} = \sigma_{\text{wk}}(1 - \sigma_{\text{wk}})\partial_p \delta\omega + \partial_t \sigma_{\text{wk}}$$

230   e_{wk} ($e_{\text{wk}} = \sigma_{\text{wk}}(1 - \sigma_{\text{wk}})\partial_p \delta\omega + \partial_t \sigma_{\text{wk}}$) without detrainment. This lateral entrainment accounts for the horizontal component of the meso-scale circulation known to entrain air from low- or mid- tropospheric air into the cold pool.

At p_{upper}, the top of the cold pool model, δX cancels for all cold pool state variables. In GL10 model and in LMDZ6A, p_{upper} was set to 600 hPa and there was also a nonzero velocity difference ($\delta\omega^{cv}$) at p_{upper}, accounting for the difference of the convective mass fluxes between (w) and (x). In the version used in this paper, this difference is now zero ($\delta\omega^{cv} = 0$) above this

235   level. This change is based on a different physical interpretation. In the GL10 model, only the convective scheme is assumed to exhibit a zero net mass flux: saturated updrafts in region (x) are compensated both by subsidence within the same region and by unsaturated downdrafts in region (w). We instead assume that each component of the convective scheme (updrafts and downdrafts) individually exhibits a zero net mass flux. Thus, updrafts in region (x) are compensated by subsidence, while downdrafts in region (w) are compensated by compensating ascent. It follows that $\delta\omega^{cv}$ is zero. This modification is not

240   discussed further in the remainder of the paper, as it is considered of secondary importance for the cold pool scheme and does not affect the variables of this model. **Fredho : je ne suis pas convaincu par cette réponse; il me semble qu'il y avait une incohérence ou un double comptage avant. Avait on une compensation du flux de masse descendant en haut de la poche ? Je serais pour mettre quelque chose de plus simple. "This change was made because their was an inconsistency with a double counting of subsidence in the convective plume and cold pool. Here only the cooling is forcing a mesoscale**

245   **circulation of the cold pool, which comes in addition to the vertical velocity inside de the downdraft of the convective scheme.**

The cold pools contribute to the physics tendencies for temperature and humidity. It is the convective scheme which accounts for cooling in the cold pools so that no phase change is associated with the cold pool model. The source terms therefore only contain the vertical convergence of the Reynolds flux associated with mass flux transport (downward in the cold pool and

250   upward in its environment) that reads $\overline{\rho w'\phi'} = 1/g\sigma_{\text{wk}} * (1 - \sigma_{\text{wk}})\delta\omega\delta\phi$ for any conserved variable ϕ so that:

$$\begin{cases} \frac{\theta}{T}Q_1{}^{\text{wk}} = -C_p\,\sigma_{\text{wk}}\,(1 - \sigma_{\text{wk}})\,\partial_p(\delta\omega\delta\theta), \\ Q_2{}^{\text{wk}} = L_v\,\sigma_{\text{wk}}\,(1 - \sigma_{\text{wk}})\,\partial_p(\delta\omega\delta q_v). \end{cases} \tag{6}$$

It is the re-evaporation of rain in unsaturated downdrafts that is the primary driver of cold pool development. This process is reflected in the model by assigning the heating term $Q_1{}^{\text{unsat}}$ to the interior of cold pools, while $Q_1{}^{\text{sat}}$ acts on their environment. Consistent with this splitting, we assume that the saturated part of the convective scheme sees the profiles outside the cold

255   pools, and the unsaturated downdrafts their interior. We further assume that thermal plumes are only active in the fraction of the horizontal surface located outside the cold pools. Thus the mass flux transport scheme is applied to any variable outside the cold pool $\phi_{\text{ex}} = \phi - \sigma_{\text{wk}}\delta\phi$, and finally $Q_1{}^{\text{th}} = -C_p(1 - \sigma_{\text{wk}})\partial_z\overline{\rho w'\theta'_{\text{ex}}}$ $(\theta/T)Q_1{}^{\text{th}} = -C_p(1 - \sigma_{\text{wk}})\partial_z\overline{\rho w'\theta'_{\text{ex}}}$ and $Q_2{}^{\text{th}} = L_v(1 - \sigma_{\text{wk}})\partial_z\overline{\rho w'q_{v\text{ex}}'}$. The thermal plume model therefore induces a differential tendency that is opposite of the average

tendency restricted to the environment. Ultimately, the contrast in convective tendencies (shallow and deep) between the cold pools and their environment reads:

$$\begin{cases} \delta Q_1{}^{\text{cv}} = \dfrac{Q_1{}^{\text{unsat}}}{\sigma_{\text{wk}}} - \dfrac{Q_1{}^{\text{sat}}}{1-\sigma_{\text{wk}}} - \dfrac{Q_1{}^{\text{th}}}{1-\sigma_{\text{wk}}}, \\ \delta Q_2{}^{\text{cv}} = \dfrac{Q_2{}^{\text{unsat}}}{\sigma_{\text{wk}}} - \dfrac{Q_2{}^{\text{sat}}}{1-\sigma_{\text{wk}}} - \dfrac{Q_2{}^{\text{th}}}{1-\sigma_{\text{wk}}}. \end{cases} \tag{7}$$

It is the terms $\delta Q_1{}^{\text{cv}}$ and $\delta Q_2{}^{\text{cv}}$ that drive the time evolution of $\delta\theta$ and δq_v given by:

$$\begin{cases} \partial_t \delta\theta = \dfrac{\theta}{T}\left(\dfrac{\delta Q_1{}^{\text{cv}} + \delta Q_1{}^{\text{wk}}}{C_p}\right) - \overline{\omega}\partial_p \delta\theta - \dfrac{K_{gw}}{\tau_{gw}}\delta\theta, \\ \\ \partial_t \delta q_v = -\dfrac{\delta Q_2{}^{\text{cv}} + \delta Q_2{}^{\text{wk}}}{L_v} - \overline{\omega}\partial_p \delta q_v. \end{cases} \tag{8}$$

This time ~~evolutions~~ evolution also includes a differential heating and moistening induced by the cold pools themselves of the air inside and outside the cold pools, under the effect of lateral air entrainment from the environment above p_{wk}, subsidence inside the cold pools, and compensating ascendance in the environment:

$$\begin{cases} \dfrac{\theta}{T}\dfrac{\delta Q_1{}^{\text{wk}}}{C_p} = -\dfrac{e_{\text{wk}}}{\sigma_{\text{wk}}}\delta\theta - \delta\omega\partial_p\overline{\theta} - (1 - 2\sigma_{\text{wk}})\delta\omega\partial_p\delta\theta, \\ -\dfrac{\delta Q_2{}^{\text{wk}}}{L_v} = -\dfrac{e_{\text{wk}}}{\sigma_{\text{wk}}}\delta q_v - \delta\omega\partial_p\overline{q_v} - (1 - 2\sigma_{\text{wk}})\delta\omega\partial_p\delta q_v. \end{cases} \tag{9}$$

The terms $-\overline{\omega}\partial_p\delta$ in (8) partially compensate for the fact that the contrasts δ are not transported by the dynamics until now. We therefore take into account, in the parameterizations, the vertical part of large-scale advection to partially compensate for this deficiency.

Finally, the last term, present only in the θ part of (8), corresponds to the reduction in temperature contrasts by gravity waves with a coefficient specified as the ratio of an efficiency K_{gw} to a characteristic time

$$\tau_{gw} = \frac{\sqrt{\sqrt{\sigma_{\text{wk}}} - (1 - \sqrt{\sigma_{\text{wk}}})}}{4Nz\sqrt{D_{\text{wk}}}} \tag{10}$$

estimated as the time required for a wave with speed Nz (where N is the Brunt-Väisälä frequency and z is altitude) to travel a distance equal to the geometric mean of the cold pool size and the interval between cold pools

The cold pool model is now fully described. It includes:

- three prognostic variables, derived directly from the model equations: the profiles of $\delta\theta$ and δq_v and σ_{wk}.

- three diagnostic variables, evaluated from the profile of $\delta\theta$: p_{wk}, C_* and $WAPE$

- three main free parameters: the coefficient k, the density D_{wk} and τ_{gw}.

2.4 Triggering and closure of the deep convection scheme

Triggering and closure formulations in LMDZ have been described in Rio et al. (2013). Deep convection is triggered when the Available Lifting Energy (ALE) at cloud base exceeds the convective inhibition (CIN) threshold. This ~~can be caused~~

either by uplift energy from the convective boundary layer lifting energy is provided either by the thermal plume model (ALE_{th}) , provided by the thermals model (Rio and Hourdin, 2008), or by energy generated by cold pools or by the cold pools parameterization (ALE_{wk}):

$$\max(ALE_{th}, ALE_{wk}) > |CIN|. \tag{11}$$

The intensity of the convection depends on the mass flux (M_b) at the cloud base, determined from the . The closure consists in expressing M_b as a function of an available lifting power ALP, provided by thermals the thermal plume (ALP_{th}) and cold pools (ALP_{wk}) . parameterizations:

$$M_b = \frac{ALP_{th} + ALP_{wk}}{(2W_b^2 + |CIN|)}, \tag{12}$$

where

$$W_b = wb_{srf} + \frac{wb_{max}}{1 + \frac{\Delta P}{(P_s - P_{LFC})}} \tag{13}$$

is the vertical velocity at the level of free convection (LFC), $\Delta P = 500$ hPa and wb_{srf} and wb_{max} are model free parameters.

Concerning the boundary layer, the available lifting energy is taken as the maximum kinetic energy in the thermal plume below cloud base

$$ALE_{th} = \frac{1}{2} w_{th,max}^2. \tag{14}$$

A notable improvement was introduced by Rochetin et al. (2014), with the implementation of a statistical representation of the size distribution of cloudy thermal bases. In the new statistical triggering, deep convection is activated if both $ALE_{th} > |CIN|$ and at least one cumulus cloud within a grid cell exceeds a given size, specified by S_{trig} (adjustable parameter). The available lifting power scales with $w_{th,max}^3$.

To calculate ALE_{wk}, the model assumes that the maximum speed (C_{max}) on the cold pool contour will trigger convection. This is assumed to be proportional to the square root of $WAPE$, with a higher coefficient of proportionality than the one used for C_* leading to the following relationship:

$$C_{max} = k'\sqrt{2WAPE}, \tag{15}$$

where k'=1.

The Available Lifting Energy associated with cold pools is thus expressed by the following relationship:

$$ALE_{wk} = \frac{1}{2}C_{max}^2. \tag{16}$$

Combining equations (16) and (15), one obtains:

$$ALE_{wk} = k'^2 WAPE, \tag{17}$$

with $k' = 1$, meaning that, in the cold pool model, the Available Lifting Energy associated with cold pools is equal to the collapse energy.

Each cold pool ~~generates its own lifting power , depending on its spreading speed (C_*), height~~ (provides a power associated with its horizontal spreading. This power is calculated as the product of the kinetic energy supplied by the pool and the mass flux, evaluated over the entire contour of the pool ($L_g = 2\pi r$), over the full height of the pool h_{wk}~~) and the length (L_g) of its gust front. The total power (ALP_{wk}) of the cold pools is the product of the~~, and using the spreading velocity C_*. The power ~~supplied by each pool times~~ ($ALP_{wk,i}$) of an individual cool pool i is therefore:

$$ALP_{wk,i} = \frac{1}{2}\rho C_*^3 h_{wk} L_g. \tag{18}$$

To obtain the average power (ALP_{wk}) over all cold pools in the domain, this individual power is multiplied by the cold pool number density ~~(D_{wk})~~:

$$ALP_{wk} = ALP_{wk,i} D_{wk}. \tag{19}$$

We then seek to express ALP_{wk} as a function of σ_{wk}. This allows us to compute this variable from σ_{wk}, which is a state variable, unlike r, which is not.

Since $\sigma_{wk} = D_{wk}\pi r^2$, the lifting power ALP_{wk} can read:

$$ALP_{wk} = \epsilon \frac{1}{2}\rho C_* C_*^3 h_{wk} L_g \sqrt{\sigma_{wk} D_{wk}\pi}, \tag{20}$$

where $\epsilon = 0.25$ is the lifting efficiency. This arbitrarily chosen value means that 25% of the power associated with cold pool spreading is available for deep convection.

$$L_g = 2\pi r$$

$$\sigma_{wk} = D_{wk}\pi r^2$$

~~Then, the lifting power ALP_{wk} reads:~~

$$ALP_{wk} = \epsilon \rho C_*^3 h_{wk} \sqrt{\sigma_{wk} D_{wk}\pi}$$

2.5 Large Eddy Simulations

Atmospheric Large Eddy Simulations (LES) are performed with non hydrostatic models, with a grid resolution fine enough to resolve the main structures (large eddies) that dominate the turbulent or convective transport. They ~~have been widely used to study the convective boundary layer with grid resolutions of a few tens of meters~~ provide an explicit and detailed representation

of turbulent and convective motions within the boundary layer and of the associated clouds (Brown et al., 2002; Siebesma et al., 2003). In the presence of water phase changes, however, these simulations can become more dependent on the microphysical schemes used. One of the major strengths of LES lies in its ability to provide three-dimensional information not available from observations, making them an indispensable complement to the latter for understanding processes. In addition, LES can be used to validate the internal variables of parameterizations, enabling their physical realism to be assessed. **Lamine et Fred, 27 mars : Le paragraphe ci-dessous reprend directement une remarque du second reviewer. Mais je (Fredho) n'ai pas vraiment compris.** Since LES include the full physics, including cold-pool effects, they do not allow validation against simulations without cold pools.

In this study, we use the outputs of two ~~oceanic LES and one continental LES~~ LES over ocean and one over land.

The LES over ocean was run with two different models, SAM and MesoNH, with the exactly same setup in order to assess the uncertainty in LES simulations.

~~Both oceanic LES~~ The LES over ocean were carried out in Radiative-Convective Equilibrium (RCE) mode. RCE is a concept in which equilibrium is achieved between convective heating and radiative cooling of the atmosphere. A detailed description of RCE simulation protocols is provided in Daleu et al. (2015). In the RCE simulations used here, radiative computation is replaced by a constant cooling of -1.5 K per day, while the surface temperature is imposed. The destabilization leads to convection. The associated heating rate, largely corresponding to the release of latent heat by cloud condensation in convective towers, compensates for the cooling once quasi-equilibrium has been reached. Two oceanic LES of this RCE are used here, one is performed with the SAM model (Khairoutdinov and Randall, 2003) and the other one with MesoNH (Lac et al., 2018). Both simulations cover an oceanic domain of 200 km×200 km with horizontal resolution of 250 m. The lateral boundary conditions are cyclic for both models. The sea surface temperature is set to 300 K. These two RCE simulations run for 44 days, with quasi steady-state regime reached after about 40 days. Output are available every 3 hours for SAM and every 24 hours for MesoNH.

The continental LES is based on the AMMA (African Monsoon Multidisciplinary Analysis) case. This case is derived from observations made on July 10, 2006 during the AMMA field campaign (Redelsperger et al., 2006), during which a relatively small, short-lived convective system formed over Niamey (Lothon et al., 2011). This system, with a lifetime of around 6 hours, was observed by various instruments (radar and atmospheric soundings), supplemented by satellite data. This case study represents a typical example of deep convection in the Sahel region (Couvreux et al., 2012). LES for this continental case is carried out with the MesoNH model over a 200 km × 200 km domain, with a horizontal resolution of 200 m. Lateral boundary conditions are cyclic and surface fluxes are imposed. Outputs are generated at a frequency of 30 minutes.

One advantage of RCE for parameterization development is that it targets a steady state regime. By contrasts, the AMMA case is corresponds to a diurnal cycle of deep convection over land, for which the time matters, and for which errors in the phasing of the triggering of deep convection can alter comparisons.

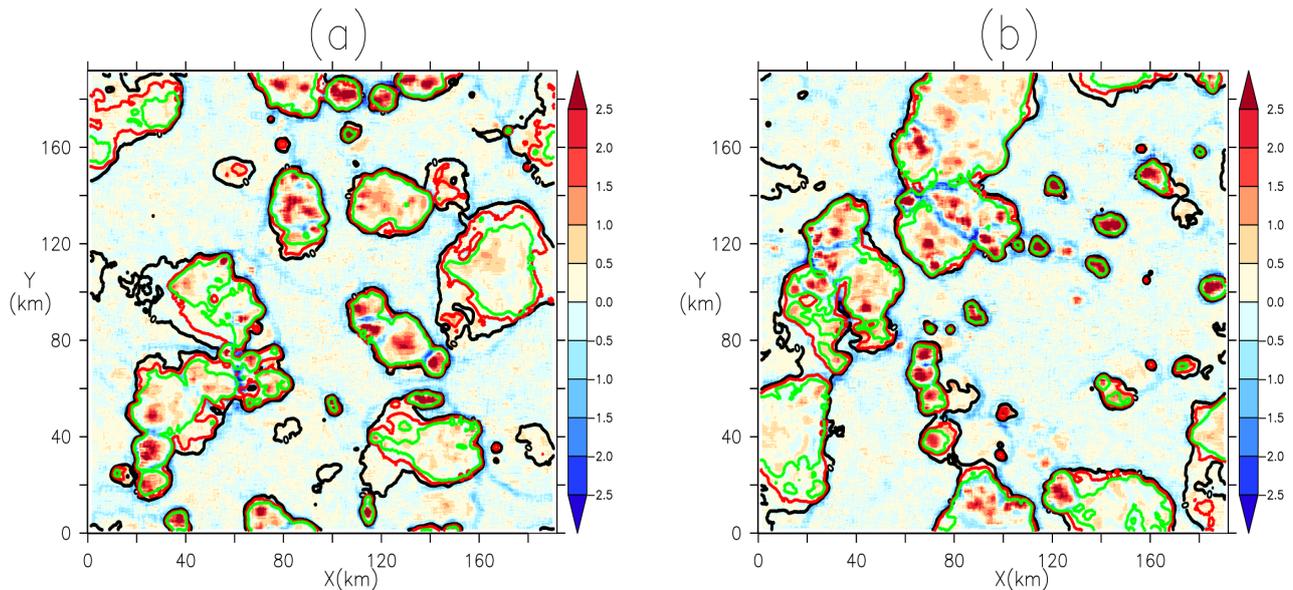**13**

Figure 2. Moving average (with a box of 3.25 km × 3.25 km) of the divergence of wind at 10 m (in unit $10^{-3}s^{-1}$ or 1 m/s/km). Panels a and b correspond to two different states of the LES SAM carried out on the oceanic RCE case. Contours of temperature anomalies at 10 m at -0.4 K (green), -0.2 K (red) and 0 K (black) are superimposed on the smoothed divergence field.

3   Assessment of the cold pool model internal equations from LES

3.1   Distinguishing the cold pools from their environment

In order to use LES for the assessment of the cold pool parameterization, the first challenge is to separate cold pools from their environment. Indeed, there is no a priori established framework for objectively identifying cold pools in observations and numerical models (Rochetin et al., 2021), and choices may depend in part on the physical picture one has of cold pools, and also, for the purpose at hand, on the picture underlying the parameterization. The first method for identifying cold pools proposed by Young et al. (1995) was based on surface precipitation rates. In more recent studies, such as those by Provod et al. (2016); Zuidema et al. (2017); Vogel et al. (2021); Rochetin et al. (2021); Touzé-Peiffer et al. (2022), the detection of cold pools is closer to a density current oriented detection, in which variations in temperature, pressure and wind are taken into account.

In the present study, the aim is not to isolate individual "cold pools objects", but only to know whether a grid cell of the LES is inside or outside cold pools. Also the boundary conditions are idealized targeting the statistical homogeneity assumption that is at the basis of the Reynolds decomposition between dynamical core and physics parameterizations. In this idealized
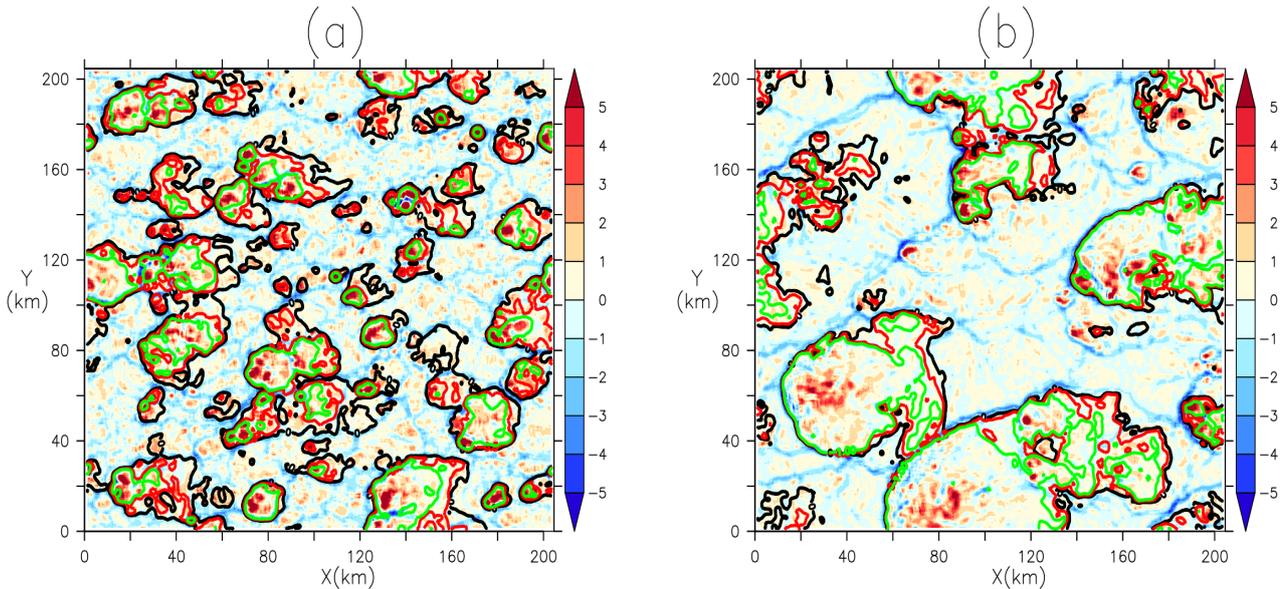
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Figure 3. Same as Fig. 2 for two successive instants, 5:30 PM (a) and 7:30 PM (b), of the LES MESONH carried out on the AMMA case. The contours superimposed corresponds to T_{10m} anomalies of -1 K (green), -0.5 K (red) and 0 K (black).

380   case with uniform surface temperature, cold pools can be identified ~~fairly immediately~~ using a threshold on the anomaly (after removing the domain average) of temperature at 10 m above surface, T_{10m}, i.e. at the first model mid layer.

Fig. 2 and 3 show a horizontal moving average with a box of 3.25 km×3.25 km of the divergence of the wind at 10 m above surface, V_{10m}. From these maps, the centers and gust fronts of cold pools can be easily identified, corresponding respectively to the maximum and minimum of divergence values. Maxima of divergence of surface wind indicate the center of cold pools

385   where cold air masses collapse. Precipitation is generally co-located with these divergence maxima (not shown). The fairly strong wind convergence observed around cold pools centers corresponds to the strong lift of air masses created upstream of the gust front at the cold pool's periphery.

Both the two LES of the RCE case and the LES of the AMMA case show cold pools clusters forming a common gust front. This can be explained by the fact that, during propagation, cold pools can merge to create a single, larger cold pool. We can

390   also observe that wind convergence (and thus associated updrafts) is more intense where cold pools meet. This is in line with some studies that indicate that convection initiation on gust fronts is more efficient when two or more cold pools collide (Meyer and Haerter, 2020; Torri and Kuang, 2019; Haerter and Schlemmer, 2018; Feng et al., 2015).

We superimpose on this map the T_{10m} anomaly contours with different values to determine an optimal threshold for this anomaly. In the RCE case, the T_{10m} anomaly at 0 K sometimes includes regions without cold pools centers, where divergence

395   of surface wind is low (Fig. 2a and b) while anomaly contours at -0.2 K and -0.4 K surround the centers of cold pools quite
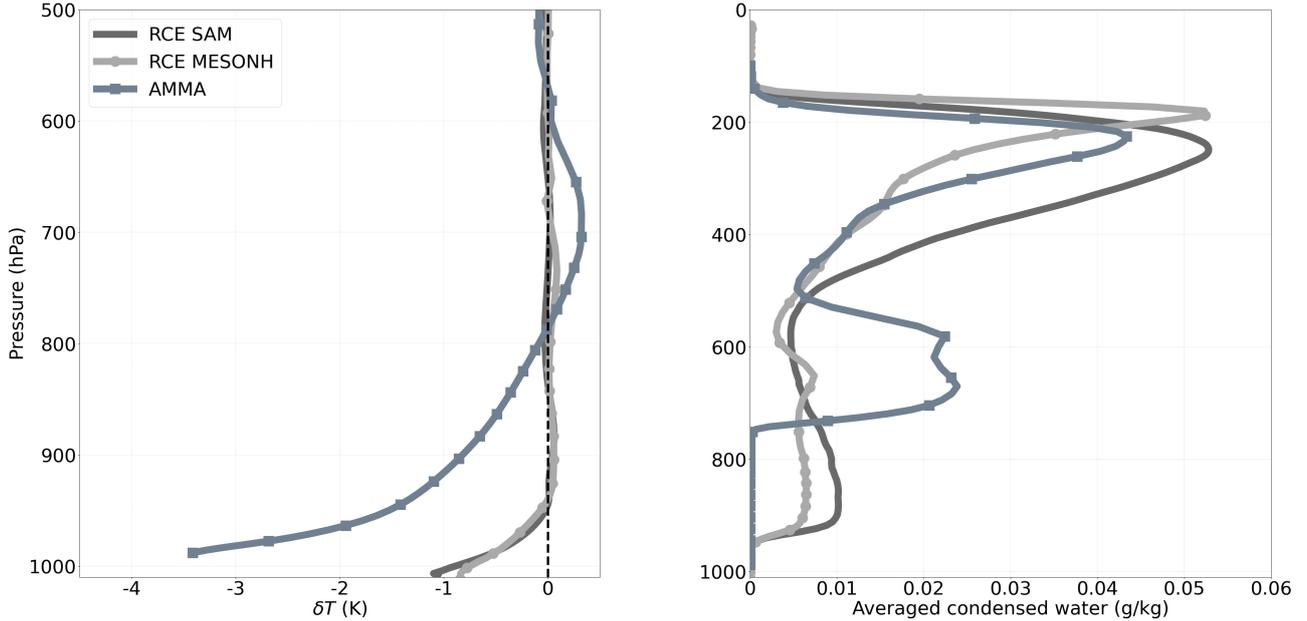
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Figure 4. Vertical profiles of the cold pool temperature anomaly (left, difference between the inside and the outside of cold pools) and of the averaged condensed water (right, g/kg).

well. In the AMMA case, figure 3a clearly shows that the 0 K threshold is too high to identify cold pools. Fig. 3b, on the other hand, shows that the -1 K threshold follows gust fronts of cold pools better than the -0.5 K threshold. On the basis of these analyses, we retain the T_{10m} anomaly thresholds at -0.2 K and -1 K to identify cold pools in the RCE and AMMA cases respectively.

3.2 Computing the WAPE from the cold pool anomalies

Once the threshold value is fixed for the T_{10m} anomaly, we separate the full 3-dimensional LES domain between cold pool region (wk) and the rest of the domain (ex) form which we can compute the horizontal averages on each subdomain, X_{wk} inside cold pools and X_{ex} outside, and then the cold pool anomaly $\delta X = X_{wk} - X_{ex}$. This sampling allows to compute the vertical profiles of cold pools anomaly for temperature (δT), humidity (δq_v) and vertical velocity (δw). Examples of temperature anomalies are shown in Fig. 4.

Note that we apply the same surface mask to the entire column to determine the vertical profiles. This simple vision of vertical cylinders is adopted to match the view underlying the parameterization but may be put into question in the presence of strongly tilted convection.

One can then compute the collapse energy ($WAPE$) of cold pools in the LES by integrating from the surface up to p_{wk}, the virtual temperature anomaly, $\delta\theta_v$ (equation, 3). As suggested by Grandpeix et al. (2010), we take for p_{wk} the pressure where the δT profile cancels out. This altitude is around 950 hPa (approximately 600 m) in the oceanic RCE case and around 800 hPa (approximately 2 km) in the AMMA case (Fig. 4).

3.3 Computing C_* from the mean wind divergence inside cold pools

It is assumed in the parameterization that cold pools are identical disks of radius r. This assumption makes it easy to determine C_* by the divergence theorem:

$$\int\int \mathrm{div}\left(V_{\mathrm{10m}}\right) dS_{\mathrm{wk}} = C_* L_g. \tag{21}$$

After applying equation 21, we obtain the following relation

$$C_* = \frac{\overline{\mathrm{div}\left(V_{\mathrm{10m}}\right)} S_{\mathrm{wk}}}{L_g}, \tag{22}$$

where S_{wk} is the area of cold pools.

$$S_{\mathrm{wk}} = \pi r^2$$

Equations ??, ?? and ?? allow us to express C_* Since $Lg = 2\pi r$, $\sigma_{\mathrm{wk}} = D_{\mathrm{wk}}\pi r^2$ and $S_{\mathrm{wk}} = \pi r^2$, C_* can read as a function of the mean divergence of wind at 10 m, the surface fraction (σ_{wk}) and the density (D_{wk}) of cold pools by the relation:

$$C_* = \frac{1}{2}\overline{\mathrm{div}\left(V_{\mathrm{10m}}\right)} \sqrt{\frac{\sigma_{\mathrm{wk}}}{D_{\mathrm{wk}}\pi}}. \tag{23}$$

The choice to calculate C_* here from σ_{wk} rather than from the radius r is explained by the fact that it is easier to estimate σ_{wk} in the LES, since we did not use automatic cold-pool detection tools that would allow the radius of cold pools to be determined directly.

To apply this calculation of C_* C_* in the LES, we take the horizontal average of the surface wind divergence inside cold pools. The surface fraction (σ_{wk}) of cold pools calculated in the LES is 0.214 (Average over the available time steps between 5:00 PM and 10:00 PM) for the AMMA case and 0.253 (Average over the 24 time steps with the SAM model) for the RCE case. To determine D_{wk}, we manually counted the centers of cold pools visible on the surface wind divergence maps (Fig. 2 and 3), as we did not use automated detection methods in this study that could generate their number automatically. We find a density, D_{wk}, of about 5 cold pools per 100 km $\times$ 100 km in the RCE case, and about 2.5 cold pools over the same domain in the AMMA case.

3.4 Computing ALP and ALE form gust front vertical velocities

Finally we derive a direct estimation of the Available Lifting Energy (ALE_{wk}) and Power (ALP_{wk}) in the LES from a sampling of the vertical wind at cloud base.

To do this, we first determine an average cloud-base height at which we extract vertical velocities $w_b(x,y)$. This height corresponds to the altitude at which the average profile of condensed water reaches its first non-zero value. It is estimated at around 950 hPa on the two oceanic LES and at around 750 hPa for the LES of the AMMA case (cf. Fig. 4).

We then separate the updrafts on gust fronts from those associated with thermal plumes. Since the updrafts on gust fronts are both stronger and more coherent horizontally than those associated with thermal plumes, we define a gust front mask based on a threshold applied to an horizontally moving average of the vertical velocity at cloud based w_b, denoted as $\tilde{w}_b(x,y)$. Because the gust fronts are stronger in the AMMA case than in the RCE case, different choices were made for the size of the horizontal box of the moving average (1.25 km×1.25 km for the RCE case and 2 km×2 km for AMMA) and for the value of the vertical velocity threshold (0.6 m/s for the RCE case and 2 m/s for the AMMA case). Those values were retained after several tests so as to separate as effectively as possible the gust front form other ascents.

Fig. 5 and 6 overlays the updrafts within (red) and outside (green) gust fronts on maps of T_{10m} anomaly (smoothed by applying a moving average with a box of 2.5 km×2.5 km), for the RCE and AMMA cases respectively. The contours of the T_{10m} anomalies used to identify cold pools (-0.2 K for RCE and -1 K for AMMA) are displayed as well. Visually, the gust fronts computed with $\tilde{w}_b(x,y)$ thresholds of 0.6 m/s (RCE) and 2 m/s (AMMA) align well with the contours of cold pools identified using these T_{10m} anomaly thresholds. It also appears that most thermals are located in the environment of cold pools for both the RCE and AMMA cases. This retrospectively validates a choice made in LMDZ6A, where the effect of thermals was only computed outside cold pools.

Both ALE_{wk} and ALP_{wk} are computed from w_b restricted to the gust front mask, noted $w_{\mathrm{b,gust}}$.

ALE_{wk} is estimated as the kinetic energy associated with the maximum value of $w_{\mathrm{b,gust}}(x,y)$:

$$ALE_{\mathrm{wk}} = \max(\frac{1}{2}w_{\mathrm{b,gust}}{}^2). \tag{24}$$

ALP_{wk} represents the average updrafts power provided by all cold pools in the domain. It is calculated as the horizontal average of the cube of $w_{\mathrm{b,gust}}$ times the surface fraction (σ_{gust}) covered by gust fronts:

$$ALP_{\mathrm{wk}} = \sigma_{gust}\frac{1}{2}\rho\overline{w_{\mathrm{b,gust}}}^3. \tag{25}$$

The gust front mask is used to calculate σ_{gust}, which is 0.048 (LES SAM) for the RCE case and 0.045 for the AMMA case, for the times shown in Fig. 5 and 6. Characteristics of the cold pools estimated from the sampling are gathered on Table 1.

3.5 Validation of phenomenological laws

Physical parameterizations are defined by sets of mathematical equations designed to represent subgrid processes within a column of the model. The formulation of these equations is based both on a phenomenological understanding of the processes
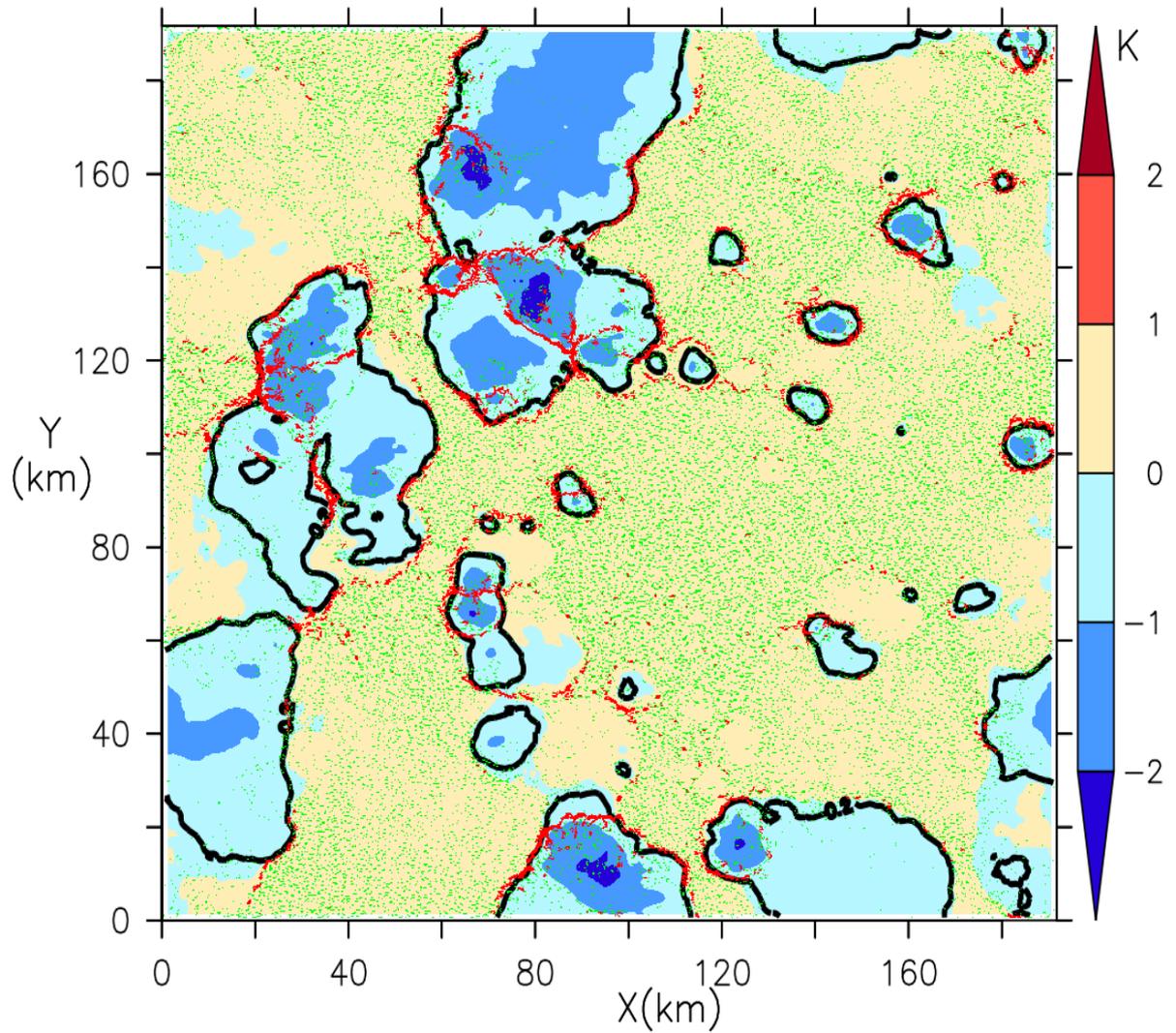
Figure 5. Map of T_{10m} anomaly (color shadings), smoothed (moving average with a horizontal box of 2.5 km×2.5 km), at an instant of the LES SAM of the RCE case. The black contour is the -0.2 K anomaly used to separate the inside from the environment of cold pools. The green and red dots show grid cells with vertical velocity at cloud base w_b larger than 0.8 m/s, inside (red) and outside (green) the gust front mask (see main text for the definition of the gust front mask).
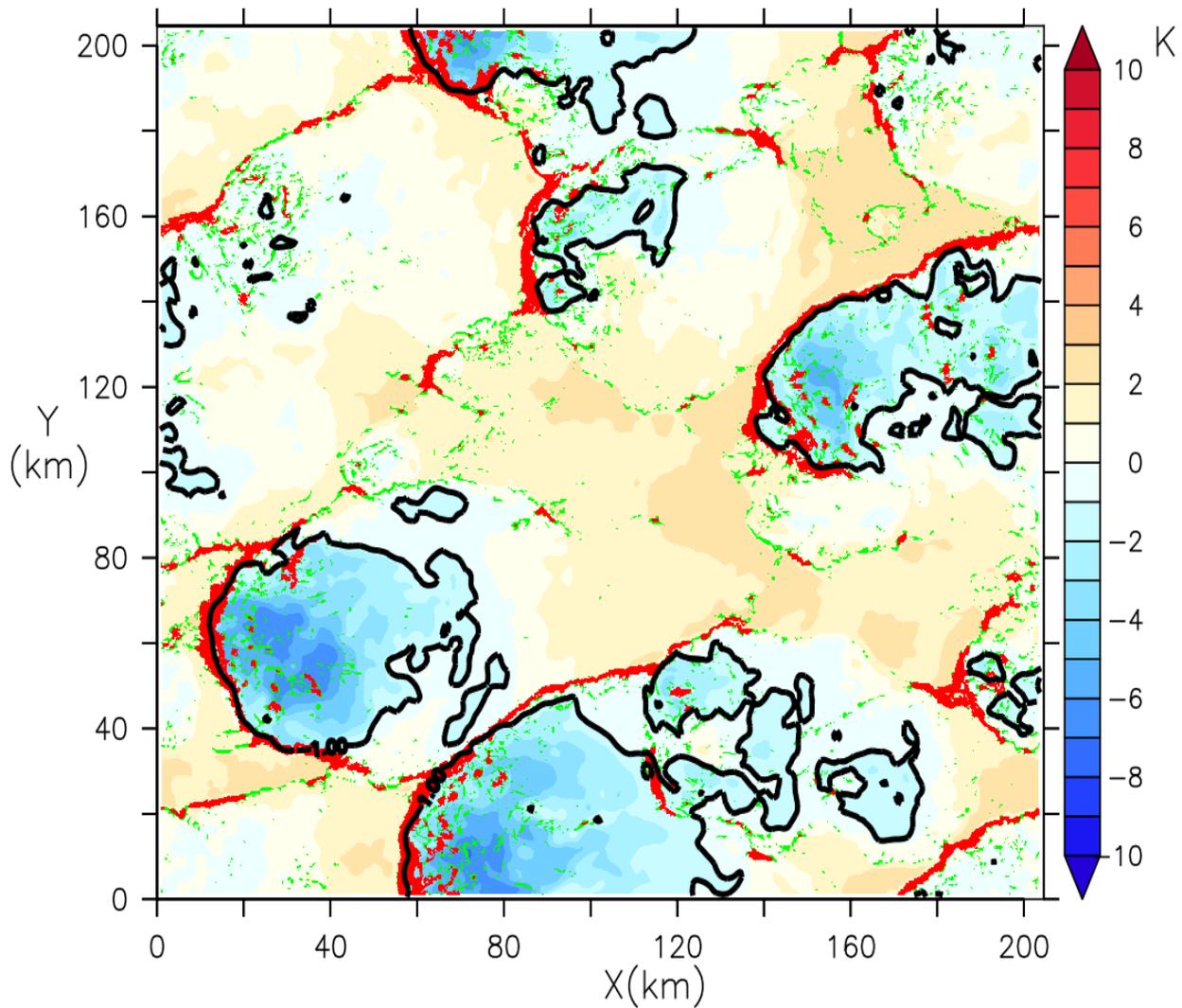
Figure 6. Map of T_{10m} anomaly (color shadings), smoothed (moving average with a horizontal box of 2.5 km×2.5 km), at 7:30 PM for the LES of the AMMA case. The black contour is the -1 K anomaly used to separate the inside from the environment of cold pools. The green and red dots show grid cells with vertical velocity at cloud base w_b larger than 2 m/s, inside (red) and outside (green) the gust front mask (see main text for the definition of the gust front mask).

	$D_{\mathbf{wk}}(10^{-10}\ \mathrm{m}^{-2})$	$\sigma_{\mathbf{wk}}$	σ_{gust}
RCE			
LES SAM	5	0.253	0.048
LES MESONH	5	0.264	0.017
AMMA			
LES MESONH	2.5	0.214	0.045

Table 1. Cold pools number density (D_{wk}), surface fraction of cold pools (σ_{wk}), and surface fraction of gust fronts (σ_{gust}) estimated from the LES for the RCE and AMMA cases. For the RCE case, the values represent an average over the 24 available time steps from the SAM LES and the 10 available time steps from the MESONH LES. For the AMMA case, the values are an average of the time steps obtained between 5:00 PM and 10:00 PM.

involved and on fundamental principles of physics. These parameterizations can be evaluated as a whole or in parts, by isolating certain equations or relationships between internal variables, or between internal variables and GCM state variables. LES offers the possibility of performing a priori validation and adjustment of these laws.

In the cold pool model, variables ALE_{wk}, ALP_{wk} and C_* are determined from the collapse energy, $WAPE$ (see equations (4), (17) and (20)). We compare in Table 2 the values obtained using the parameterization formulations (parameterized value P), based on $WAPE$ deduced from $\delta\theta_v$, with those obtained directly from resolved wind in the LES (sampled value S): the vertical speed at cloud base (w_b) for ALE_{wk} and ALP_{wk}, and the mean divergence of wind at 10 m in cold pools for C_*. These analyses are performed by averaging over the available time steps: 24 time steps for SAM and 7 for MESONH in the RCE case, and between 5:00 PM and 10:00 PM for the AMMA case.

The values of ALE_{wk} calculated by both methods are very close to each other. The largest error is an underestimation by about 30% of the ALE_{wk} computed from $WAPE$ compared to the $w_{\mathrm{b,gust}}$ estimate. These results for the three LES confirm the validity of the hypothesis of equality between ALE_{wk} and $WAPE$ assumed in the parameterization.

Table 2 shows that, C_* values computed from the $WAPE$ are systematically lower than those coming from the mean divergence of wind at 10 m in cold pools. This difference could be due to an underestimation of the coefficient k, imposed here at 0.33. With $k = 0.56$, the calculation of C_* based on the $WAPE$ becomes comparable to those obtained from the mean divergence of wind at 10 m in cold pools (Table 2). As discussed above, the value of 0.33 was retained following an oral communication by Lafore (2000). But other studies propose different values: Lafore and Moncrieff (1989) estimate k at 0.68 based on CRM simulations of 2D squall grain, Bryan (2005) estimate it at 0.5 from observations of cold pools during the BAMEX experiment in the American Great Plains. Our results are thus compatible with the hypothesis of the model which postulates that the kinetic energy of cold pools results from the transformation of $WAPE$ into kinetic energy with a coefficient k compatible with the published estimates.

Table 2 also shows that, for the three LES cases, the values of ALP_{wk} calculated with $C*$ from $WAPE$ are at least three times lower than those obtained from $w_{\mathrm{b,gust}}$. Two coefficients are involved in the calculation of ALP_{wk} with the parameterization formula: the coefficient k and the lifting efficiency ϵ, imposed respectively to 0.33 and 0.25. Using k=0.56 however in

from:	ALE_{wk} (J/kg) w_b sampl.	$WAPE$ (J/Kg) $\int \delta\theta_v$	C_* (m/s) div $(V_{10\text{m}})$	C_* (m/s) P: k=0.33	C_* (m/s) P: k=0.56	ALP_{wk} (W/m^2) w_b sampl.	ALP_{wk} (J/kg) P: k=0.33	ALP_{wk} (W/m^2) P: k=0.56
RCE SAM	**10.460**	7.962	**2.228**	1.315	2.232	**0.054**	0.008	0.044
RCE MESO	**6.965**	7.912	**2.264**	1.313	2.228	**0.020**	0.008	0.044
AMMA MESO	**59.760**	45.870	**5.362**	3.133	5.316	**1.733**	0.279	1.368

Table 2. Comparison of the variables $WAPE$, ALE_{wk}, C_*, and ALP_{wk} obtained directly from the resolved wind in the LES (from w_b sampling or div $(V_{10\text{m}})$), with those calculated using the formulations of the parameterization (parameterized values P, comming from the $WAPE$ computation based on the $\delta\theta_v$ profile). The S values are derived from the vertical velocity at cloud base (w_b) for ALE_{wk} and ALP_{wk}, from the mean divergence of wind at 10 m in cold pools for C_*, sampled directly from the LES. The P values are calculated from the $WAPE$ deduced from $\delta\theta_v$, itself sampled from the same LES, considering the coefficients k = 0.33 and k = 0.56. The analyses are based on the average of the available time steps: 24 time steps for the LES performed with SAM and 7 with MESONH in the oceanic RCE case, and between 5:00 PM and 10:00 PM for the LES of the AMMA case.

the calculation of C_*, and keeping ϵ at is nominal value of 0.25 allows to reconcile the various estimates. This is compatible with the hypothesis of the parameterization according to which 25% of the horizontal power provided by the cold pools during its propagation would be used to reinforce the intensity of the convection while a large part dissipates.

4   Evaluation in the single column configuration of LMDZ

In this section, we evaluate the cold pool parameterization in the SCM configuration of LMDZ. The comparison is more demanding here, since all parameterizations interact with each other and because the state of the atmosphere at the time of evaluation depends on the interaction of all those parameterizations during the preceeding hours (AMMA) or days (RCE). The SCM simulations are performed with exactly the same initial and boundary conditions as the corresponding LES for both cases.

For the RCE case, we represent diagnostics once a quasi-steady state has been reached by averaging results between day 40 and 44.

In the AMMA case, cold pools appear around 5:00 PM in the LES but as early as 1:30 PM in LMDZ CTRL, revealing a model limitation. Adjusting the S_{trig} parameter involved in the triggering criteria could delay this onset, though a more physical approach would be required. For comparison, we focus on the times when cold pools are most developed: 7:30 PM in the LES and 2:30 PM in LMDZ CTRL, where the intermediate analysis of δT shows colder and thus more pronounced pools.

In order to facilitate comparisons between LMDZ and LES, we also impose in the LMDZ simulations the density of cold pools estimated in the LES. We thus set a density of 5 cold pools per 100 km×100 km for the RCE case and 2.5 cold pools

per 100 km×100 km for the AMMA case. To represent the profiles of δT, δq and δw in LMDZ CTRL for the RCE case, we perform a time average between the 41st and 43rd day of simulation, in order to compare with the LES at the same times. For the AMMA case, the analysis is performed at 7:30 PM in the LES and at 2:30 PM in LMDZ CTRL, as specified above. The same procedure is applied to compare the $WAPE$, ALE, and ALP variables between LMDZ CTRL and the LES for both cases.

4.1 Vertical profiles of δT, δq and δw

The analysis of the δT profiles in the LES confirms that cold pools are colder at the surface with temperatures increasing towards the top for the three LES. The cold pools are about three times deeper in AMMA (Fig. 7a) than for the RCE case (Fig. 7d). In the LES, the cold pool temperatures for the AMMA case (around 4 K) are lower than those of the RCE case (around 1.2 K). This is consistent with observations which indicate much colder pools over land than over the ocean. For the AMMA case in particular, observations reveal a temperature drop of approximately 5 K during the passage of the cold pool (Lothon et al., 2011), a value fairly close to that of the LES. It should be noted however that the AMMA case corresponds to a relatively weak episode of continental convection. The δq profiles indicate that at the surface, cold pools are wetter than the surrounding air in the RCE case and the AMMA case (Fig. 7b and 7e). In both cases, the excess of humidity within cold pools decreases with altitude up to the cold pools top. The humidity deficit above this level is due to the lateral entrainment of dry air from the mid troposphere and its subsidence into the cold pools (Fig. 7c and 7f). For the RCE case, this subsidence vanishes below 800 hPa (Fig. 7c), while for the AMMA case, it vanishes at a higher level, around 600 hPa (Fig. 7f).

The δT profiles simulated with LMDZ CTRL are qualitatively consistent with LES, with a cold pool top (where δT cancels) at about the right altitude. Cold pools simulated with LMDZ are however warmer than in the LES for the RCE case (Fig. 7a), and colder at the surface than the LES for the AMMA case (Fig. 7d). Consistently with LES, cold pools are also wetter at the surface and drier close to their top top (Fig. 7b and Fig. 7e). However the variations of δq are much larger in LMDZ than in the corresponding LES. In particular, the cold pools are much too dry at their top in LMDZ. In both cases, cold pools are associated with subsidence. The height at which the subsidence of air masses into cold pools begins, fixed at 600 hPa in LMDZ CTRL, is too high compared to LES for the RCE case (Fig. 7e).

4.2 WAPE, ALE and ALP

For the RCE case, the $WAPE$ is significanlty smaller in LMDZ CTRL than in the LES, with a difference of at least a factor of 2 (Table 3). These low values of $WAPE$ in LMDZ CTRL also translate into low ALE_{wk} values compared to LES (Table 3). On the other hand, for the AMMA case, the $WAPE$ simulated by the model, and consequently ALE_{wk}, are slightly higher than the values derived from the LES (Table 3). The value of C_* simulated by LMDZ CTRL is at least three times smaller than that of the LES in the RCE case and slightly lower for the AMMA case (Table 3). ALP_{wk} is at least twenty times weaker in LMDZ CTRL than in the LES for all cases (Table 3).

Various modifications of the cold pool parameterization are explored in the following section to try to correct the defects listed above.
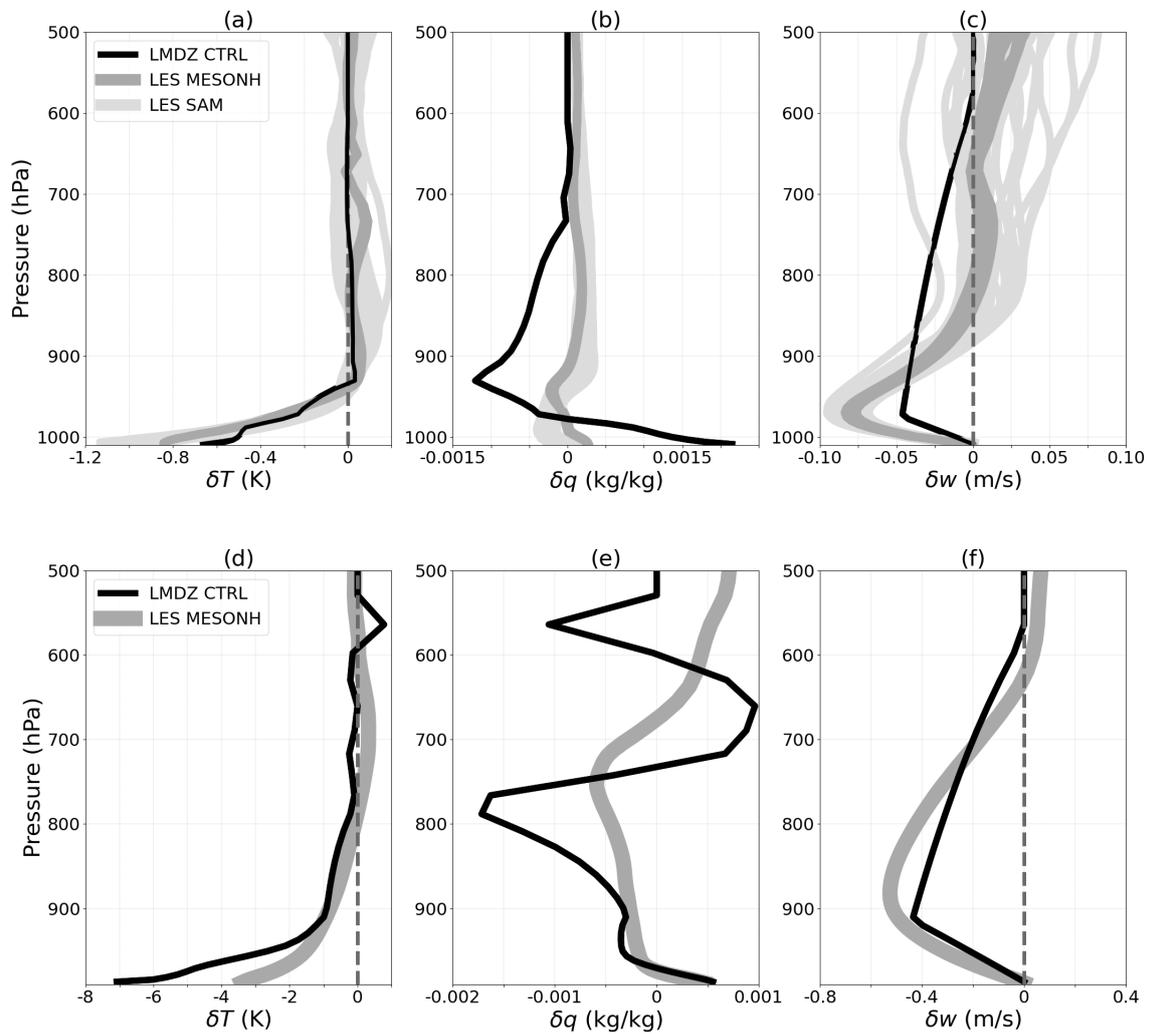
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Figure 7. Vertical profiles of δT, δq and δw calculated in the LES and simulated by LMDZ control (LMDZ CTRL). For the RCE case (a, b, c), the profiles are shown for a set of 24 times for the SAM LES (light grey) and 10 for MESONH (dark grey). For LMDZ CTRL, results are averaged from day 41 to 43. For the AMMA case (d, e, f), the profiles correspond to the times when cold pools were most developed, i.e., 7:30 PM in LES and 2:30 PM in LMDZ CTRL.

	$WAPE$ (J/Kg)	$ALE_{\mathbf{wk}}$ (J/kg)	C_* (m/s)	$ALP_{\mathbf{wk}}$ (W/m^2)
RCE				
LES SAM	7.962	10.460	2.228	0.054
LES MESONH	7.912	6.965	2.264	0.020
LMDZ CTRL	2.957	2.957	0.802	0.001
AMMA				
LES MESONH	62.110	66.960	4.762	2.304
LMDZ CTRL	71.300	75.170	3.941	0.103

Table 3. Comparison of the $WAPE$, ALE_{wk}, C_* and ALP_{wk} computed from sampling of the LES and by LMDZ control (LMDZ CTRL) for the RCE case and the AMMA case. For the RCE case, comparisons are made using an average of the days following the achievement of equilibrium (days 41, 42, and 43). For the AMMA case, they are performed at the times when the cold pools are most developed (7:30 PM in the LES and 2:30 PM in LMDZ CTRL).

Simulations	Protocols
LMDZ CTRL	simulation of LMDZ with the standard configuration except that D_{wk} is set to 5 per 100×100 km^2 for the RCE case and 2.5 for AMMA
LMDZ V1	LMDZ CTRL + change of k to 0.56
LMDZ V2	LMDZ V1 + changed computation of p_{upper}
LMDZ V3	LMDZ V2 + activation of thermals throughout the domain

Table 4. Description of simulations performed with LMDZ in the standard configuration and with various modifications

5 Improvements of the cold pool model

540 Here, we start by correcting the identified discrepancies between the LES and the model concerning the value of the coefficient k and the pressure height p_{upper}, and by assessing the impact of these changes on the temperature and humidity difference between the cold pools and their environment, before exploring other avenues for improvement.

5.1 Coefficient k

We present here the impact of increasing the coefficient k from 0.33 to 0.56 (LMDZ V1 simulation) on the profiles of δT, δq,
545 δw as well as on the variables C_*, $WAPE$, ALP_{wk} and ALE_{wk} (see Table 4). In the RCE case, this modification significantly improves the profile of δw below p_{wk} (Fig. 8c). It also allows for a better representation of the δw profiles below p_{wk} in the AMMA case (Fig. 8f). These improvements are directly linked to the increase in C_* for both cases (Table 5), since the δw profile below p_{wk} depends on the spreading of cold pools. The increase in C_* could be associated with stronger air mass subsidence within the cold pool, which would contribute to a slight drying near the surface in both cases (Fig. 8b and 8e). For
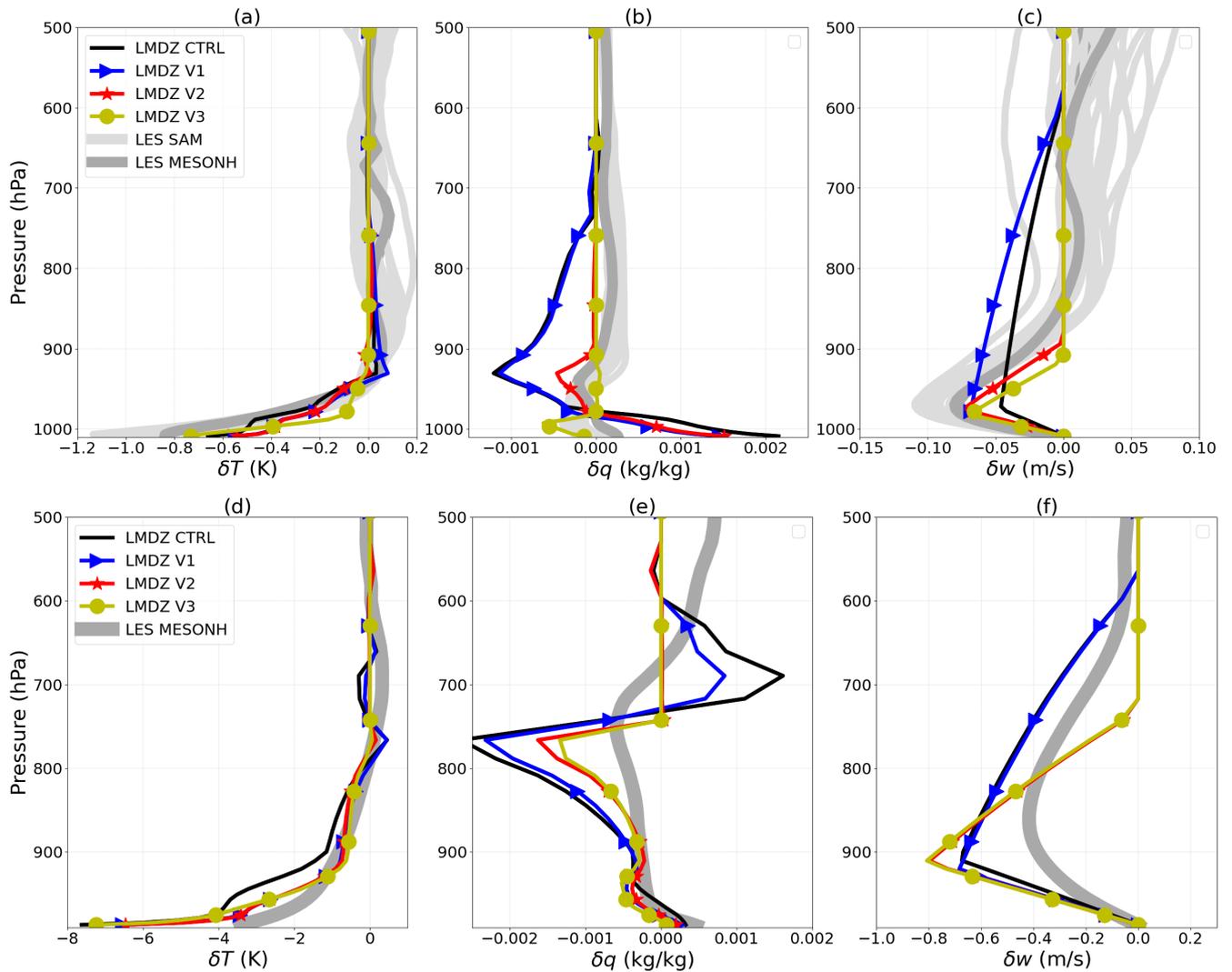
Figure 8. Vertical profiles of δT, δq and δw calculated in the LES and simulated with LMDZ: for a control simulation (CTRL, same curves as Fig. 7), with adjustment of the coefficient k to 0.56 (V1), with the modified computation of p_{upper} (V2) and with the activation of thermals in the entire domain (V3). Both the RCE (a, b, c) and AMMA (d, e, f) cases are shown for the times as in Fig. 9.
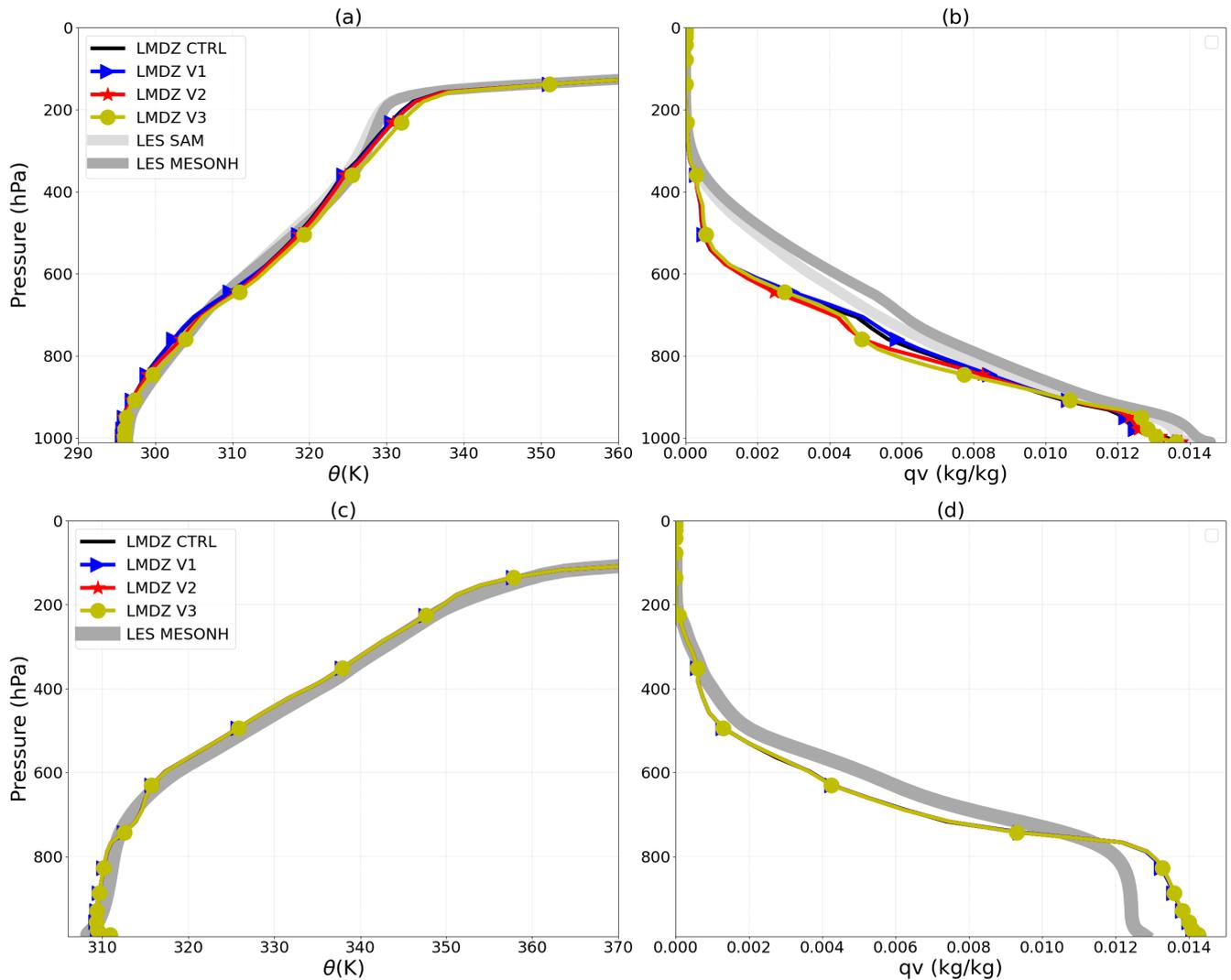
Figure 9. Vertical profiles of potential temperature (θ) and specific humidity (q_v) calculated in the LES and simulated with LMDZ: for a control simulation (CTRL), with adjustment of the coefficient k to 0.56 (V1), with the modified computation of p_{upper} (V2) and with the activation of thermals in the entire domain (V3). Both the RCE (a, b) and AMMA (c, d) cases are shown for the same times as in Fig. 7

550 the AMMA case, this drying results in slightly drier cold pools at the surface in LMDZ V1 than in the LES, but they remain overall comparable to the latter. The increase in C_* in both the RCE and AMMA cases also leads to a better representation of ALP_{wk} (an increase by at least a factor of 5 for both cases), even though this variable remains underestimated (Table 5). We also note a warming effect from this modification in both the RCE and AMMA cases. The impact on the δT profiles in the AMMA and RCE cases is responsible for the decrease in the values of $WAPE$ and ALE_{wk} for these two cases (Table 5).

555 Fig. 9 shows that the modification introduced in version V1 has a low impact on the θ and q_v mean profiles (Fig. 9), the black and blue curves being almost superimposed. Both CTRL and V1 simulations reproduce the θ profiles fairly well. Around 600 hPa, the temperature is too warm in the RCE case. Regarding humidity, a dry bias is present in the boundary layer in the RCE case, as well as between 800 and 400 hPa. For the AMMA case, there is a wet bias in the boundary layer and above 600 hPa, and a dry bias between 700 and 600 hPa.

560 ## 5.2 Choice of cold pools scheme upper bound, p_{upper}

In the previous sections, we found that the altitude at which the subsidence of dry air above cold pools initiate is located around 800 hPa in the LES for the RCE case and around 600 hPa for the AMMA case, while in LMDZ, p_{upper} is arbitrarily set to 600 hPa in the original version of the parameterization. In version V2, in addition to the change of the value of k from 0.33 to 0.56, we impose $p_{\text{srf}} - p_{\text{upper}} = \gamma_{\text{wk,upper}}(p_{\text{srf}} - p_{\text{wk}})$ with $\gamma_{\text{wk,upper}}$, fixed here to 3, is considered as a new free parameter in 565 the following section.

Note that the numerical scheme used to estimate p_{wk} was also modified compared to GL10 in order to solve instability issues.

The principle of the new scheme is to compute the height at which the vertical integral of $\delta\theta$, from the surface to that level, reaches a fraction χ of the total integral from the surface to the first positive value of $\delta\theta$. This fraction is taken slightly below 570 100% to avoid fluctuations of p_{wk} from one time step to the other, which happens when $\delta\theta$ is close to zero on a large range of altitudes around p_{wk} as seen in Fig. 7 and Fig. 8. The new computation was activated already in CTRL and V1, not affecting the results significantly (figure not shown). The new computation becomes really important when p_{upper} is deduced from p_{wk} rather than being imposed.

Comparisons between LMDZ V2 simulations and LES show a better representation of the δq profiles at the top of cold 575 pools in both the RCE and AMMA cases (Fig. 8b and 8e). These results show that the dry bias at the top of the cold pool in the original version was due to advection of dry air from too high an altitude. This modification also reduces slightly the humidity of cold pools near surface in the RCE case, although they remain more humid than in the LES. Note finally that this modification has a very limited impact on the δT profiles.

Table 5 shows that the change in p_{upper} weakly affects the variables $WAPE$, C_*, ALE_{wk} and ALP_{wk} for these two cases. 580 Versions V2 does not modify much the mean vertical profiles except for a drying of the mid-troposphere in the RCE case (Fig. 9b), in a region where the CTRL simulation was already too dry. Although the time evolution of the mean profiles is the first target of physics parameterizations, we think however that the improvement of the internal variables is so strong for this modification that it should be adopted in the future in LMDZ.

5.3 Activation of thermals throughout the domain

As explained above, in the standard LMDZ configuration, thermals only interact with temperature and humidity profiles outside cold pools, inducing a differential heating in moistening (equation (7)). This choice was originally made to account for the fact that the atmosphere is more stable inside cold pools, and indeed the analysis above shows that the thermal plumes that reach cloud base are essentially located outside cold pools. Version V3 is identical to version V2, except that we consider that thermal plumes are active everywhere in the grid cell. Consistently, the terms $Q_1{}^{\text{th}}$ and $Q_2{}^{\text{th}}$ are removed from (7). For the RCE case, this leads to a decrease in the surface humidity of cold pools, closer to the LES results (Fig. 8b). In the AMMA case, the effect is also present, although less pronounced (Fig. 8e). This result is expected because the vertical transport by thermals systematically dries the surface (Diallo et al., 2017). This confirms the key role of boundary layer convection in regulating surface humidity on both continent (Diallo et al., 2017) and ocean (Hourdin et al., 2020), via the mixing of moist air with dry air above. One way to improve the representation of humidity anomaly profile without activating the thermal plumes everywhere would be to add a simple parameterization of shallow and cloud-free boundary layer convection (a simplified version of the thermal plume model) within the cold pool region.

In version V3, cold pools are colder than in version V2 in both the RCE and AMMA cases (Fig. 8). In the RCE case, however, cold pools remain less cold than in the LES despite this effect. In the AMMA case, this cooling accentuates the overestimation of the cold anomaly. In both cases, this cooling leads to an increase in the $WAPE$, C_*, ALE_{wk}, and ALP_{wk} variables (Table 5). Version V3 does not introduce any notable changes, compared to V2, in the profiles of θ and q_v for the RCE and AMMA cases.

5.4 Tuning of free parameters

The tests presented above show possible avenues for improving the cold pool parameterization. However, we see that the modifications do not sufficiently affect the mean profiles to reduce these biases significantly. All tests underestimate (for the RCE case) or overestimate (for the AMMA case) the cold temperature anomaly inside cold pools, as well as $WAPE$, ALE_{wk}, C_*, and ALP_{wk}. We also observe systematic errors in the mean profiles, notably profiles that are much too dry for the RCE case.

In the GCM, these variables are not sensitive only to the parameters or formulation of the cold pool model. They are influenced by all other parameterizations, and in particular by the convection scheme to which the cold pool scheme is strongly coupled. In an attempt to see how modifications to other parameterizations could help reduce these biases, we performed automatic calibration simulations using the `htexplo` tool.

In practice, we decided to start from a tuning performed for the convective boundary layer by Hourdin et al. (2021), for a configuration with 95 levels rather than 79 and using more recent versions of the codes than those used in the rest of the paper. This version indeed serves as the basis for preparing the future version of the climate model for the FastTrac part of the CMIP7 project, whose simulations are scheduled to begin in early 2026. We assume that the boundary layer parameters have already been optimized to accurately represent the convective boundary layer and associated clouds, cumulus and stratocumulus.
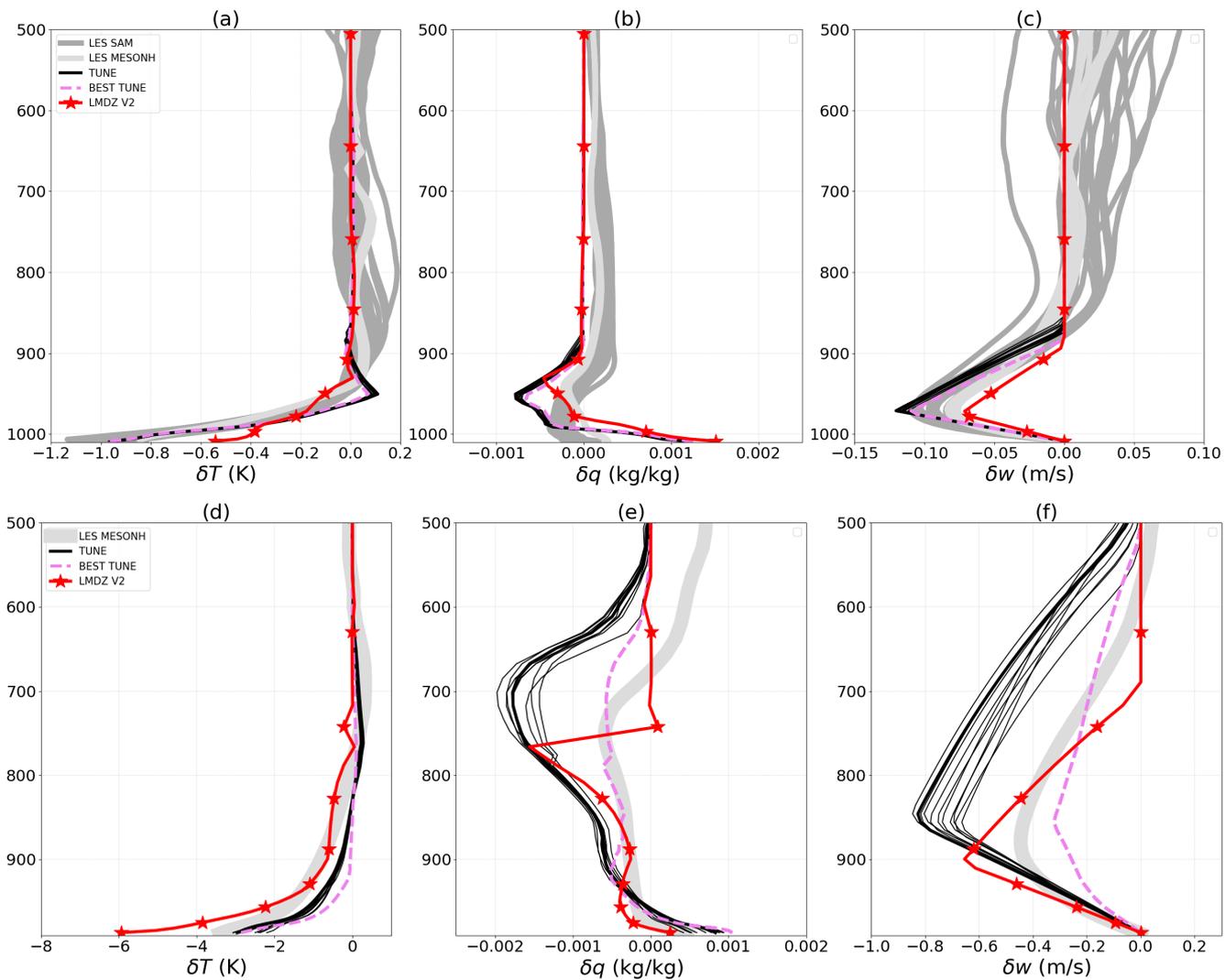
Figure 10. Like Fig. 8, but showing for LMDZ, the V2 simulation, the 12 best simulations from the tuning (TUNE, in black) as well as the best one among them (TUNE BEST, in green).
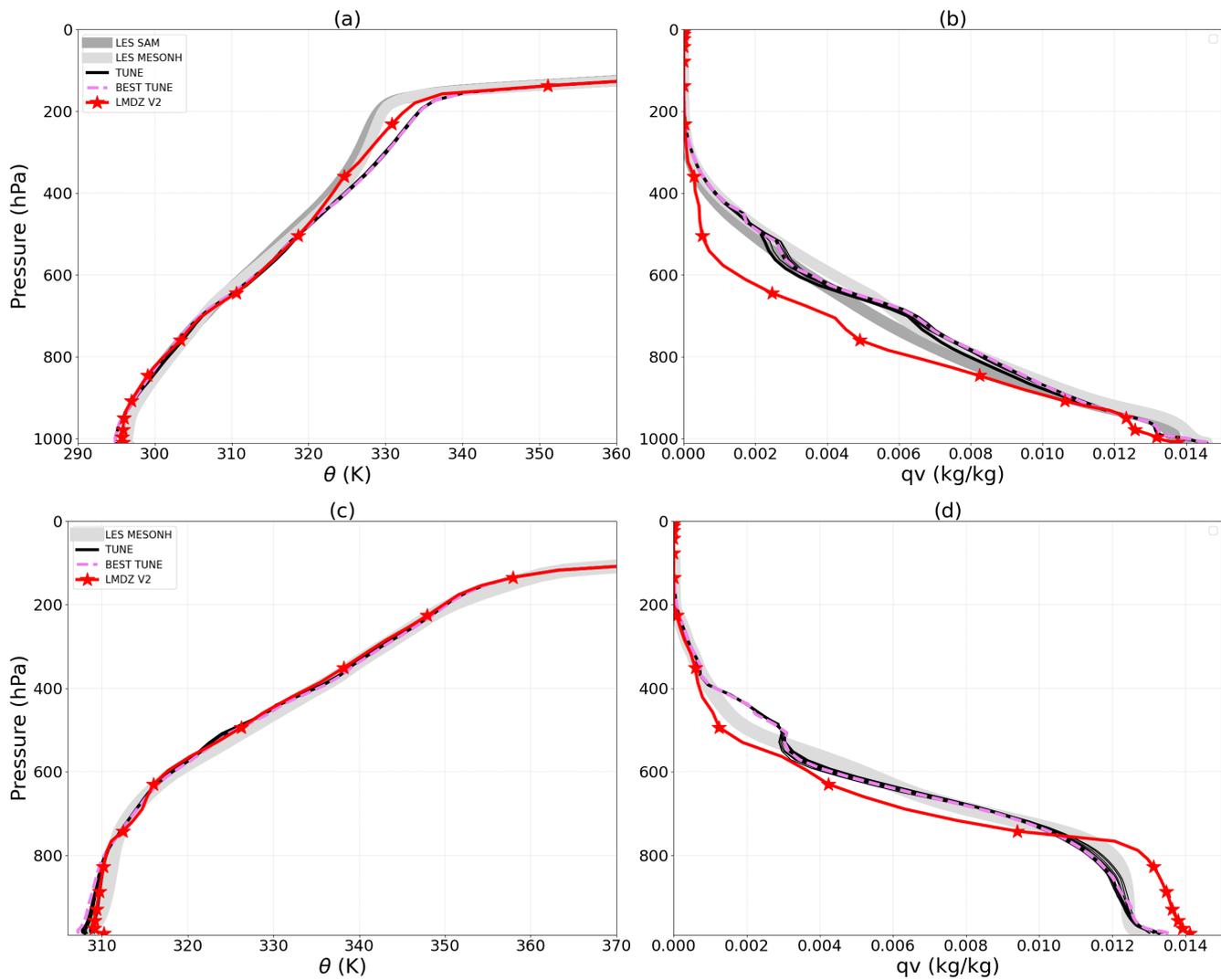
Figure 11. Like Fig. 9, but showing for LMDZ, the V2 simulation, the 12 best simulations from the tuning (TUNE, in black) as well as the best one among them (TUNE BEST, in green).

	$WAPE$ (J/Kg)	$ALE_{\mathbf{wk}}$ (J/kg)	C_* (m/s)	$ALP_{\mathbf{wk}}$ (W/m^2)
RCE				
LES SAM	7.962	10.460	2.228	0.054
LES MESONH	7.912	6.965	2.264	0.020
LMDZ CTRL	2.957	2.957	0.802	0.001
LMDZ V1	2.663	2.663	1.292	0.004
LMDZ V2	2.620	2.620	1.282	0.004
LMDZ V3	3.585	3.585	1.500	0.0055
12 bests	[5.1,5.3]	[5.1,5.3]	[1.79,1.83]	[0.013,0.025]
AMMA				
LES MESONH	62.110	66.960	4.762	2.304
LMDZ CTRL	71.300	75.170	3.941	0.103
LMDZ V1	56.930	56.930	5.975	0.234
LMDZ V2	57.990	57.990	6.031	0.252
LMDZ V3	58.190	58.190	6.041	0.334
12 bests	[40,60]	[40,60]	[4.5,5.1]	[0.5,2.5]

Table 5. Comparison of the variables $WAPE$, ALE_{wk}, C_* and ALP_{wk} calculated from the samplings in the LES, with those obtained with LMDZ: in a control simulation (CTRL), with the adjustment of the coefficient k to 0.56 (V1), with the modified computation of p_{upper} (V2), the activation of thermals in the entire domain (V3) and for the 12 best simulations of a tuning experiment, for the RCE and AMMA cases.
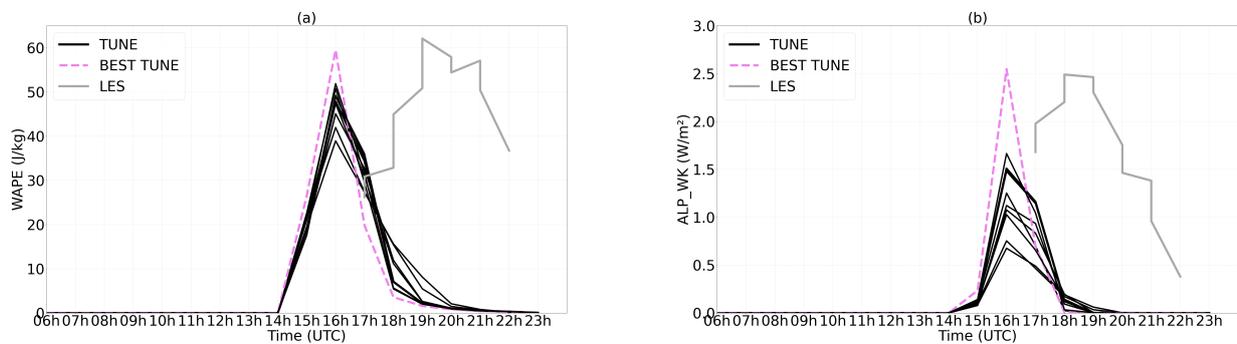

Figure 12. Time series of the collapse energy, $WAPE$ (J/kg, panel a), and the available lifting power, ALP_{wk} (W/m^2, panel b), associated with cold pools, shown for the 12 best simulations from the tuning (TUNE, in black), for the best among them (TUNE BEST, in green) and for the LES (in grey) over times steps between 5:00 PM and 10:00 PM

Regarding modifications to the cold pool model, those affecting the coefficient k and p_{upper} are taken into account, as in the V2 configuration. Adjustments related to thermals (V3) are not considered here because they raise as many questions as they solve.

The tuning is performed using the `htexplo` tool as explained in Appendix A. We choose metrics preferentially on the RCE case targeting the WAPE, ALP and the profiles of anomalies and mean variables. Indeed, we wish to avoid being overly dependent on errors in the phasing of the deep convective diurnal cycle. The adjustable parameters selected for the cold pool model are: k, $\gamma_{\text{wk,upper}}$, χ, and ϵ. Parameters involved in the deep convection scheme are also included: the minimum wb_{srf} and maximum wb_{max} vertical velocities at the base of the convective column; the fraction of the grid cell area in which precipitating downdrafts occur, σ_{desc}; and the maximum precipitation efficiency in the Emmanuel scheme (EP_{max}). This efficiency is a maximum efficiency at the top of the convective columns. The difference 1-EP_{max} controls how much condensed water exits the convective clouds, and thus the moisture source in the upper atmosphere. Details on the metrics and parameter ranges chosen are given in Appendix A.

The result of this tuning is the product of extensive trial and error regarding the choice of parameters, their bounds, the metrics to adjust, and the associated tolerances. We present here the 12 best simulations resulting from 13 waves of tuning. Among them, the simulation considered to be the most performant (TUNE BEST) is also identified. The analysis of the results for the RCE case reveals that the simulations improve the representation of the targeted variables, particularly the mean humidity profile and the amplitude of the potential temperature deviations $\delta\theta$. These deviations are more negative, consistent with a stronger WAPE and C_* coefficient. Furthermore, the δq profiles at the top of the cold pools, as well as the δw profiles, remain well represented across all 12 simulations.

By applying the parameters from the tuning performed on the RCE case to the AMMA case simulations, a significant reduction in the cold bias at the surface of cold pools is obtained (Fig. 10d), as well as an improvement in the mean humidity profiles across all 12 simulations. Only the results from the BEST TUNE simulation reproduce δq and δw profiles consistent with the LES, the others tending to generate cold pools that are too dry at their top due to slightly overestimated δw profiles (Fig. 10e and 10f). The BEST TUNE simulation also provides a better representation of $WAPE$ (Fig. 12a) and ALP_{wk} (Fig. 12b) in the AMMA case, with values very close to those from the LES at the time when cold pools reach their maximum development (Table 5), despite a shift by about 3 hours earlier in the afternoon. This premature triggering in the LMDZ model for the AMMA case has already been showed in Rio et al. (2009) and represents a known limitation of the model. A parameterization of the transition between shallow and deep convection, currently prescribed according to a cumulus size threshold as discussed above, could correct this bias. Nevertheless, despite this shift in convection triggering, the BEST TUNE simulation shows good agreement with the LES in terms of the duration and intensity of convection. Nevertheless, a moist bias and a cold bias persist in the boundary layer. It would be difficult to attribute this results in BEST TUNE simulation to a specific parameter. The calibration result actually arises from a combination of the values of the different parameters used for tuning. Even if a parameter has been significantly modified, its effect on the final result still depends on the other parameters.

Several lessons can be learned about the range of the free parameters involved in the tuning when considering the best values (last column of Table B1). First the fraction of the grid cell assigned to unsaturated downdrafts, σ_{desc} with a selected range of

[0.042, 0.048], is larger than the nominal value of 0.015, which contributes to first order to the increased intensity of cold pools, in particular for the RCE case. Concerning the parameters of the cold pool model itself, first the tuning of k from (4) confirms the findings of Section 3.5, with selected range of [0.56, 0.57]. The value of $\gamma_{\mathrm{wk,upper}}$ that controls the height of the cold pool model is [3.6, 4.1], compatible as well with the previous findings. With a range of [0.26, 0.46], the tuning suggest that more than 25% of the power associated with cold pool spreading is available for deep convection. Note finally that the χ parameter of the new numerical scheme for p_{wk} computation is also strongly constraint by the tuning exercise (to a value of about 0.97). This exercise confirms the extraordinary progress represented by the availability of automatic retuning methodology.

6 Conclusions

~~Although the cold pool model proposed by Grandpeix and Lafore (2010) has improved the representation of convection in the LMDZ climate model (Rio et al., 2009), its internal variables and physical properties had never been evaluated in details so far. This work proposes~~This study presents, for the first time, a detailed evaluation of the ~~cold pool~~ cold-pool model Grandpeix and Lafore (2010) within the LMDZ climate model, based on ~~LES~~Large Eddy Simulations (LES). We evaluate both the ~~physics~~ fundamental assumptions of the model, its internal variables and those involved in the coupling with deep convection, based on two oceanic LES in the RCE regime and a continental LES of the AMMA case.

For this, we introduce two samplings of the LES. The first one separates the interior from the outside of the cold pools, based on a threshold of the 10 m temperature anomaly of -0.2 K for the RCE case and -1 K for AMMA. The second one separates the zone of gust fronts by smoothing horizontally the vertical wind at cloud base (moving average over a square of 1.25 km side for the RCE case and 2 km for AMMA) with a threshold of 0.8 m/s for the RCE case and 2 m/s for AMMA. The coincidence of the temperature contour used for the cold pool sampling with the lines of maximum wind converge near the surface and with the gust front mask provides a very consistent view of the cold pools. It reinforces the choices that guided the conception of the cold pool scheme. It also confirms that most of the thermals reaching cloud base are located outside cold pools.

We started by validating relationship internal to the parameterizations, by diagnostics of the LES. ~~The results show that the ALE_{wk} calculated from the $WAPE$ (computed from the vertical profile of the temperature anomaly between the cold pool and its environment) is comparable to that estimated from the vertical velocity in gust fronts $w_{\mathrm{b,gust}}$. This result is consistent with~~ This validation mainly relies on comparisons between LES. The cold-pool model variables, diagnosed within the LES according to the formulation of the parameterization, were compared with those obtained directly through sampling in the same simulations. The good consistency between the results confirms the fundamental assumptions of the ~~model hypothesis, which estimates an equality between ALE_{wk}~~ model. The discrepancies observed for some variables are mainly explained by the choice of a free parameter value, which we adjusted in agreement with the estimates provided by the LES. The validation was then carried out in the SCM version of the LMDZ model for the AMMA and RCE cases. In this framework, validation is much more demanding due to the influence of other parameterizations. The LMDZ simulations were performed with initial and boundary conditions strictly identical to those of the LES. Overall, the comparisons demonstrate the relevance of the model, although some discrepancies remain. The sources of these differences have been identified, and ~~$WAPE$. The spreading speed~~

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685 ~~C_*, determined from the mean of divergence of wind at 10 m inside cold pools, is consistent with the estimate based on the square root of $WAPE$, if coefficient k entering in equation ((4)) is fixed to 0.56, a value consistent with published values Bryan (2005); Lafore and Moncrieff (1989). ALP_{wk}, calculated using C_* (computed from the $WAPE$ with $k = 0.56$), is close to the estimate derived directly from $w_{b,gust}$. This result is compatible with the model hypothesis according to which a quarter of the cold pool Avaliable Potential Power, ALP_{wk}, feed deep convection, the remaining being dissipated. All of these results~~

690 ~~show the overall consistency of the model hypotheses with the three LES (RCE and AMMA) used in this study.~~

~~We then compare LES results with the SCM version of LMDZ. The results show that the initial version of the parameterization represents the cold pool properties well to first order, but with a dry anomaly in the cold pool region much too strong for the RCE case above the cold pool top, and a general tendency for both cases to underestimate the cold anomaly within cold pools and in turns $WAPE$, C_*, ALE_{wk} and ALE_{wk}.~~

695 improvements have been implemented. The dry bias simulated at the top of cold pools is attributed to the pressure of the maximum subsidence height (p_{upper}) which was imposed at a fixed value of 600 hPa in the original scheme. This value which was inspired from continental situations is well suited for the AMMA case but much to small for the RCE case for which the LES indicate a value of about 800 hPa. By making p_{upper} dependent on p_{wk}, the pressure at cold pool top, we significantly improve the simulated humidity at the top of cold pools for both cases. These results highlight the control of the cold pool

700 humidity anomaly profile by lateral entrainment of dry air from the mid troposphere and subsidence within the cold pool. They also confirm the relevance of the cold pool transport model with lateral entrainment between p_{upper} and p_{wk} feeding the maximum subsidence at p_{wk}.

~~Increasing the value of coefficient k from 0.33 to 0.56, as suggested by the analysis of the LES, almost doubles the estimation of C_* for both the RCE and AMMA cases and multiplies the value of ALP_{wk} by 6 for AMMA and more than 10 for the RCE~~

705 ~~case, without affecting much the vertical mean and anomaly profiles. However, despite this improvements, C_* and ALP_{wk} remain underestimated in both cases.~~

A wet bias is also obtained at the surface of cold pools in the RCE and AMMA cases. Our analyses show that this bias is linked to the absence, in the model, of the effect of thermals on the variation of humidity at the surface of cold pools. The evaporation flux plays a weak role in this variation, which seems to be mainly controlled by thermals.

710 ~~Despite all the improvements,~~ Warm and cold biases were also observed at the surface of the cold pools~~remain not cool enough in the RCE case, inducing an underestimation of~~, respectively for the RCE and AMMA cases. These biases led to a poor estimation of certain cold-pool model variables ($WAPE$ and C_*~~by about 25% and~~), as well as those involved in the coupling, notably ALP_{wk}~~by a factor of 3. In the AMMA case, where~~, since these variables strongly depend on the temperature of the cold pools ~~are colder, the value of C_* is, conversely, overestimated by about 35%, while that of ALP_{wk}~~

715 ~~remains underestimated by a factor of 4.~~ in the model. In order to check whether this limitation may come from a coupling with the other model parameterizations, and in particular that of deep convection, we conducted a calibration experiment using the HighTune explorer software to jointly adjust the free parameters of the cold pools and deep convection models. This tuning procedure also aimed to correct the dry and wet biases still present in the potential temperature and specific humidity profiles.

These adjustments led to a significant improvement in the representation of cold pool temperature, as well as specific humidity for the RCE and AMMA cases, even if a humid and cold bias persists in the boundary layer for the AMMA case. The values of $WAPE$, ALP_{wk} and C_* are also improved.

The above mentioned changes have been adopted in the new version of the LMDZ global model, used as the atmospheric component of the IPSL-CM7 coupled model under development for the forthcoming CMIP7 Fast-Trac exercise.

Although significant progress has been made in recent years in modeling cold pools, due to their important role in convection, challenges remain. First a simple parameterization of boundary layer convective transport, based for instance on a simplified version of the thermal plume model, could be included to better represent vertical mixing within the cold pools without activating the thermal plume model uniformly over the grid cell. The cold pool number density should become an internal variable of the model since we know it presents very different values when considering popcorn like convection over ocean or continents, or well organized long live system such as squall lines. A parameterization of this number density, based on a population dynamic model is presently under test. To end with, the issue of the propagation of cold pools from grid cell to grid cell needs to be also integrated into GCMs.

Code and data availability. The codes used are distributed openly through `subversion`. The LMDZ GCM is available at:

http://svn.lmd.jussieu.fr/LMDZ/LMDZ6/trunk

It can be installed automatically on a laptop with the command http://lmdz.lmd.jussieu.fr/pub/install_lmdz.sh The `htexplo` tool is available at:

https://svn.lmd.jussieu.fr/HighTune/trunk

The data and scripts used to make the figures of the document will be made available as well on a DOI if the article is accepted for publication. The scripts that will be made available include downloading the correct versions of the LMDZ and `htexplo` software.

Appendix A: and the tuning setup

A1   High-Tune Explorer (`htexplo`) tool

The tuning experiments shown here are done with the `htexplo` tool.

`htexplo` has been developed in collaboration between the LMD (Paris), the Centre National de Recherche Météorologiques (CNRM/Météo-France) and the University of Exeter (UK). It is an automatic calibration tool for free parameters, based on machine learning techniques from the uncertainty quantification community (Williamson et al., 2013). This approach proposes a new calibration paradigm: instead of optimizing parameter values, it aims to identify the subset of parameters that enables the model to reproduce certain observables to a certain accuracy. The main steps involved in using the tool, as well as its mathematical foundations, are well described in Couvreux et al. (2021). The `htexplo` tool was used for the first time in a SCM/LES comparison on several boundary layer cases of the LMDZ model, in order to characterize the subspace of free parameter values for which SCM simulations are consistent with LES for certain metrics and a given tolerance (Couvreux et al.,

metric	unit	target	tolerance
RCE case, average from day 41 to day 43			
WAPE	$m^2\ s^{-2}$	8	2
C_*	$m\ s^{-1}$	2.2	0.2
$\delta\theta_{\text{0-50 m}}$	K	-0.83	0.045
$\delta\theta_{\text{0-600 m}}$	K	-0.48	0.063
$q_{v\,\text{0-500 m}}$	g/kg	14.1	0.45
$q_{v\,\text{1-3 km}}$	g/kg	9.14	0.45
$q_{v\,\text{5-6 km}}$	g/kg	2.55	0.33
$q_{v\,\text{8-10 km}}$	g/kg	0.289	0.063
$\theta_{\text{0-500 m}}$	K	296.5	1.47
$\theta_{\text{1-3 km}}$	K	301.0	1.
$\theta_{\text{5-6 km}}$	K	317.4	1.
$\theta_{\text{8-10 km}}$	K	328.8	3.
AMMA case, average from 10:00 AM to 5:00 PM			
WAPE	$m^2\ s^{-2}$	20	3

Table A1. Metrics (targets and 1-σ tolerances) used for the tuning. For the RCE case, they concern the averages between days 41 and 43 of the WAPE and the cold pool spreading rate C_*, as well as the vertical profiles of $\delta\theta$, q_v, and θ averaged over the altitude ranges specified in the right column. For the AMMA case, only the WAPE averaged between hours 10 and 17 of the simulation is used.

750   2021). This information was then used by Hourdin et al. (2021) to calibrate the 3D configuration. These authors demonstrated how reducing the parameter space using this method significantly saves computing and human resources. They also pointed out that this approach eases the burden on the modeler, enabling him or her to concentrate more on understanding and improving the physical parameterizations of the model.

For the RCE case, we target the quasi-equilibrium phase by considering averages between days 41 and 43. The metrics
755   selected for these calibration exercises are the profiles of δT, q_v, and θ, evaluated from vertical averages at different levels as indicated in.

Details on the metrics, with targets and tolerances to error, are given in Table A1.

The parameters chosen for tuning are listed in Table B1 together with the a priori ranges given to `htexplo` at the beginning of the tuning exercise and ranges of the best 12 simulations obtained after 13 waves of tuning.

Parameter	units	[min,max] prior	exploration	[min , max] 12 best simulations
Cold pool model				
ϵ ((20))	-	[0.25 , 0.5]	linear	[0.26 , 0.46]
$\gamma_{\text{wk,upper}}$	-	[3.5 , 5]	linear	[3.6 , 4.1]
k ((4))	-	[0.33 , 0.66]	linear	[0.56 , 0.57]
χ	-	[0.75 , 0.99]	linear	[0.96 , 0.987]
Convection model				
wb_{srf}	m/s	[0.5 , 1.2]	linear	[0.55 , 0.98]
wb_{max}	m/s	[2.8 , 6]	linear	[2.8 , 3.5]
σ_{desc}	-	[0.015 , 0.05]	linear	[0.042 , 0.048]
1-EP_{max}	-	[0.05 , 0.1]	log	[.93 , .95]
$k_{\text{ALP,BL}}$	-	[0.2 , 0.5]	linear	[0.33 , 0.47]

Table B1. Free parameters considered in the tuning exercise.

760 *Author contributions.* Mamadou Lamine Thiam: work design, diagnostics, analysis, figures and writing

Frédéric Hourdin: work design, diagnostics, analysis and writing

Jean-Yves Grandpeix: conception of the work, analysis and writing

Catherine Rio: analysis and writing

Maëlle Coulon–Decorzens: tuning expertise

765 *Competing interests.* None

Disclaimer. None

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