Project **HIGH-TUNE** Major Societal Challenge:
PRC Proposal Efficient Resource Management and Adaptation to Climate Change
Generic Call - 2016

HIGH-TUNE: HIGH-resolution simulations to improve and TUNE boundary-layer cloud parameterizations

Using state-of-the-art statistical tools and advanced radiative models applied to Large-Eddy simulations to improve cloud dynamics and cloud radiative effects in atmospheric models

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2. Project Summary

Because of their large coverage and cooling effect of the Earth system, boundary-layer clouds are key elements of the climate system. They modulate the water and energy cycles of the atmosphere and strongly impact surface temperatures at various scales. These clouds are often much smaller than a grid cell of global weather forecast and climate models and must thus be “parameterized” through a set of approximate equations that aims at representing the collective behaviour of an ensemble of clouds and their impact on the large-scale model variables. The approximate nature of parameterizations and the diversity of approaches for the choices of associated free parameters through tuning are responsible for important biases in global models. Moreover, the spread of the boundary-layer cloud radiative effects dominates the spread of climate change projections for global warming, in response to a given perturbation of greenhouse gases.

The main objective of HIGH-TUNE is to improve the representation of boundary-layer clouds focusing on the boundary-layer dynamics and cloud-radiation interaction. Important progresses have been made in the last decades in boundary-layer cloud parameterizations, based on the comparison of single-column versions of the global models (SCM) with explicit 3D high-resolution Large-Eddy Simulations (LES) of the same scene of boundary layer clouds. To go one step further, we will build on this approach based on SCM/LES comparison, thanks to two important methodological breakthroughs that benefited from recent advances in other scientific disciplines: i/ estimation of the radiative effect of clouds from LES results using efficient Monte-Carlo algorithms will be used as a reference for parameterization evaluation and tuning; and ii/ state-of-the-art statistical tools for automatic tuning will be adapted to the SCM/LES comparison. Combining automatic tuning tools and full radiative computations will allow us: 1/ to address the energetic tuning of climate models on process-based studies and propose parameter ranges for the final global tuning and 2/ to progress in the representation of clouds themselves and in the understanding of how they depend on boundary-layer dynamics and radiative approximations. To reach these objectives, the consortium gathers applied mathematicians, radiative transfer experts, climate and atmosphere modelling experts, which guarantees a real and significant outcome of the project in state-of-the-art global weather forecast and climate models.

Beyond the range of acceptable parameters values, the automatic tuning with radiative metrics will provide a more comprehensive documentation and understanding of the parameterization behaviour in several cloud regimes. It will be used to revisit several aspects of cloud parameterizations and consider new developments as: (i) adding the representation of dry air intrusion (key process in the transport of water vapour) (ii) improving the representation of the subgrid horizontal and vertical heterogeneities of clouds, the overlap assumption for cloudy grids as well as the solar zenith angle dependency at high latitudes and (iii) refining the assumptions made on cloud optical properties and microphysics. The improved and tuned parameterizations will be systematically tested in full 3D configuration and compared with satellite and in-situ observations.

The main outcomes of the project will be: 1/ the first demonstration of a tuning strategy at the process scale, with in particular, the use of cloud radiative effects as a central metrics; 2/ the availability of an efficient code for computing radiation on 3D cloud scenes from LES; 3/ improved representation of boundary layer clouds for global weather forecast and climate models, through improved parameterizations and better tuning of free parameters.

3. Partnership:

The consortium is composed of three partners: CNRM, LMD and LAPLACE. It gathers applied mathematicians, radiative transfer experts, climate and numerical weather prediction modelling experts from IPSL-LMD and Météo-France, which guarantees a real outcome of the project in the French operational forecast and climate models. Below are listed the different participants to the project with their respective implication.

Name	Status	man. month	Role or expertise and responsibilities in the project
Partner: CNRM			
Couvreux F	MétéoFrance/IPEF	15	LES, boundary-layer processes and their representation, Project leader, LES uncertainties, boundary-layer dynamic parameterization
Roehrig R	MétéoFrance/IPEF	9	In charge of the development of the physics of ARPEGE-Climat SCM runs, tuning strategy and impact of improved cloud parameterizations
Rio C	CNRS CR1	8	Parameterization of dry and moist convective processes Metrics for tuning, boundary-layer dynamics parameterization
Favot F	MétéoFrance/IPEF	7	Computer sciences, website to automatically visualize the comparison of SCM and LES
Honnert R	MétéoFrance/IT	7	Boundary-layer parameterizations in AROME, LES uncertainties, metrics for tuning, boundary-layer dynamic parameterization
Riette S	MétéoFrance/IT	7	Cloud and microphysics parameterizations in AROME
Bazile E	MétéoFrance/IT	5	Boundary-layer parameterizations in ARPEGE, metrics and parameters for tuning, boundary-layer dynamic parameterization
Marquet P	MétéoFrance/IPEF	4	Boundary-layer parameterizations in ARPEGE, thermodynamical metrics; turbulence scheme
Bouteloup Y	MétéoFrance/IPEF	3	In charge of the development of the physics of Meteo-France operational models, tuning, radiation parameterizations in ARPEGE
Guichard F	CNRS CR1	3	Energetic budgets and convective cloud modelling 1D radiative model, evaluation of the 3D simulations over the Sahel
Bouniol D	CNRS CR1	3	Cloud observations by remote sensing, evaluation of the 3D simulations
Lac C	MétéoFrance/IPEF	expert	Leader of Meso-NH model, support on sensitivity tests of LES results, expertise on microphysics

Vié B	MétéoFrance/IPEF	expert	Microphysics parameterizations, support on sensitivity tests of LES
Ribes A	MétéoFrance/IPEF	expert	Statistical tools
SaintMartin D	MétéoFrance/IPEF	expert	Radiation model
Partner:LMD			
Hourdin F	CNRS DR1	11	Atmospheric parameterizations, LMDZ model leader, Task 2 leader, tuning, boundary-layer dynamic parameterizations
Dufresne JL	CNRS DR1	11	Atmospheric radiation, Climate change, Representation of the geometrical cloud effects
Madeleine JB	UP6/MdC	7	Microphysics, Parameterization of cloud macro & microphysics
Lefebvre MP	MétéoFrance/IT	7	In charge of SCM infrastructure, tuning
Musat I	CNRS IR2	7	In charge of evaluation and tuning of the LMDZ model Tuning and metrics for the IPSL-LMD climate model
Fairhead L	CNRS IR1	7	High Performance Computing, in charge of LMDZ source code Tuning and automatic tools for LMDZ
Chéruy F	CNRS CR1	2	Surface energetic budget and clouds, comparison to SIRTA observations
Jouhaud J	PhD	18	Subgrid cloud heterogeneities in global models, LES and SCM analyses
Jam A	Pr	expert	Cloud parameterizations
Williamson D	Un. Exeter/Pr	expert	Statistical tools proposed for the tuning strategy
Partner: LAPLACE			
Fournier R	UPS/Pr	9	Radiation code, Task 3 leader, simulation of LW/SW radiative effects from LES-clouds - parameterization improvements (radiative transfer)
Blanco S	UPS/MdC	9	Radiation code, simulation of LW/SW radiative effects from LES-clouds - parameterization improvements (radiative transfer)
El Hafi M	Mines-Albi/MdC	3	Monte Carlo for spectral/temporal integration in complex geometries, sensitivity evaluation
Dauchet J	UBP/MdC	3	Radiative properties of particles, analysis of multiple-scattering radiative transfer in complex geometries -simulation of cloud radiative effects
Szczap F	UBP/MdC	4	3D radiative transfer in cloudy atmospheres evaluation of cloud emulators for the identified cases, metrics on cloud optical properties, sensitivity of radiation to microphysics

It should also be mentioned that HIGH-TUNE will collaborate with INRIA-AIRSEA for the applied mathematics and in particular with Elise Arnaud and Clémentine Prieur from Université Joseph Fourier (Grenoble) who will act as expert on statistical tools (<5% of implication in the project).

Acronyms in this table:

Partner Laboratories:
CNRM: Centre National de Recherches Météorologiques, Toulouse, UMR 3589
LMD: Laboratoire de Météorologie Dynamique, Paris, UMR 8539
LAPLACE: Laboratoire Plasma et Conversion d'Energie, Toulouse, UMR 5213

Partner Institutions:
CNRS: Centre National de la Recherche Scientifique
UP6: Université Paris 6, Paris
UBP: Université Blaise Pascal, Clermont-Ferrand
Météo-France
UPS: Université Paul Sabatier, Toulouse
Mines-Albi, UMR 5302, Albi

Partner status:
DR: Directeur de recherche
CR: Chargé de recherche
IR: Ingénieur de recherche

Pr: Professeur	MdC: Maître de Conférences
IPEF: Ingénieur des ponts, eaux et forêts	IT: Ingénieur des Travaux TS: Technicien Supérieur

4. Evolutions with respect to the pre-proposal and responses to reviewer comments:

There is no significant difference in the content of the project with respect to the pre-proposal. There have been only minor changes that are listed below:

- we have added several experts : experts in microphysics (C Lac and B Vié) and expert in applied mathematics (A Ribes). I Beau does not any more belong to the persons involved in the project as she moved to another position. J Jouhaud a PhD student that specifically works on the development of the representation of the subgrid variability of clouds is explicitly referred to in the project
- to answer one reviewer comment, we have decreased the time of the requested funding to the ANR for non-permanent staff by 10 %. However, in the budget presented in the pre-proposal we did not take into account the 8% of amount removed for management fees and structural costs, so despite the reduction of 10%, the total requested is slightly larger (435 k€ instead of 420 k€) than the pre-proposal.

Six remarks were made by the reviewers of the pre-proposal and are addressed below:

- "*this is a pure-modelling project, need to use real cases*"; "*should use data from field campaign*":There is indeed a strong modelling component in this project. However, the link with observations is present more or less directly in all the project: reference cases chosen are most of the time derived from field campaigns (as shown in Table 1) whose observations have been or will be used to assess the realism of the simulations (see Task 2.1 and Task 3). In addition, the improved parameterizations will be tested systematically in full 3D configuration and compared with satellite and in-situ observations (see Task 4.4).
- "*It is not clear how the new parameterizations will be made available to the modelling community?*" HIGH-TUNE plans to assess and improve directly the different parameterizations (turbulence, cloud and radiation) of the different French Numerical Weather Prediction Models (AROME and ARPEGE) and of the two French climate models (IPSL-CM6 and CNRM-CM6). So any parameterization development will directly benefit to the French modelling community. Also, as AROME and the research model Meso-NH share the same physics, evolutions in AROME physics would benefit to the Meso-NH code, which is open-source and is used by a large research community. LMDZ is open source as well and the most recent developments are accessible at any time through the LMDZ web site (access managed through the open source "subversion" software). In addition, the main results will be published in peer-reviewed articles and be therefore available to the international modelling community. This project will also promote a new tuning strategy by proposing first a tuning at a process level based on dynamical, thermodynamical and energetic constraints. It will be disseminated through international papers and promoted in workshops. The international community will also have access to these new tools (radiative code and tuning tool) as well as the setup and main outputs of the high-resolution simulations available via the website.
- "*Tuning unique strategy for the development of parameterizations*" This is not the unique strategy and several parameterization developments listed in Task 4 are considered. However, we believe that the tuning tool at the process level will allow to explore the limits of the parameterizations and provide a better understanding of their behaviour. The articulation of this tuning at the process level with the tuning of the global model, which is actually rather poorly controlled and may hide compensating errors, is also very promising.
- "*Microphysics expertise would have helped the consortium*" There were already two experts in microphysics (Jean-Baptiste Madeleine and Sébastien Riette) included in this project, but we have now also included two more experts on microphysics (Christine Lac and Benoit Vié) who have worked specifically on the microphysics of Meso-NH. The microphysics is one of the parameterization in which free parameters will be tuned and several developments are proposed (see Task 2.3 and 4.2).
- "*Which parameters will be tuned? Not clear enough*" This is now explained in the document (see Task 2.3) but the choice of the parameters may depend on the particular model and will evolve along the project with new parameterization developments.
- "Too *expensive project... justify the use of the budget and the links with the financial support from LEFE*" We have decreased the requested funding for non-permanent staff of 10% in order to take into account this comment. Note that in the initial budget we forgot to include the 8% corresponding to the fees removed for management and structural costs. This project was identified as a priority by DEPHY-2 (Development and Physical Evaluation of the Atmospheric Models, funded by the CNRS/LEFE program)

that aims at networking and coordinating the French community working on the development of parameterizations. However, there is no position funded by DEPHY-2 and the funding from CNRS/LEFE only aims at covering one to two annual meetings.

5. Context, state of the art, objectives:

5.1 Context:

Atmospheric radiation is the first engine of the atmospheric motions. Clouds, by reflecting shortwave (SW) radiation back to space and trapping longwave (LW) radiation, modulate the water and energy cycles of the atmosphere and strongly impact the net input of energy to Earth's surface. Globally, the SW reflection is estimated to be of the order of 50W/m^2 and the cloud green-house contribution of 30 W/m^2, more than an order of magnitude larger than the radiative forcing associated with a doubling of the CO_2 concentration. Due to their large coverage and their strong cooling effect of the Earth system (Fig 1), boundary-layer clouds strongly impact surface temperatures at various scales (Bony and Dufresne 2005). Those low clouds also play an important role in redistributing energy and moisture between the Earth’s surface and the upper atmosphere, in turn controlling the vertical thermodynamic structure of the atmosphere. Therefore, they influence the large-scale circulation. Despite recent progress in satellite observations (*e.g.* A-train constellation with a lidar and a radar), it remains difficult to observe these clouds at the temporal and spatial scales required to achieve a comprehensive understanding of their properties (internal dynamics, microphysics, geometry and radiation) and the various processes involved. Much of our understanding of cloud dynamics has come either from aircraft measurements acquired from field campaigns and through explicit numerical simulations of clouds (Zhao and Austin 2005). With a resolution of a few tens of meters, these 3D non-hydrostatic high-resolution simulations (also called Large-Eddy Simulations, LES) resolve the turbulent eddies that constitute the roots of the cumulus and the cloud dynamics. They provide 4D spatio-temporal consistent fields of many variables and allow to access to several cloud properties that are difficult to observe. They have been widely used for the study of clear and cloudy boundary layers and have been extensively validated in studies of the clear boundary layer (Schumann and Moeng 1991; Moeng and Sullivan 1994; Couvreux et al. 2005), cumulus clouds (Siebesma and Jonker 2000; Neggers et al. 2003, Heus and Jonker 2008, among others) and stratocumulus clouds (Stevens et al. 2005, Wang et al. 2009).

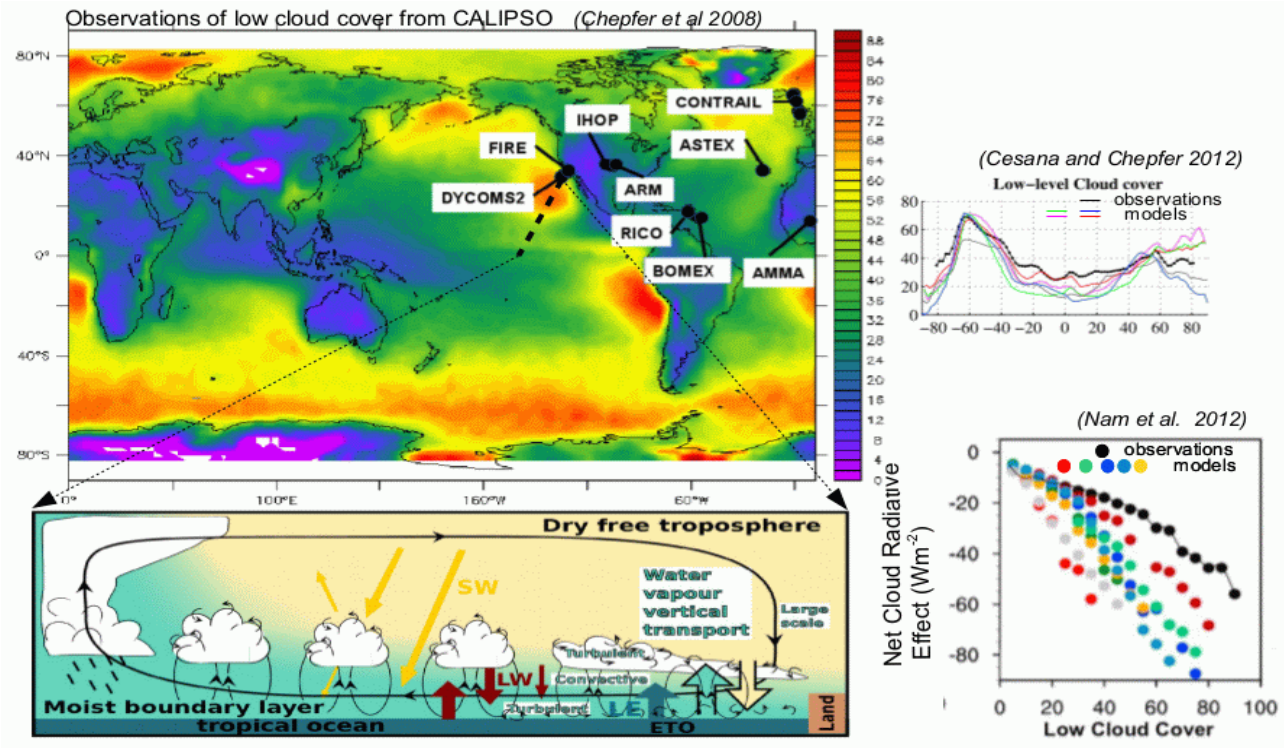


Figure 1: (upper left) map of the March mean occurrence of low clouds obtained from CloudSat/Calipso (from Chepfer et al. 2008), (upper right) latitudinal distribution of the low-level cloud cover in observations (black) and climate models (colors) (Cesana and Chepfer 2012), (lower left) schematic of the processes and clouds involved in a Pacific transect from the Californian coast to the Equator (adapted from Hourdin et al, 2015) and (lower right) net cloud radiative effect as a function of the non-overlapped low-cloud cover in observations (black) and climate models (colors) (from Nam et al. 2012)

The representation of clouds and their radiative effect in global forecast and climate models remains a big challenge. Due to their small size, these clouds can not be explicitly represented in those models even from the finest global simulations (Tomita et al. 2005; Satoh et al. 2008) that have a horizontal grid of a few kilometres. Their impacts on the larger scale must be represented through so-called parameterizations, subgrid models that aim at representing, in a simplified way, the most relevant processes that can not be resolved explicitly by the discrete model system equations. These parameterizations introduce new equations involving hypotheses that need to be assessed and parameters that need to be determined. Despite a long-term effort of the modelling community and in particular recent advances in the French models, the representation of boundary-layer clouds still remains a challenge in state-of-the-art models used for both numerical weather prediction and climate studies (Nuijens et al. 2014). Some deficiencies of those parameterizations are shared by most models: a tendency to produce trade wind cumulus that are “too few“ (underestimation of cloud cover) and “too bright” (overestimation of optical thickness) as shown in Fig 1 (Webb et al. 2001; Zhang et al. 2005; Karlsson, et al. 2008; Nam et al. 2012) or the under-representation of the stratocumulus decks that cover the eastern part of oceanic basins (Ma et al. 1996; Yu and Mechoso 1999; de Szoeke et al. 2010; Richter 2015), contributing to first-order **persistent and systematic biases** in sea surface temperatures (Hourdin et al. 2015). The moistening of the mid-troposphere by these clouds is often underestimated (Couvreux et al. 2015), which prevents a realistic representation of the life cycle of convection. Boundary-layer clouds have also been shown **to dominate the spread in climate change predictions** (Bony and Dufresne 2005; Randall et al. 2007; Williams and Webb 2009; Vial et al. 2014). These errors limit the skill of numerical forecasts at all scales from days to decades.

Although most developments will have implication beyond the particular case of boundary-layer convective clouds (i. e. cumulus and stratocumulus), we limit ourselves to those clouds because of their climatic first order role. The microphysics associated to these clouds is also simpler as it does not involve ice phase at least in the Tropics. The representation of such clouds in a global model requires the representation of three components:
1) the dynamics within the convective boundary layer must be first accounted for. It consists in turbulent motions at various scales, including organized motions which scale with the depth of the boundary layer, the so-called thermal plumes, rolls or cells. The vertical turbulent transport affects the mean profiles of temperature, wind, water vapour and minor compounds. The convective structures or large eddies, are responsible for most of the transport through the boundary layer while smaller scale turbulence controls the coupling with the surface and the cloud geometry through mixing with the tropospheric air.
2) the processes controlling the cloud characteristics (both the micro and macro-physics) must then be accounted for. Some assumptions need to be made on the subgrid scale distribution of temperature and moisture, to determine the fraction of the horizontal surface covered by clouds, the in-cloud water content and its conversion to rainfall. This statistical description is now often coupled to the boundary-layer dynamics. The competition between drying from condensation and moistening from lower-tropospheric mixing controls the drying of the free troposphere which is crucial for low cloud climate feedback.
3) the cloud effect on radiation must finally be accounted for. Currently most of the radiative codes in models consider that the atmosphere within a model grid box is horizontally infinite and homogeneous (parallel plan assumption). However, some aspects of the 3D geometry of clouds need to be accounted for. In particular, so far, the subgrid horizontal heterogeneity is often still simply represented by a constant factor (Mauritsen et al. 2012) and the subgrid vertical heterogeneity is most often neglected. The cloud overlap, which states how clouds from different vertical levels on a given vertical column overlap, is frequently represented by a random, maximum overlap, or using a decorrelation length. In addition, no model so far accounts for angular and shadowing effects, in particular for the fact that at low zenith angle, a field of cumulus can hide completely the surface to direct solar radiation. **This calls for a better determination of the radiative effect of boundary-layer clouds.**

Regardless of the precise way clouds are represented, the uncertainty in the parameterizations are far larger than the admitted accuracy in the energy balance of global climate models, needed to avoid climate drifts. Implicitly or explicitly, all climate models are therefore "tuned” in order to represent reasonably well some key features of the observed energy budget, but also sometimes some other aspects of the observed climate like the mean rainfall distribution in the tropics, modes of variability like El Nino Southern Oscillation. *Tuning* consists in searching for optimal or acceptable values of internal parameterization parameters (mostly related to clouds and poorly constrained at the global scale), which gives a realistic behaviour of the model under various conditions compared to a suite of observations (Mauritsen et al. 2012). It is therefore a necessary and fundamental aspect of climate modelling and numerical weather prediction activities but is often performed without much control on the way it modifies the parameterization behaviour at the process scales. So far, the strategy adopted in the different modelling groups is poorly or incompletely documented and often based on a trial/error approach. A workshop was organized on this issue of climate model tuning in 2014 and a paper gathering its main conclusions is in revision for BAMS (Hourdin et al. 2016). Its outcome confirms that in most groups, most of the parameters used to tune global models are related to clouds (droplet size, fall velocity, entrainment rate,…) (Golaz et al. 2013; Suzuki et al. 2013) highlighting the large uncertainty associated to their representation. **Improved representation of cloud processes in these numerical models is therefore required to enhance the skill of current weather forecasts and improve our confidence in climate projections**. A general concern also emerges in the climate community that a too strong optimization of the models may result in hiding compensation errors and even constraining too much the response to increasing greenhouse gases. **The elaboration of a well-defined tuning strategy based on solid physical and statistical methodologies is thus urgently needed. In this project, we propose the boundary-layer cloud radiative effect as a central metric for the tuning of the models.**

5.2 State of the art:

In order to achieve a significant breakthrough in the representation and tuning of clouds for climate and numerical weather prediction models, the project gathers three domains of expertises: parameterization of clouds, 3D radiative computations and tuning strategies. Recent advances have been made in each of these domains and are briefly discussed below.

First, large-eddy simulations (LES) that resolve explicitly any circulation with scales larger than 20–100 m have proved their relevance for the understanding of cloud dynamics and the quantification of convective and cloud processes, providing full three-dimensional fields of various variables. They have been shown to satisfactorily reproduce the coherent structures of the boundary layer (Couvreux et al. 2005), the vertical transport of scalars (Siebesma and Cuijpers 1995), the statistical properties of clouds (Neggers et al. 2003), the impact of aerosol concentration on the control of mesoscale organisation of stratocumulus (Wang et al. 2009), the cloud structures and the associated circulation (Jonker et al. 2008) including fine dynamical structure such as the subsiding shells at the border of the cumulus. Different studies showed the LES to be sensitive to the microphysics and turbulence, both parameterizations still being active in such simulations (Van Zanten et al. 2011; Matheou et al. 2011). The use of tracers has led to a better understanding of the cloud dynamics (Zhao and Austin 2005; Heus et al. 2008), helped in a better characterization of thermals, organized patterns of turbulence in the convective boundary layer (Fig 2) and provided physically-oriented diagnostics well suited for the evaluation and improvement of boundary-layer parameterizations (Couvreux et al. 2010; Honnert et al. 2016). Recently, a microphysics scheme with two moments has been implemented in Meso-NH (Vié et al. 2016) and we will assess its impact in the LES.

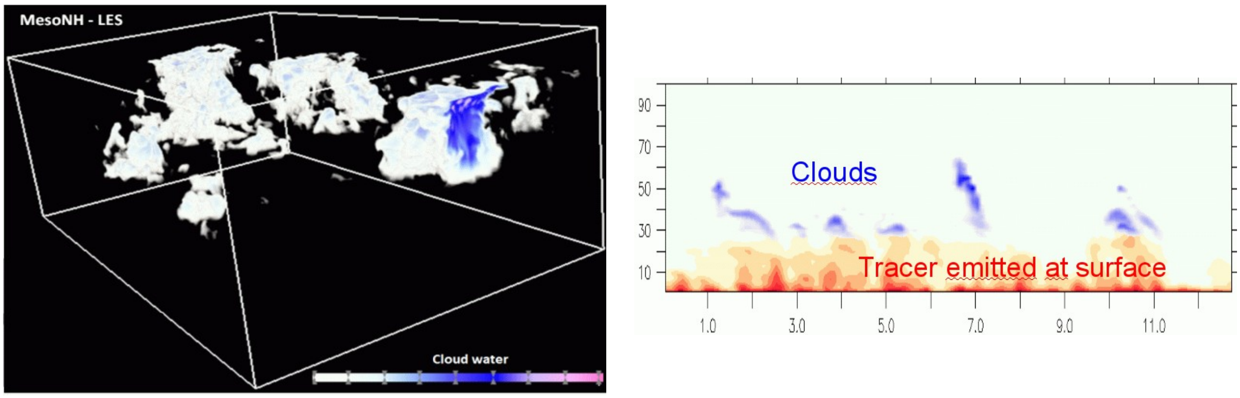


Figure 2: Large-eddy simulation using MesoNH -(a) 3D-visualisation of liquid water content of cumulus clouds from the ARM simulation at 1130LT over a subdomain of 4x4x3 km^3 (courtesy F Lamraoui) and (b) vertical cross-section of tracer concentration (in red) emitted at the surface that locates the thermals with the clouds (in blue) on top of them.

In the last decade, significant progresses have also been achieved in the parameterization of the boundary-layer dynamics, especially in the two French models. Both now use a so called "eddy-diffusivity mass-flux representation", which consists in combining an eddy-diffusivity scheme, traditionally used for the representation of turbulent eddies, and a mass-flux scheme, traditionally used for moist convection. This new approach has been shown to be efficient to represent the vertical mixing in the CBL (for example, Chatfield and Brost 1987; Hourdin et al. 2002; Soares et al. 2004; Siebesma et al. 2007; Rio and Hourdin 2008; Pergaud et al. 2009). Thanks to tracer-based diagnostics, the formulation of entrainment and detrainment rates for the mass-flux scheme has been revisited (Rio et al, 2010) and a cloud scheme based on a bi-gaussian distribution has been proposed (Perraud et al, 2011; Jam et al, 2013). However, those state-of-the-art parameterizations involve numerous internal parameters that need to be calibrated, such as those included in the formulation of entrainment and detrainment rates (Rio et al, 2010) and in the equation for the updraft vertical velocity (Rio et al, 2010; De Roode et al, 2012). **In this project, we will extensively use Single Column Model (SCM) runs, which is a central tool for the development of parameterizations.** SCM simulations correspond to a single column version of the large-scale models which integrates the same suite of parameterizations. The joint utilization of the LES and SCM is now part of a common methodology (Randall et al., 1996) widely used within the GEWEX Cloud System Study (GCSS; where GEWEX is the Global Energy and Water Cycle Experiment) project (Browning et al., 1993) for the development of parameterizations (Siebesma and Cuijpers, 1995; Hourdin et al., 2013). It presents the advantages of having exactly the same forcing for both simulations.

This strategy based on SCM/LES comparisons has been used so far mainly for the description of the dynamics of the boundary layer turbulence and for constraining statistical cloud schemes (e.g. Jam et al, 2013) through the distribution of clouds and condensates within the grid cells. Once these distributions are known, issues still remain concerning the computation of the radiative effect of subgrid scale. Zhang et al (2013) demonstrated that one important source of differences between radiation schemes of global models was their treatment of cloud overlap. Using observations, Tompkins and Di Giuseppe (2015) and Di Guiseppe and Tompkins (2015) have shown that (i) random overlap may overestimate cloud fractions for cloudy layers separated by clear sky and (ii) the rate of decorrelation of vertically continuous clouds depends on the horizontal cloud scale and meteorological characteristics such as vertical wind shear. This suggests the need for revisiting the cloud overlap assumptions. In addition, Barker and Raisanen (2004), Di Guiseppe and Tompkins (2003) and Neggers et al (2011) have shown that vertical and horizontal variability of clouds inside the grid box leads to significant biases in cloud radiative forcings. Konsta et al (2016) also suggested that the absence of vertical variability is at the origin of large biases in the LMDZ radiative fluxes, a conclusion that probably applies to most atmospheric models. Therefore greater development efforts are now being made to account for the effect of subgrid-scale on radiative fluxes (see e.g. Pincus et al. 2003, Hill et al. 2015). However, the subgrid-scale heterogeneity in total water impacts processes other than radiation, and the need for consistency between subgrid-scale schemes used for radiation, boundary layer dynamics, turbulent mixing and microphysics now adds a new layer of complexity (see e.g. Boutle et al. 2014).

The recent decades have also been marked by numerous works on tuning, not only in climate science, and by the emergence of the "Uncertainty Quantification" (UQ) framework (Neelin et al, 2010), which promotes the use of mathematical and statistical methods for addressing uncertainty in the parameters of complex numerical models. Most often, tuning is viewed as an optimization problem, which targets the determination of a set of parameters that minimizes some distance of the model solutions to a set of observations. This approach is however questionable, as by selecting one set of parameters, one artificially reduces the diversity of possible model configurations. This reduction of the model spread may be larger than what could legitimately be inferred from uncertainties in observations and model structural errors, a problem known as over-tuning, explaining the relative reluctance to use such approaches in some important climate modelling groups. This concern is probably quite general to tuning, but is particularly the case in climate modelling, because of the complexity of the system, the very approximate nature of some key parameterizations, the chaotic nature of the atmospheric flow and the unquantified uncertainty in observations (Mauritsen et al, 2012). A more appropriate approach called 'history matching' was proposed for climate model tuning recently. This approach aims to remove `unphysical' regions of parameter space iteratively, refocusing the search for `acceptably tuned' models at each stage (Williamson et al, 2013; Williamson et al, 2015). Because climate models are too complex for direct optimisation, there is a need to develop a statistical model, an emulator that mimics their behaviour (Rougier et al. 2009; Sexton et al. 2011). The approach we will use identifies and accounts for the various uncertainties arising in this problem: the observation uncertainty, the uncertainty added by the emulator and the structural uncertainty (induced for example by the misrepresentation of specific processes and the inaccuracy of numerical solvers).

There is a consensus among a large part of climate modellers that there is a risk of putting too much weight, when tuning models, on 'climate performance' metrics, i.e. metrics that verify some important properties of the observed sensitive climate (statistics on surface precipitation, temperature…). By tuning on such metrics rather than on process-oriented ones, we may obtain good performance in those metrics for wrong reasons (i.e. hiding compensating errors), limiting the confidence in future climate projections with such a model, and inhibiting further developments. This is an example of over-fitting or over-tuning (Hourdin et al. 2016). It is therefore often difficult to demonstrate the improvement of a new physical development on a model which has been previously over-tuned, inducing strong error compensations. By focussing on process oriented metrics and by looking only to rule out parameter choices that do not represent the processes well, we will avoid this difficulty.

As explained in introduction, ultimate metrics used in climate model tuning tackle the energetics, and the so called Cloud Radiative Effect (CRE), as clouds impact the energetic balance at the first order. The CRE is defined in models as the difference of the effective radiative fluxes or heating/cooling rates and the same quantities computed on the same temperature and humidity profiles without clouds. CRE can be deduced from satellite images by differentiating cloudy and clear sky pixels into the same scene of clouds. So far however, the comparison of LES and SCMs has been restricted to dynamic and thermodynamic fields, without considering the CRE. This is explained first because radiation is not always activated (in most cumulus cases, the atmospheric radiative processes are neglected but the imprint of radiation is taken into account via the prescribed surface fluxes and atmospheric prescribed heating rate profiles). Also, the radiative codes used in current LES are generally similar to those used in the large-scale climate or numerical weather prediction models, make use of the parallel plan assumptions and are thus not relevant to serve as a reference. Even if the codes used for interactive radiation in LES remain coarse, we can start using accurate radiation solvers off-line to evaluate the radiative impact of now quite realistic LES clouds as was first proposed by Chosson et al (2007). **In this project, we will use the LES to derive, through the use of 3D radiative transfer code, the boundary-layer cloud radiative effect that will be used as a reference for the SCM runs adding an energetic constraint on the representation of those clouds.**

In principle, for such off-line evaluations, any accurate 3D radiative transfer code could be used, which leaves essentially the choice between Discrete Ordinate Methods (DOM) and Monte Carlo. But when considering the transition from LES simulations to global model parameterizations, we address energetic quantities that need to be integrated over the full infra-red/short-wave spectra and over a global model grid cell (from tens of km to be compared of tens of meter for LES grid cell) and time-step, typically of 20 min, to be compared with 1s for LES time-steps. Spectrally and temporally averaging the 4D cloud-scenes defines an integration problem for which DOM is not suited, but Monte Carlo is. The contexts where Monte Carlo is successful are essentially those defining high-dimension integration problems (Marskak and Davis 2005; Pincus et al., 2003). Statistical sampling of the domain remains indeed practical, whatever the dimension: numerical convergence is driven by the component associated with the stronger variance, but is insensitive to the vector-size (Buras and Mayer, 2011). Here this will mean that we will not only sample optical paths across the cloud, but also sample simultaneously a time and a frequency. LAPLACE have the experience of facing similar questions in engineering contexts, partially abandoning analogue algorithms (following photons from emission to absorption) and making use of recent integral formulation advances (Eymet et al, 2005; Dauchet et al. 2013; Galtier et al. 2013; Delatorre et al. 2014). This experience shows that integrating over large frequency intervals (compared to the width of gaseous absorption-lines, Mathieu et al. 2015) and over large time intervals (compared to the characteristic fluctuations, Farges et al. 2015) requires similar, or even smaller computer costs that evaluating monochromatic radiation at a single time using classical Monte Carlo methods.

In the context of such tools, the handling of large volumes of input data is critical. The developments made in the present project will anticipate a significant increase of the LES resolutions by making use of a recent theoretical proposition, allowing **to maintaining a strict orthogonality between statistical-algorithm and data-representation** (Galtier et al. 2013). This formalism was used by Walt Disney Animation Studios to achieve fast and accurate cloud representations (such visualization of the LES cloud scenes is proposed as outreach of this project see section 7). For combustion applications this was translated into pure grid-free algorithms (Eymet et al. 2013), but in our context this essentially means that the question of accessing the data is identified as a separate computer-engineering task: the LES grid will never appear in the radiative transfer part of the algorithm (the optical paths will not be followed across successive meshes).

5.3 HIGH-TUNE Objectives:

The overarching objective of the HIGH-TUNE project is to improve the global model parameterizations involved in the representation of boundary-layer clouds and their effect on radiation. To reach this objective, we will extensively use the comparison of LES and SCM simulations, and experience and promote a new strategy for process oriented tuning of climate models.

Two main methodological breakthroughs are proposed in this project, based on approaches developed outside atmospheric sciences (engineering and applied mathematics): i/ **advanced Monte-Carlo 3D radiative computations** applied to high-resolution LES simulations will provide reference cloud radiative effects and ii/ state-of-the-art statistical tools will be used to develop an **original, objective, process-based and efficient model tuning strategy. The latter will be applied in the context of LES/SCM comparison** to constrain the many parameters of cloud parameterizations. This has not yet been applied at the scale of physical processes.

The statistical tools available in the applied mathematics community will be first adapted to the context of boundary-layer cloud processes. They will use metrics based on dynamic and thermodynamic fields (e.g., mean profiles of temperature, humidity, clouds, wind, turbulent fluxes..). This will frame a new and interesting way to assess many hypotheses done during the development phase of currently-used parameterizations of boundary-layer processes. So far, the exploration of the possible range for the free parameters was done by hands with no dedicated methodology. It was therefore difficult to get objective criteria to qualify or disqualify some aspects of the parameterization formulations, not being sure whether a given bad or good result was resulting from a good/bad formulation or from a good/bad tuning. In a second step, metrics considering internal aspects of parameterizations will be developed and used targeting for instance vertical velocity of plumes, plume fractions, mass fluxes, entrainment and detrainment rates. Tracer-based sampling of the organized structures will provide the required reference.

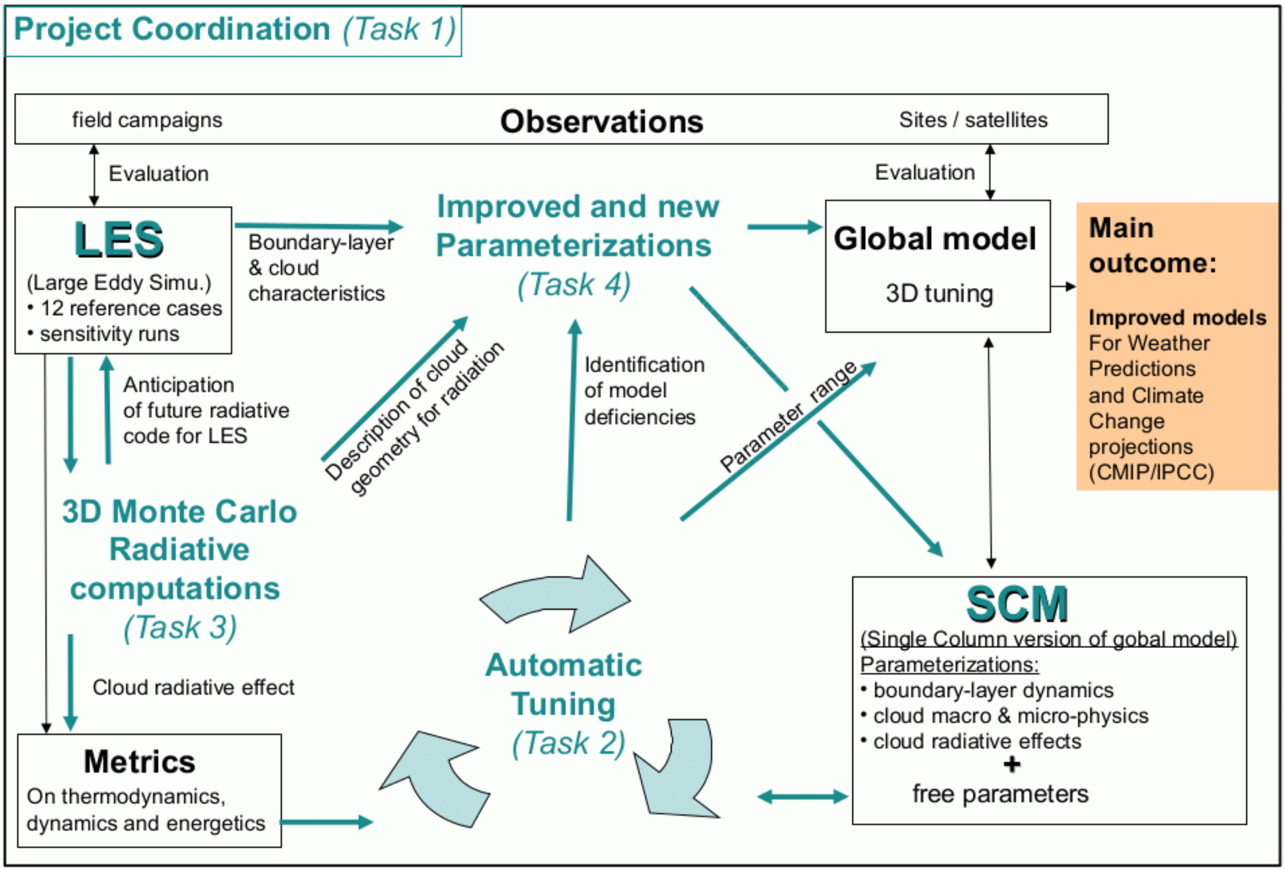
To tackle energetic constraints in the LES/SCM comparison framework, boundary-layer cloud radiative effect will also be included as a new metric. Radiative computation will be applied offline on LES outputs to quantify the Cloud Radiative Effect (CRE, difference of full computation and same computation without clouds) using very efficient and improved Monte-Carlo algorithms for radiation. This tool will also quantify the sensitivity of the CRE to the LES inputs (by varying optical properties, microphysics assumptions). In addition, this off-line radiative computation will provide guidance for a future implementation of an interactive 3D radiative code in the LES.

The combination of tuning tools and the new radiative metrics will increase our understanding of boundary-layer processes and associated clouds and help to disentangle the contribution of boundary-layer dynamics, microphysics, and 3D effects linked to both cloud geometry and angular effects. These new approaches will also allow us to propose and test new developments concerning in particular the representation of the boundary-layer dynamics, cloud characteristics and cloud radiative effect. In particular, we intend to test the added value of including a representation of the dry air intrusion around thermal plumes in the mass flux parameterizations, a representation of the subgrid vertical variability of clouds.

Beyond its use for the tuning and understanding of the particular parameterizations developed or tested here, it is really a new approach to climate model tuning which is explored in this project. Tuning is classically performed directly on the full model in which the dynamical core and parameterizations are assembled, using some statistics on the global simulated climate (latitudinal distribution of the SW and LW CRE for instance or a seasonal distribution of surface temperature or rainfall) as metrics. Internal parameters of parameterizations are often critical parameters for the full model but are generally poorly constrained by observations, especially at the global scale and often even not observable. The most uncertain of those parameters that affect most the radiation are generally used for tuning at global scale, but without much control on the way it is affecting the representation of clouds at process level. The proposed strategy consists in tuning parameterization in a LES/SCM framework 1/ to make a large part of the tuning at a process level based on dynamical, thermodynamical and energetic constraints, 2/ to provide the range of parameters value that can be used for the full 3D global model tuning (probably needed in any case, whatever the quality of the process-level tuning), and 3/ to identify where the process-level tuning is in conflict with the global model tuning.

This approach should help accelerate the process of model improvement, by clarifying the tuning process and providing efficient tools. The complementary and relevant expertise to be gathered in this project, as well as the availability of most of the tools required to achieve our main objectives, make us confident in our ability to make substantial progresses in the representation of boundary-layer clouds.

This project is not only the initiative of the people directly involved. It was identified as a priority during the international workshop on tuning (Hourdin et al. 2016) as well as by the DEPHY (Development and Evaluation of PHYsical parameterizations) community, a networking activity supported in France by the LEFE/IMAGO program and the environment ministry (MEEM[1]). This national-level funding allows regular meeting of the model development community and helps to identify priorities, share expertise and tools and reinforce collaborations between the various labs and community involved in the project. This networking activity has contributed to give a leading position to the French community in terms of development of original parameterizations for clouds and convection. The need to make a breakthrough by getting expertise from the Engineer science community for radiation and from applied mathematics to rationalize the work on parameterizations is issued from the brainstorming of this DEPHY network.



6. Scientific and technical work plan, project organisation:

6.1 Project structure and description:

The project is organized in 4 major tasks. Task 1 ensures the coordination of the project, while the three other tasks are devoted to the scientific questions and will deliver the main results.

Task 1- Project coordination

Task leader: **F. Couvreux**

Because the tasks are interconnected and because the expertise gathered in this project (expertise in applied mathematics, in radiation, in climate modelling and in physical process understanding) is varied, the scientific animation is crucial for the success of this project. In particular, each task involves at least two partners and there are, at least, one task leader from each partner.

The project coordinator, partner PIs and task leaders will form the project steering committee. This committee will be convened to assess the advancements of the project at least three time a year (by teleconference twice a year and concomitantly with the project meeting) and a status report, mentioning the main results, the difficulties encountered in the work progress will be established and provided to the

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[1] Ministery of Environment, Energy and Sea

participants of the project. The coordinator will represent the project in the ANR events (kick-off, workshops).

Formal project meetings will be organized on a yearly basis. They will be organized in Paris or in Toulouse. The 1st formal meeting will take place in Toulouse. All participants will be required as possible to physically participate to build a tight group since the beginning of the project despite the varied expertise. The time frame for each formal meeting is one full day plus half a day for the steering committee. Intermediate less formal meetings will take place in-between annual formal meeting concerning each scientific individual task. The last formal meeting will be the wrap up, within one month of completion of the project.

The HIGH-TUNE project activities will be promoted and coordinated within the DEPHY community.

This task is also in charge of the dissemination of the HIGH-TUNE results. Results of the project will be regularly presented to the parameterization development community during the course of the project, and in particular, the use of the tuning strategy at the process level will be promoted as an important tool for the development of parameterizations.

Deliverables:

- Kick-off meeting (M1.1)
- Project mailing list and web site (M1.2)
- Yearly Project reports (D1.3, D1.4)
- Project presentations at ANR workshops (D1.5)
- Final report (D1.6)

Mx: stands for milestones while Dx stands for deliverables

Task 2-Development and application of an automatic tuning strategy at the process scale:
Task leader: **F Hourdin**

The goal here is to propose and experience a new methodology to objectively determine the values of free parameters of the parameterizations of turbulence, convection and clouds, based on comparisons of single-column simulations using parameterized physics with explicit LES simulations of the same scenes. We will apply for this the 'history matching' approach developed by Williamson et al (2013) that consists in determining, in an iterative way, sets of values for these parameters that are Not Ruled Out Yet (NROY). At each iteration, one defines an acceptable set of values for a metric or set of metrics, and determines and removes the space of input parameters that fails to satisfy these constraints. Those parameter values are definitely ruled out. The following iteration will be done with other metrics, and will be used to reduce this NROY space. This method presents the advantage to avoid the need of defining priorities among the metrics and to completely avoid thinking in terms of optimization, limiting the risk of over-fitting. It will also provide a range of possible parameter values for a further tuning of the full climate model. The concept proof of application of history matching to SCM/LES tuning will be demonstrated with the LMDZ model before being tested on the CNRM models.

Some LES simulations are already available at the beginning of the project, which can be used to start working on tuning algorithms (this task) and radiation (Task 3). One important goal of the project however will be to rerun a series of LES on well documented cases of boundary-layer clouds with a new micro-physical scheme and to explore the sensitivity of these simulations to key model aspects (resolution, micro-physics, turbulence). Those simulations will be performed with Meso-NH (Lafore et al. 1998), the French community code for high to mesoscale simulations, equipped with tracers in order to sample the dynamical structures and compute exchange matrices on the vertical, and associated metrics. The sensitivity experiments will provide a tolerance to error for the various metrics accounting for known limitations of LES.

Beyond the determination of the acceptable ranges of parameter values, exploring the behaviour of the SCM within the parameter space will lead to a more comprehensive documentation and understanding of the parameterization behaviour. This tool will help distinguish between formulation choices and parameter tuning in a consistent way through a variety of boundary-layer cloud regimes. For some parameters, it may appear that the predefined range does not allow the model to satisfy all the metrics for all the chosen regimes. This will emphasize potential deficiencies of parameterizations and hopefully suggest new developments to be undertaken for further improving the representation of key cloud processes (Task 4).

Task 2.1: LES simulations

ANR Postdoc1, F Couvreux, R Honnert, F Favot, C Lac, B Vié

A series of LES will be performed for the 12 identified cases (see Table 1) that sample various conditions encountered over the globe: clear conditions, continental and oceanic cumulus clouds, stratocumulus, transition from stratocumulus to cumulus as well as initiation of deep convection, warm and mixed microphysics.

For each case, a reference simulation will be performed at the beginning of the project with a standard horizontal and vertical resolution (see Table 1), a 1-moment microphysic scheme, no subgrid condensation scheme and a 2nd order advection scheme for the dynamical variables. This series of simulations will be made available early in the project to be used for radiative computations and first tests of the tuning strategy. Sensitivity simulations to the horizontal and vertical resolution (finer/coarser resolution), size of the domain, advection scheme (a more efficient but less accurate scheme), existence of subgrid condensation and changing the microphysic scheme for a two-moment scheme LIMA (Vié et al, 2016; which also includes prognostic equations for particle number concentration and aerosols in addition to prognostic equations for mixing ratio) will then be performed. Those simulations will be run on the super-computer of Météo-France (the computing hours are already allocated, with about 72h of simulations for a 12 hours simulation with 500x500x200 grid points using 600 processors). Most of the cases correspond (in a more or less idealized way) to field campaign experiments whose observations will be used to assess the realism of the simulations, their set-up is already defined and some of them have already been run with Meso-NH but not with the exact same configuration.

In order to make the results available to the international community, we will develop a website where each individual case will be presented with the definition of the set-up and forcing as well as several diagnostics derived from the LES, similarly to http://gcss-dime.giss.nasa.gov. In addition, this website will be equipped from a tool of visualization in order to directly visualize the comparison of SCM runs with LES.

Case name	grid resolution dx=dy, dz (m, m)	Domain Lx=Ly, H (km, km)	Specificity	Radiation	Reference	Observations
Academic cases of dry convective boundary-layer						
AYOTTE-1	50, 40	10, 2	Strong capping inversion	No	Ayotte et al. 1996	No
AYOTTE-2	50, 40	10, 2	Weak capping inversion	No	Ayotte et al. 1996	No
Cases of clear sky continental convective boundary-layer						
IHOP	50, 40	10, 5	USA great plains	No	Couvreux et al., 2005	Yes
AMMA	50, 40	10, 5	Semi-arid, West-Africa	No	Canut et al., 2011	Yes
Boundary layer cumulus						
ARM	50, 40	13, 4	Continental shallow, USA	No	Brown et al., 2002	Yes
BOMEX	50, 40	13, 4	Oceanic shallow, Caraibes	No	Siebesma et al., 2003	Yes
RICO	50, 40	13, 4	Precipitating oceanic, Caraibes	No	Van Zanten et al., 2011	Yes
Marine strato-cumulus clouds						
FIRE	25, 5-15	5, 1.2	Day and Nighttime stratocumulus	Yes	Duynkerke et al. 2004	Yes
DYCOMS2	25, 5-15	5, 1.5	Stratocumulus	Yes	Stevens et al., 2005	Yes
ASTEX	25, 5-15	5, 2	Transition to cumulus, Atlantic	Yes	Van Der Dussen et al., 2013	Yes
GreyZone	250,25-90	100, 5	Transition to cumulus,North Sea	Yes	De Roode et al, in prep	Yes
Transition to deep convection						
AMMA	100, 50	100, 20	Niamey, initiation of local storm	No	Couvreux et al., 2012	Yes

Task 2.2: Metrics definition and tolerance

ANR Postdoc1, C Rio, F. Hourdin, F Couvreux, R Roehrig, R Honnert, E Bazile, P Marquet

The first approach to metrics definition will be to formalize implicit choices that were made in the past for the evaluation of the development of the parameterization with respect to LES simulations. The metrics will consists in: 1/ time evolution of the mean profiles of standard atmospheric state variables like wind, temperature, liquid potential temperature, total and condensed water but also profiles of turbulent fluxes (Reynolds stress). New variables will also be considered like moist entropy (Marquet, 2011). 2/ inner variables of the parameterizations such as the mean vertical wind in organized structures, surface coverage of thermal plumes, or lateral entrainment/detrainment rates of air into/from the plume, which can be computed with a sampling of the LES results (Couvreux et al. 2010). The subgrid scale variances could also be considered. 3/ exchange matrices (sometimes called transilient matrix: Stull 1991) on the vertical, which can be estimated by injecting idealized tracers in predefined vertical layers (typically of 100 to a few hundred meters deep) with a life time of a fraction to a few hours. Of course this metric requires injecting the same tracers in the LES and in the single-column model; 4/ cloud radiative effect which will be made available later on in the project thanks to the radiative computations presented in Task 3.

Beyond reference metrics value, the sensitivity experiments presented in Task 2.1 will be used to quantify the LES uncertainties and provide the tolerance around the mean metric value to be used in the tuning tool. As for the radiative metrics, a contribution of some model aspects (in particular microphysics description) to this tolerance will be computed thanks to the capability of the Monte-Carlo radiative code to compute the sensitivity of outputs to input parameters (including microphysics assumptions, see Task 3.3).

Task 2.3: Automatic tool to explore the sensitivity of SCM result to tuning parameters

ANR Postdoc2, MP Lefebvre, L Fairhead, F. Hourdin, R Roehrig, E Bazile, S Riette

The single column framework has become one standard benchmarking of new configurations of a climate model. To take the example of LMDZ, a new configuration of the model consists both in a new version of the Fortran source code of the model and a new set of values for the free parameters. All the free parameters which are currently used in model tuning are already stored in text files which are read by the model at the beginning of the 1D or 3D simulation. A script is already available that runs a series of 15 test cases (including some of the boundary-layer cases targeted in the HIGH-TUNE project) automatically. This script will have to be automatized one step further to take as input the set of parameter values generated automatically by an optimal sampling algorithm developed for history matching. The single column model is very fast. Numerical cost is not an issue: on a coreI7 processor, it takes typically 1second CPU to run one day with the current configuration using a 79-layer vertical grid.

More important will be the selection of the ensemble of parameters which will be used for tuning. The current practice at LMD, for the handy tuning of the full 3D climate model, is to use about 10 cloud related parameters. One important income of the automatic tools is to allow the exploration of a larger number of parameters, typically about 30. The free parameters concern in particular the mass flux parameterization of thermal plumes with the formulation of entrainment/detrainment rates (typically 4 parameters) and the equation of the updraft vertical velocity (2) (Rio et al. 2010), the prognostic equation of the turbulent kinetic energy, the formulation of turbulent fluxes or the definition of the mixing length (3-8), the statistical cloud scheme (3) (Jam et al. 2013) or the microphysics scheme (such as the threshold for conversion of liquid water to rain, 3-6), the definition of the optical properties of clouds used in the radiative parameterization (single scattering albedo, asymmetry factor or effective radius, 3-10) as well as in the representation of cloud-radiation interaction (overlap function, dependency on solar angle).

The generation of ensemble of simulations will be experienced first with LMDZ, and then with the CNRM models. It will be written in a generic way to be easily usable for other models, outside the project. For this, the forcing of the various cases and the output will follow a standard format under definition in the frame of the DEPHY project. For a model which follows this standard, the set-up of the SCM and the computation of the metrics from the output will be transparent. More specific will be the definition of the parameters to be changed and the way to read them in the model. But there also, the idea is to define a standard easy interface with any model. At the end, the only things to change in practice would be the list of input parameters (which are most often model dependant) and executable file of the model.

Task 2.4: Applying “history matching” to revisit previous tuning

ANR Postdoc2, D Williamson, I Musat, L Fairhead, A Jam, F. Hourdin, C. Rio, J Jouaud, R Roehrig, F Couvreux, Y Bouteloup

The development of the tuning tool is decomposed in three steps:
(i) identify metrics and associated tolerance and the set of free parameters (Task 2.1 and 2.2)
(ii) run many SCM runs (using the tools developed in 2.3) for each identified cases with varying values for the free parameters. For 30 parameters, we need to run about 300 simulations and this for each identified case, leading to a total of about 3000-4000 simulations.
(iii) develop an emulator for any chosen metric. The emulator is a fast statistical function with a few parameters that are fitted (using a Bayesian way) using the pool of SCM simulations. It also includes the estimation of uncertainties in addition to the prediction of the value of the metric for given values of the free parameters. We will probably need to develop one emulator for each metric and each case. Novel methods could also be introduced to share information across cases for the emulator, thus leading to many fewer simulations being needed.

This sequence will be experienced first to revisit the work done previously (and published) for LMDZ on the development of the thermal plume model and associated statistical cloud scheme. We will first apply the tuning on the non-cloudy cases to provide NROY for parameters involved in the representation of boundary-layer dynamics and then to cloudy cases. One question will be to know if compatible NROY are found for both the non-cloudy and cloudy cases within the tolerance issued form the LES sensitivity experiments.

A first meeting will be organized at T0+6 months to exchange between parameterization experts from LMDZ and CNRM team and tuning experts, and define more precisely the strategy and tools for the tuning. The work will require a long stay of Daniel Williamson at LMD and probably also a long-stay of the ANR Postdoc2 in Williamson’s team in order to increase the tuning expertise of the modelling team.

The experience gained with this first study with LMDZ will be communicated to the project through both a report and workshop, between month 12 and 18. This workshop may include a coding time to work simultaneously on the tuning of the LMDZ and CNRM models and directly exchange on methods and results, favouring capacity building.

Deliverables:

- Series of LES simulations (two stages : 6 months and 20 months) (M2.1, M2.2)
- Publication on LES uncertainties explored from the systematic sensitivity experiments (D2.3)
- Automatic tool for the realisation of thousands of simulations with varying values of free parameters usable for LMDZ and CNRM models (M2.4)
- Report and meeting on the use of history matching (D2.5)

Risk assessment:

Although the use of 'history matching' for LES/SCM tuning is completely new, we do not anticipate any technical barriers. The approach has already been applied to full 3D global model and it should be easier here because of the much smaller cost of SCM runs which could be rerun very easily in case of reconsidered strategy.

All the cases are well-defined in the literature and there are no identified difficulties for the realisation of all the LES simulations as well as the SCM runs, except for the computational cost needed for these simulations but which is already guaranteed.

Task 3-Quantify the 3D radiative impact of the clouds:

Task leader: **R Fournier**

The objectives of this task are threefold i/ to provide reference computations for the cloud radiative effect from LES outputs of the above mentioned cases, ii/ to assess the uncertainties associated to the reference models (LES + accurate off-line radiation) and iii/ to revisit the hypotheses at the basis of the rrepresentation of the cloud radiative effect in weather forecast and climate models.

We will perform 3D radiative computations using a state-of-the-art radiative code applied to the cloud scenes simulated with LES. The radiative code is based on a 3D Monte-Carlo algorithm performing a multiple-dimension integration over the space of multiple-scattering optical paths, the space of all shortwave or infrared frequencies, and the time interval corresponding to one timestep of the global model. This code has the advantage to also allow parameteric sensitivities. No additional sampling is required: only additional Monte Carlo weights are computed (which hardly increases the computation costs, Roger et al, 2005). Sensitivities to the uncertain parameters will therefore be evaluated without repeatedly running the code. A very similar code has already been designed for simulation of infrared radiation in combustion chambers (detailed gaseous radiation without scattering, Eymet et al. 2013) and for solar radiation in photobioreactors (multiple scattering in liquids, Dauchet et al. 2013). It was recently recoded using up-to-date open-source libraries to gather the best of today's engineering capacities as far as line-tracing and complex geometries are concerned. The new code has already been validated against reference 3D test cases for both longwave (Galtier et al. 2013) and shortwave radiation (intercomparison of cloud radiation, I3RC, http://i3rc.gsfc.nasa.gov/).

The main addressed infrared/shortwave radiative quantities will be the surface and top-of-atmosphere fluxes, as well as the vertical profile of cooling/heating rate. As we focus here on the cloud radiative effect, we will exactly need the difference between those quantities with the ones obtained without considering clouds. These quantities will be integrated over the whole surface of the simulated field. This defines an averaging process that we believe should be sufficient to simulate the averaging required at the scale of the grid of global models. In particular we expect the spatial statistics to be quasi-stationary as assumed during a 10-30 minute global-model time-step. Temporal integrations within such time interval will be used to assess this assumption, and potentially for compensating insufficient surface extension by temporal statistics (relying on an ergodicity assumption).

In such analysis, we will assume that 3D radiative transfer induces no uncertainty in itself: the uncertainties associated to radiative properties of droplets and gazes should be much lower than the uncertainties induced by the LES data themselves and Monte Carlo integration is “exact”, meaning that a reliable error-bar is systematically computed (and that no convergence difficulties should prevent us to lower it as much as required by increasing the sample size). So the uncertainties associated to the simulated radiative quantities will come from the input data (mainly the moments of the water droplet distribution) transfered through the Monte Carlo code.

Once they will be set up and interfaced with the LES data, all these tools will be readily available not only for the computation of metrics and tolerance around metrics but also for the evaluation of the global-model parameterisation assumptions, concerning the geometry of clouds (overlap, sub-cloud heterogeneities). This is a rigorous statement since data-representation and algorithm are fully orthogonal: unplugging the LES grid and plugging instead any simplified function of space is straightforward (a simple call to the function with no need to discretize it). We count on this flexibility to evaluate each of the parameterization assumptions using the very same radiative measures as those used to define the LES reference.

Along the project, we will gather other additional radiative data and tools. First, an inventory of radiative observations made during the field campaign associated to the selected cases will be realised. These will be used to assess the realism of the radiation outputs. The analysis of those data could help to identify the observational needs for the estimation of the cloud radiative effect in future field campaigns. Second, we will evaluate against the 12 cases, cloud emulators, which provide realistic 3D cloud scenes from vertical profiles of temperature, pressure, total water and liquid water (Szczap et al, 2014) and are often used to develop satellite algorithm and radiative parameterization (in particular in the formulation of subcolumns in radiative code such as in McICA; Barker et al. 2008).

Task 3.1 Apply 3D radiative code to LES outputs

ANR Postdoc3, R Fournier, S Blanco, M El Hafi, J Dauchet, ANR Postdoc 1 for the LES

The first step will concern the final adaptation to the LES context and evaluation of the 3D radiative code. To represent the spectral dependence of radiative properties throughout the whole spectrum, we will make use of tabulated solutions of Mie theory for spherical liquid droplets (together with their sensitivities to the parameters of the radius distribution) and k-distributions for gazes. The corresponding implementations and their validations will be easily performed: the code is indeed an upgraded version of an initial code that is still available and was carefully validated for both full-infrared and full-shortwave integrations (Dauchet et al. 2013; Eymet et al. 2013). The radiative transfer part of the code will be further tested on two monochromatic references cases involving stratocumulus and scattered shallow cumulus clouds (see phase II of I3RC).

We will then integrate the radiative computation over the whole spectrum and over time.
The main difficulty here is to build an efficient routine for the interface between the radiative code and the LES outputs. For this, we ask the realisation of an external service from engineers specialised in such code: for each sampled time and location, we need indeed to efficiently address a 10 Gbytes pool of data to get thermodynamic properties as predicted by the LES.

Task 3.2 Computation of 3D cloud radiative effects
ANR Postdoc3, F Szczap, R Fournier, J Dauchet
This task is dedicated to the application of the previously developed tool (Task 3.1) to all LES scenes of the cloudy cases (cases 5 to 12) to quantify the cloud radiative effects of the 3D cloud scene on top-of-atmosphere and surface fluxes and on heating/cooling rate mean profiles both in LW and SW radiation. In practice, at first, several periods of 20 min to 1 hour duration will be selected such as (i) appearance of cumulus clouds, (ii) development stage of cumulus, (iii) dissipation of cumulus, or (iv) stratocumulus, (v) broken stratocumulus. This will provide surface and top of the net radiative fluxes in both shortwave and longwave integrated at the horizontal scale of a global model. This will also provide parameteric sensitivities which are inherent products of this code without repeatedly running the code.

Task 3.3 Quantify uncertainties in the cloud radiative metrics
ANR Postdoc 3, S Blanco, M El Hafi, J Jouhaud, JB Madeleine, F Szczap, F Couvreux
In addition to the mean value of the above mentioned radiative metrics, we need to determine an uncertainty to be used in the SCM tuning procedure (Task 2.2). Here, the objective is a quantification of the sources associated to the LES itself. Theses sources will be translated into uncertainties of top-of-atmosphere and surface CRE, vertical profiles of the CRE on radiative cooling/heating rate. For the determination of these uncertainties, no additional sampling will be required: only additional Monte Carlo weights will have to be computed, which is very little expensive. The first uncertainty will be derived from the used as inputs of the different sensitivity simulations realised in Task 2.1. The leading uncertainties are expected to be those associated to the moments of the water droplet distribution, but the procedure will allow all types of parametric studies, including field sensitivities if some of the uncertainties of LES predictions can be synthesized as functional patterns. The second one concerns the uncertainties associated to the radiative properties of clouds (optical properties such as extinction, absorption, and phase function). The sensitivity to the resolution carried out in Task 2.1 will also allow to analyse if in the reference LES, most of the turbulence/radiation interactions are correctly captured.

Task 3.4 Exploring the structural uncertainties of global model plan parallel radiative computations.
ANR Postdoc 3, R Fournier, S Blanco, JL Dufresne
The uncertainty quantification described above concerns the metrics to be used during the automatic tuning of the free parameters of the SCM. In addition to this, the availability of the Monte-Carlo code will offer the possibility to address directly some key issues concerning the representation of the radiative effect of clouds in large-scale models. Those “structural uncertainties” are of two types: the one associated to the representation of the 4D variability of the clouds in 1D and the one associated to the relatively coarse radiative parameterization used in global models. To disentangle the impact of both, we will first coarse-grain the LES (modification of the vertical and horizontal resolution, simplification of the cloud distribution) and apply the 3D radiative code to this modified field. This will provide some guidance of the importance of subgrid horizontal and vertical variability as well as guidance for the overlap formulation, namely revisiting the hypotheses concerning the 3D cloud geometry in the radiative code under plan parallel assumption. This task has therefore strong links with Task 4.3. In a second time we could run the radiative code of the global model off-line also to this modified field in order to assess the second uncertainty.

Task 3.5 Importance of 3D radiative effects for LES
R Fournier, S Blanco, J Dauchet, M El Hafi, F Couvreux
All the reference cases will be rerun with an interactive 1D radiation code and the radiative outputs will be compared to the results provided by the 3D radiative code for given times. This will provide a first estimate of the main errors linked to the use of a too simplistic radiation code in the LES. We will also analyse how this error varies among cloud types. This will provide some guidance on the best way to represent 3D radiative effects in the LES. Several approaches will be considered, the use of Discrete Ordinate Methods on

a coarser grid, or the development of a parameterization based on the Monte-Carlo code to focus on the radiative fields at the surface.

Deliverables:

- 3D radiative code with an interface that reads efficiently 4D (3D+time) data available for the community (M3.1)
- 3D visualisation of cloud scenes for each individual case (M3.2)
- Publication on the temporally, geometrically and spectrally integration of the radiation for LES-clouds (D3.3)
- Estimation of the 3D radiative effect at different horizontal scales from the LES to the global model (report or publication, D3.4)
- Estimation of the uncertainties in radiative computation (M3.5)

Risk assessment:

Application of radiative code taking into account 4D spatial and temporal variability of realistic cloud scenes has never been done and therefore presents a risk. However, this code has already been tested and validated on academic cases for both the SW and LW spectra.

No interface with the 3D LES outputs exists however a similar code has already been developed for combustion applications. So there seems to be no strong technical limitations. This is a fundamental step in order to be able to efficiently access to a very large amount of data.

Task 4-Development of parameterizations involved in the representation of boundary-layer clouds:

Task leader: **C Rio**

This task strongly relies on Tasks 2 and 3. The goal here is to propose and test new developments on the representation of the boundary-layer clouds. These developments are structured along three main ingredients, keys for their representation in global models: boundary-layer dynamics, cloud macrophysics and microphysics, and radiative effects. For each ingredient, we will both (i) analyse the results of the tuning framework developed in Task 2 including the CRE metrics of Task 3 and (ii) propose and test new developments. The tuning framework provides a novel and systematic way to comprehensively document and understand the behaviour of a suite of parameterizations in various boundary layer regimes and within their parameter space. It will emphasize some of the potential deficiencies of parameterizations and suggest new paths to follow to further improve the representation of key cloud processes. In particular, the tuning tool will identify free parameters that are strongly correlated. This may require a revision of some aspects of parameterization formulations to better take into account the processes involved. The tuning tool will also help identify the most uncertain parameters for which formulations need to be revisited. The present project will try to develop or suggest new ways for representing these parameters, introducing for instance some dependency to parameterization internal variables or to the large-scale state variables. If for a given parameter, optimized values are too close to the boundaries of the accepted physical range, this will highlight important deficiencies of the parameterization. The a-priori parameterization developments proposed below tackle (i) the revisit of fundamental assumptions used in turbulence schemes or in cloud vertical overlap and (ii) the assessment of the consistency of the results for a large panel of boundary-layer regimes (covered by the 12 different cases of the project, Task 2.1), and (iii) new developments such as the introduction of boundary-layer top-down coherent features, the representation of the subgrid vertical and horizontal variability of cloud properties, and the dependency of cloud radiative effects on the solar zenith angle. These improvements will be tested systematically in 3D climate simulations, in which several aspects of cloud properties, including their radiative effects can be estimated at the global scale using satellite observations.

Task 4.1 Parameterization of boundary-layer dynamics

ANR Postdoc, F Couvreux, R Honnert,F Hourdin, P Marquet, C Rio, E Bazile

The systematic exploration of the parameter space (Task 2.4) of the current sets of parameterizations involved in the project will provide some answers of long-standing questions regarding the determination of the parameters involved in the formulation of lateral entrainment/detrainment rates and vertical acceleration within the thermal plume (Task 2.3).

The present subtask will also revisit some aspects of currently-used parameterizations and develop new ways of representing important features of the boundary-layer dynamics. Namely, we will:

(i) analyse the Lewis number in the ensemble of LES simulations performed in Task 2.1. This number is the ratio of exchange turbulent coefficients for heat and humidity and is assumed to be equal to 1 in all current turbulent schemes, including those used in the French models involved in the project. If it is found to depart from 1, we will analyse the implications and derive a new set of equations for parameterizing turbulence.
(ii) test the impact of newly-introduced equations for representing the total turbulent energy budget in the ARPEGE/AROME turbulent scheme on the development of convective boundary layers for the 12 cases of this project. This total turbulent energy is the sum of the turbulent kinetic energy and the turbulent potential energy (Mauritsen et al, 2007; Zilitinkevitch et al, 2013) and its introduction is aimed at improving stable boundary layers. It remains unclear how it can impact convective boundary layers.
(iii) develop and introduce a new representation of top-down coherent features (e.g. dry air intrusion: Couvreux et al. 2007), thought to play an important role in the boundary-layer dynamics and clouds. To our knowledge, no parameterization has been yet developed for representing such features. It will be based on a mass-flux approach and we will quantify their impact on the boundary-layer dynamics, especially in terms of water vapour transport.
(iv) revisit the coupling of the mass-flux scheme with the turbulent kinetic energy prognostic equation: the kinetic energy, created by shear of vertical wind on the frontiers of the thermal plume can be transported by the mass-flux scheme. In turn, it can contribute to the mixing between thermal plumes and their environment.

Task 4.2 Parameterization of cloud macro and micro-physics

J Jouhaud, J.B. Madeleine, J.L. Dufresne, S Riette

The tuning tool (Task 2.4) will first help us to identify the most uncertain parameters and limitations of the statistical cloud scheme (macrophysics). It will also reveal the sensitivity of the SCM to microphysical parameters (see Task 2.3) and will allow us to understand the impact of microphysical assumptions on SCM radiative calculations. The set of LES performed in Task 2.1 will provide a unique dataset to comprehensively assess the subgrid-scale distribution of various macrophysical (e.g., liquid water) as well as microphysical (e.g. droplet sizes) properties in boundary-layer clouds. Based on these results, we will improve the existing parameterizations and assess the sensitivity of the SCM results to these new developments. These include:
(i) the inclusion of the cloud vertical subgrid-scale heterogeneity. Currently in the French models (as in most large-scale models), only the cloud horizontal subgrid-scale variability of the liquid water is taken into account. The calculation of cloud fraction based on the bi-gaussian statistical cloud scheme (Jam et al. 2013) will therefore be improved. These developments are already underway as part of a thesis by J. Jouhaud (supervised by J.-L Dufresne and J.-B. Madeleine). The vertical variability will modify the relationship between cloud fraction and water content as well as cloud radiative effects.
(ii) the introduction of subgrid-scale variability of rain. For instance, in the case of stratocumulus, precipitation or drizzle often occurs in a subdomain of the cloud. Accounting for a subpart of the cloud in evaporation and collection processes therefore impacts on the whole precipitation and cloud dynamics. This development will request a revisit of liquid-water-to-rain autoconversion rate parameters, for which the tuning tool is well adapted.

Task 4.3 Parameterization of cloud effect on radiation

J.L. Dufresne, Y Bouteloup, F Hourdin, I Musat, R Roehrig

The tuning framework of Task 2 will highlight most critical parameters involved in the representation of cloud-radiation interactions. Because of their importance for climate, new metrics dedicated to assess cloud radiative effects (Task 3.2) on surface and top-of-atmosphere budgets and on atmospheric heating, both in the solar short-wave and thermal long-wave spectral ranges, will be added along the tuning process. Based on the work done in Task 3.4, we will use progressive coarse-graining (vertical and horizontal) of LES input to the 3D radiative code to assess the 3D radiative impacts from complex (LES) to more simple (global model) cloud distributions. This will provide guidance for further developments required to an appropriate representation of cloud radiation effects.
Task 2 and 3 will thus help in the following parameterization developments:
(i) the inclusion of subgrid distribution of cloud liquid water and other cloud parameters, evaluated against the set of LES, in the calculation of subgrid-scale heterogeneities of cloud radiative properties, developing thus a regime-dependence of the classical constant heterogeneity numbers currently used in global models.
(ii) the use of the independent column approximation framework and the implementation of heterogeneities

in cloud layer properties among sub-columns
(iii) the dependency of cloud radiative effects on the solar zenith angle
(iv) the improvement of overlap assumptions and introduction of a decorrelation length, as well as the dependency on vertical wind shear.

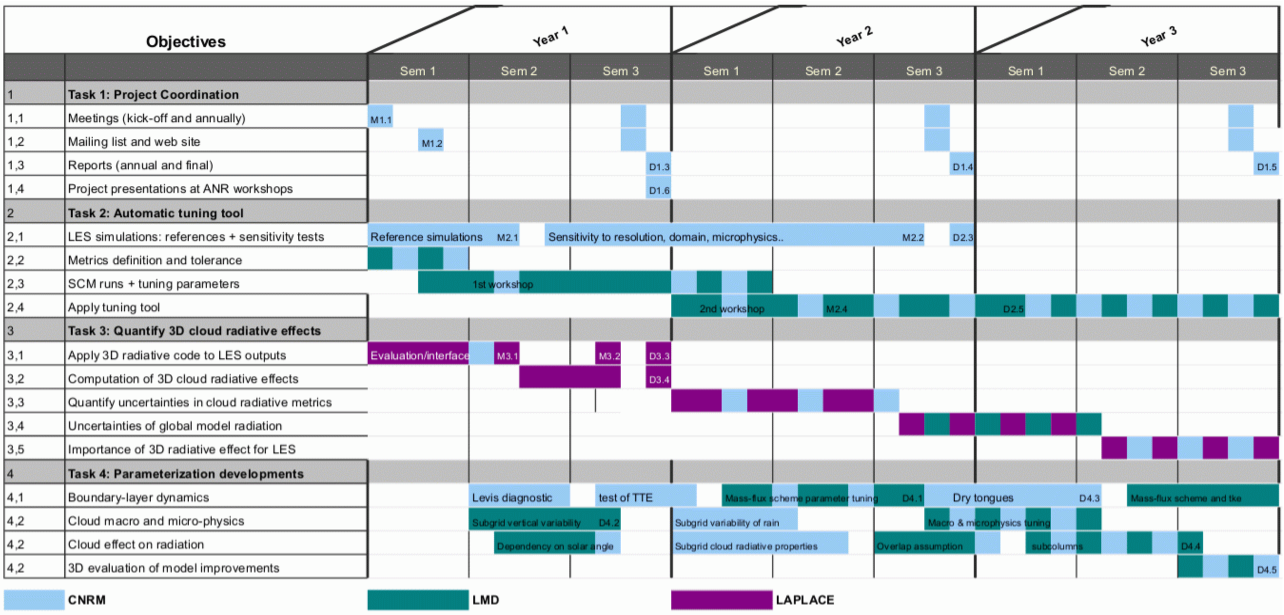
Task 4.4 3D evaluation of the model improvements
F. Chéruy, I Musat, D Bouniol, F Guichard, R Roehrig
Even if the systematic use of a comprehensive ensemble of 12 boundary-layer cloud regimes in an SCM/LES framework to develop and assess global model physics is so far unique in the community, it remains a small sample for evaluating the behaviour of model physics all over the globe. As 1D and 3D models share the same fortran source files and same definition of input parameters, parameterization improvements as well as the optimized parameter ranges resulting from Task 2, are of immediate use in global model 3D configuration. The added value of parameterization developments and tuning will thus be evaluated all along the project, as often as possible. The expertise on model/observation comparison is very strong in the proposing team (Roehrig et al, 2013, Chéruy et al, 2013, Couvreux et al, 2014, Konsta et al, 2016). 3D model outputs will be compared to observations with two focuses:
(i) Evaluate the simulated 3D cloud structures against observations derived from the CALIOP Lidar and Cloudsat Radar on-board satellites of the A-Train constellation. These satellites provide now and for the first time details of 3D cloud structure at the global scale (Konsta et al, 2016). The French models involved in the project are already equipped with simulators of such observations, through the COSP software.
(ii) Evaluate cloud radiative effects and boundary-layer properties using site observations, both at SIRTA (nearby Paris, Haeffelin et al, 2015) and in the Sahel (AMMA-catch network). This site evaluation will make use of nudged experiments in which model dynamics is relaxed toward the model dynamics of a reference, such as operational weather forecast analyses or reanalyses. By doing so, the comparison with observations can be done on a day-to-day basis, benefiting from high-frequency almost continuous measurements of radiative and turbulent fluxes at the surface. The SIRTA site also provides long-term monitoring of the atmospheric column via notably active and passive remote sensors.
Beyond its role of benchmarking new developments and tuning strategy proposed in the project, this a-posteriori evaluation will help to start answering two important questions with regards to climate modelling and model tuning: (i) is it possible to tune a climate model based only on the process-oriented strategy proposed in Task 2, or is the tuning step of the model global energetics still crucial? (ii) to which degree the climate sensitivity (amplitude of the global warming in response to a given radiative forcing) can vary using the same model but with various set of free parameters that fulfil the criteria retained at the process-level tuning?

Deliverables:

- Publication on the revisit of the thermal plume model with 'history matching' approach (D4.1)
- Publication on the impact of the representation of the subgrid vertical cloud distribution (D4.2)
- Report or publication on the impact of the introduction of the dry air intrusion in the mass-flux scheme (D4.3)
- Report on the impact of different improvements in the representation of cloud-radiation interactions (D4.4)
- Report on the added value of parameterization development and tuning in the 3D configuration of the model involved in the project (D4.5)

Risk assessment:
As for any parameterization development, there are some risks: first, parameterization development is a long-time effort and the developments may take longer than expected; then, the expected results may be disappointing asking for further work. However, some developments are already underway and show promising results. Also, we expect that the tuning tool proposed in this project will provide an essential tool in the parameterization development allowing a better understanding of the behaviour of a given parametrization.
For the 3D evaluation, there is no risk. This is currently done for each main version of the climate models.

6.2 Quicklook of Project activity timeline



	Objectives	Year 1 (Sem 1, Sem 2, Sem 3)	Year 2 (Sem 1, Sem 2, Sem 3)	Year 3 (Sem 1, Sem 2, Sem 3)
1	**Task 1: Project Coordination**			
1,1	Meetings (kick-off and annually)	M1.1		
1,2	Mailing list and web site	M1.2		
1,3	Reports (annual and final)	D1.3	D1.4	D1.5
1,4	Project presentations at ANR workshops	D1.6		
2	**Task 2: Automatic tuning tool**			
2,1	LES simulations: references + sensitivity tests	Reference simulations M2.1 Sensitivity to resolution, domain, microphysics..	M2.2 D2.3	
2,2	Metrics definition and tolerance			
2,3	SCM runs + tuning parameters	1st workshop		
2,4	Apply tuning tool		2nd workshop M2.4	D2.5
3	**Task 3: Quantify 3D cloud radiative effects**			
3,1	Apply 3D radiative code to LES outputs	Evaluation/interface M3.1 M3.2 D3.3		
3,2	Computation of 3D cloud radiative effects	D3.4		
3,3	Quantify uncertainties in cloud radiative metrics			
3,4	Uncertainties of global model radiation			
3,5	Importance of 3D radiative effect for LES			
4	**Task 4: Parameterization developments**			
4,1	Boundary-layer dynamics	Levis diagnostic test of TTE	Mass-flux scheme parameter tuning D4.1	Dry tongues D4.3 Mass-flux scheme and tke
4,2	Cloud macro and micro-physics	Subgrid vertical variability D4.2	Subgrid variability of rain Macro & microphysics tuning	
4,2	Cloud effect on radiation	Dependency on solar angle	Subgrid cloud radiative properties Overlap assumption	subcolumns D4.4
4,2	3D evaluation of model improvements			D4.5

🟦 **CNRM** 🟩 **LMD** 🟪 **LAPLACE**

6.3 Complementarity of the consortium:

The consortium includes three different partners:

Partner 1: CNRM: The Centre National de Recherches Météorologiques (CNRM) at Toulouse is a joint laboratory of Météo-France and CNRS (UMR3589). It has a recognized expertise in atmospheric modelling, in terms of meteorological weather forecast and climate prediction as well as physical processes understanding and parameterizations. The Meso-NH research model, conjointly developed by CNRM and the Laboratoire d'aérologie, is widely used in the mesoscale process studies carried out by the lab, including for carrying out Large-Eddy Simulation (LES) of boundary layer and clouds. The CNRM is also in charge of the development of the Météo-France model suite (AROME, ARPEGE) used for operational meteorological forecasts and climate model predictions.

Partner 2: IPSL/LMD: Laboratoire de Météorologie Dynamique (UMR8539 CNRS/IPSL/UPMC/X/ENS) is a leading laboratory in the theory, observation and numerical modelling of atmospheric dynamics and physics. It has a strong expertise in atmospheric radiation, in particular for remote sensing and numerical modelling of other planetary atmospheres. The team involved in the project, hosted by University Pierre et Marie Curie (UPMC), is in charge of the development of the general circulation model LMDZ, the atmospheric component of the coupled ocean-atmosphere model and Earth-System-Model of Institut Pierre Simon Laplace (IPSL). The activity around LMDZ is characterized by a long term investment on the physical parameterizations of boundary layer processes, convection and clouds and their role in the uncertainties and confidence in climate change projections.

Partner 3: LAPLACE: Laboratoire PLAsma and Conversion d'Energie (UMR5213/UPS/INP) is the first French concentration of research in the field of Electrical Engineering and Plasma nationally with 160 fulltime researchers and a similar number of PhD students and postdocs. Within LAPLACE, the research activities of GREPHE (Groupe de Recherche Energétique, Plasma et Hors-Equilibre) lie at the interface between engineering, physics and fundamental; technological issues are also addressed. Most of the physical systems that are studied are non-equilibrium or far from equilibrium. Modelling and simulation are an essential part of the group's activities and the group has developed an expertise in the modelling of non equilibrium plasmas (for a wide variety of applications) and radiation transport.

The collaborations among the different partners are already active as highlighted in the list of references. Two of the three partners (IPSL/LMD and CNRM) have been working together for more than a decade now. This fruitful and ongoing collaboration already resulted in (i) many developments of the boundary-layer parameterizations in the French models with in particular a new paradigm for the representation of convective boundary layers and (ii) new methodologies to assess parameterizations using advanced comparisons between SCM simulations and LES. The project heavily relies on those pioneer works. The link between the LMD team and LAPLACE team is also well established and resulted in particular in the development of radiative transfer codes for the atmospheres of planets Mars and Venus. The link with Daniel Williamson from Exeter University (an attached scientist to IPSL/LMD) has been established through an international workshop on tuning that occurs last year. HIGH-TUNE will contribute to reinforce the international efforts around the tuning issue.

6.4 Curriculum of most involved persons:

Fleur Couvreux, 38-year old, ICPEF at Météo-France (CNRM, Toulouse, France). Researcher with expertise in observations, high-resolution modelling and parameterization of atmospheric physical processes in particular boundary-layer processes. She has a long experience in comparing SCM versions of global models with LES. 35 publications in peer-reviewed rank A journals- Full list available at http://www.cnrm-game-meteo.fr/spip.php?article502&lang=fr. She has been involved in eight national and European projects and has been a task leader in several of them. For instance, she recently coordinated an international intercomparison of climate models on a case of diurnal cycle of convection over the Sahel endorsed by the European EMBRACE project. She is also currently coordinating the LES intercomparison for the GABLS4[2] exercise, based on a boundary-layer case with very stable conditions. She mentored 5 PhD students (among them, two ongoing) and 3 post-doctoral research scientists.

Frédéric Hourdin, 50-year old, CNRS (DR1), deputy head of LMD. Researcher with expertise in climate modelling in : *i*) Study and numerical modeling of the general circulation of planetary atmospheres (the Earth, Mars, Titan, Venus), *ii*) Coupling between atmospheric dynamics, chemistry and haze micro-physics on Titan, *iii*) Numerical modelling of the Earth climate and climate change; *iv*) Numerical modelling of the advection of atmospheric trace species, *v*) Inversion of atmospheric transport, Parameterization of the atmospheric boundary-layer and associated clouds; *vi*) Parameterization of pyro-convection, *vii*) West African climate. He is coordinating the development of the LMDZ climate model, the atmospheric component of the IPSL Earth System Model. Involved in the organization of several national and international projects (AMMA, ACASIS, ESCAPE). At the origin of the DEPHY networking activity and of the 2014 international workshop on model tuning. 79 publications in peer-reviewed rank A journals, h-index 33. Publications available at http://www.lmd.jussieu.fr/~hourdin/publis

Richard Fournier, 50-year old, professor at University Paul Sabatier and researcher at LAPLACE-GREPHE (Research Group in Energetics, Plasma and Non-Equilibrium Phenomena). He focuses on the statistical approaches to complex-systems engineering, for energetic, atmospheric and biological applications. Together with Mouna El Hafi (Mines Albi), and in collaboration with Meso-Star (http://www.meso-star.com), he animates the EDStar Plateform that makes available to engineers a set of open-source libraries inheriting of recent statistical-physics and computer-graphics advances (http://edstar.lmd.jussieu.fr/). He also animates the axe "Approche statistique du rayonnement" of the GDR ACCORT, federating Thermal Radiation research at the national scale (http://www.gdr-accort.cnrs.fr). 55 publications in peer-reviewed international journals.

Jean-Louis Dufresne, 55-year old, senior scientist (DR1) at CNRS, LMD, head of the IPSL Climate Modelling Centre since 2009, deputy director of IPSL since 2010. He has 20 years research experience in coupled global climate modelling, climate change, cloud evaluation, climate feedback analysis and radiative transfer computation. Since 2004, he is involved in the major European projects that contribute to the development of climate models: ENSEMBLES (2004-2009), COMBINE (2009-2013) and EMBRACE (2011-2015). He contributed to bout 80 publications in peer-reviewed journals, acts as Lead Author in the Working Group-1 of the IPCC-AR5, h-index 32

Romain Roehrig, 34-year old, IPEF at Météo-France (CNRM, Toulouse, France) is conducting research in climate modelling, parameterizations of atmospheric moist processes (convection, clouds) and West African monsoon dynamics. He is currently contributing to the development and evaluation of the atmospheric component of the CNRM global and regional climate models. He is involved in several European and national projects, which targets climate model improvements (e.g., FP7-EUCLIPSE, FP7-EMBRACE, ANR-REMEMBER, LEFE-DEPHY2), in some of which he is having task leadership. He has contributed to 18

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[2] GEWEX Atmospheric Boundary-Layer Studies : 4th intercomparison case: *http://www.cnrm.meteo.fr/aladin/meshtml/GABLS4/GABLS4.html*

publications in peer-reviewed rank A journals and mentored 4 PhD (among them, three ongoing) and 4 post-doctoral fellows.

Catherine Rio, 36-year old, CR1 at Météo-France (CNRM, Toulouse, France). Researcher with expertise in the development of parameterizations of convective processes in climate models. In particular, she has been strongly involved in the development of the thermal plume model in the LMDZ model and its coupling with the deep convection scheme. She was awarded the WCRP/WWRP International Prize for Model Development 2015 (http://www.wcrp-climate.org/resources-room/wcrp-news/739-international-prize-model-development-2015). 20 publications in peer-reviewed international journals.

6.5 Project budget summary:

PARTNER 1: CNRM – Total requested grant:213 k€

- Staff:

CDD scientist – Task 3 & 4 (years 1-2-3: 27 months; 3-5 year of experience level)	136354
Gratification for 1 Master 2 these (year 2; 6 months)	3000
total:	139354

rationale for CDD scientist:

The Postdoc will be involved in the realisation of the various LES including the reference cases as well as the different sensitivity tests (to resolution, domain, turbulence parameterization and microphysics parameterizations). He/she will be the correspondent when developing the efficient interface with the radiative code. He/she will also help in the development of the introduction of the dry air intrusions in the mass-flux framework.

- Operating costs:

External service for the realisation of an interface between the radiative code and the LES outputs	40000
Project meetings (Paris, years 1, 3 – 5 pers each meeting, 1 day)	6000
Participation of the coordinator to the ANR events (France; years 1,3: 1 day, 1 pers)	1000
Attendance of a CNRM scientist to the following international conferences during the project (BLT, Radiation) (OutsideEurope, years 1,2,3, 5 days)	8000
3 disks of 4 Tbytes for LES simulations	1500
Computer (1 workstation for CDD scientist)	1500
total:	58000

rationale for the need for the external service:

The interface between the radiative code and the LES outputs is a key element and has to be designed efficiently in order not to strongly increase the computational cost, this will be realised by engineers specialised in such code.

PARTNER 2: LMD- Total requested grant:156 k€

- Staff

CDD scientist – Task 2 (years 1-2, 21 months, 3-5 year of experience level)	109284

rationale for CDD scientist:

The Postdoc will be involved in the development of the tuning tool for the LMDZ model. He will strongly interact with Daniel Williamson, who developed the 'history matching' theory.

- Operating costs:

Project meetings (Toulouse, years 1(kick-off),2- 5 pers each meeting, 1 day)	6000
Visit of D Williamson in France and of the postdoc to Williamson's team	24600
Publication costs, incl. Open Acess (1 papers)	1000
total:	31600

rationale for the visit of Daniel Williamson:

Various visits of Daniel Williamson will be organised at LMD during the development stage of the tuning tool at the process level as this is the first time that this method will be applied for SCM simulations. A workshop will be organised during his stay in France in order for the people involved in the development of the French models to benefit from his experience and be trained on the use of the different statistical tools.

PARTNER 3 LAPLACE- Total requested grant:67k€

-Staff:

CDD scientist- Task 3 (year 1, 11 months, 3-5 year of experience level)	55030

rationale for CDD scientist:

The Postdoc will be involved in the computation of the 3D cloud radiative effects for the reference cases and will also quantify the associated uncertainties.

Operating costs:

Other expenses:

Project meetings (Paris, 3 pers, years 1,3 each meeting, 1 day)	3600
Mission Toulouse/Clermont-Ferrand	2000
1 publication	1000
total:	6600

Other financial and logistical support contributions obtained:

- still-18 months PhD student (J Jouhaud) already funded on the representation of the subgrid distribution of the clouds in LMDZ
- 1000khours on fast computer of Meteo-France for the high-resolution simulations

The cost of 3D weather forecast and climate simulation is not relevant here since the simulations will be performed in the standard cycles of models improvement/evaluations in each center.

7. Strategy for valorisation, global impacts of the proposal:

Boundary-layer clouds dominate the spread of the Earth system response to increasing greenhouse gazes as simulated by climate models. By improving the parameterizations involved in the representation of these clouds, this project will increase our confidence in climate projections on long time scales. The project thus contributes to three research lines of the first major societal challenge *"Efficient resource management and adaptation to climate change"* of the call: (i) *understanding the climate system through (ii) a better representation of the physical processes at play and (iii) the reduction of the main biases and uncertainties of the climate models.* It will also contribute to the initiative 'Towards more reliable models' included in the challenge *"Clouds, circulation and climate sensitivity"*, one of the five "grand challenges" identified by the WCRP[3]. Formalizing the tuning has been recognized recently as a key issue in climate modelling, motivating a specific international workshop in October 2014 endorsed by the WCRP-WGCM[4] and co-leaded by a member of the team (Hourdin et al 2016). The present project is a promising contribution to this very important issue. In particular, it offers a methodology to articulate tuning at the parameterization level, with the final (needed) tuning of global climate models. This project can be thought as a proof of concept of such innovative tuning strategy and its use in the development of parameterizations.

New tools and cases for the community: The 3D radiative code as well as an interface capable of reading efficiently 4D (3D+time) fields will be available freely to the international community. The different case studies with their associated set-up and the main outputs of the high-resolution simulations, in particular the different model-parametrization-oriented diagnostics derived in Task 2, will be available to the international community through a dedicated website. The development and promotion of a tuning strategy at a process-scale will be promoted via a dedicated workshop. If conclusive, this tool could then be applied on any set of parametrizations. In addition to providing the range of acceptable values for the free parameters, it is also an interesting tool that allows a better understanding of the behaviour of a given parametrization. This tool may prove to be an essential ingredient in the development of parametrization. In particular, it offers a methodology to articulate tuning at the parametrization level, with the final (needed) tuning of global climate models. This project can be thought as a proof of concept of such innovative tuning strategy and its use in the development of parametrizations.

Scientific communications: The HIGH-TUNE results will be presented in dedicated scientific international conferences as well as disseminated via the annual meeting of the DEPHY community. The main outcomes of the project will be published in peer-reviewed articles. The website will also strongly contribute to the dissemination of the HIGH-TUNE results. Finally, the recent developments in the radiative code used in this project were performed by heat-transfer engineers that were strongly inspired by computer-graphics research.

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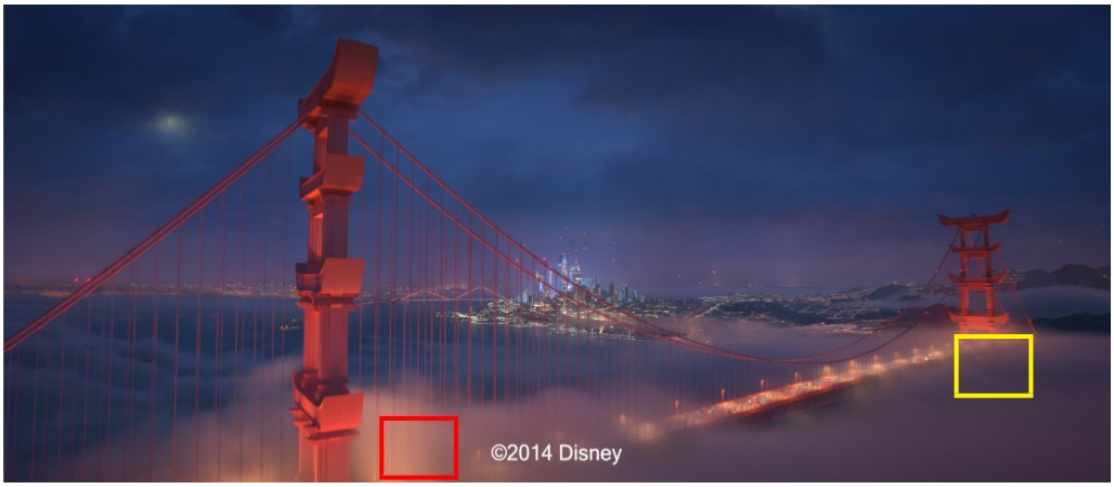
[3] WCRP: World Climate Research Programme

[4] WCRP-WGCM is the working group on coupled modeling from the World Climate Research Programme

Moreover, these advances have inspired in turn the cutting-edge developments in the most demanding graphical industry (Walt Disney Animation Studios, see the figure below) in order to get a visually accurate representation of clouds. Applied to each of the project cloud scenes, those representations are themselves of scientific value as they provide dynamical visual counterparts (movies) to the huge amount of LES 4D numerical outputs.



Socio-economic benefits: This project will contribute with direct parameterization improvements in the Numerical Weather Prediction and climate models of IPSL and Météo-France. Those climate models are among the 15-20 “CMIP-class” models that contribute regularly to the international comparison exercises and produce climate change projections made available to the international community. Those simulations serve as a basis for many studies, concerning the evolution of the climate under global warming and the anticipation of socio-economic impacts of those climate changes. The studies performed from these CMIP climate projections constitute a large part of the publications synthesized in the IPCC reports, that are further used by politics to discuss mitigations at an international level in Conference of Parties (COP) and anticipate adaptation strategies. This project will contribute to reduce the persistent biases in the surface energy balance that limit the ability of current numerical models to provide reliable and useful forecasts at daily, monthly, seasonal and interannual timescales. This is particularly important for agrometeorology, electrical production or air quality applications as well as the emerging climate services.

Education and training: Climate modelling is a hybrid domain which combines High Performance Computing, numerical issues for global hydrodynamical cores, highly uncertain process representation, complexity of the number of components and processes coupled together and chaos of the simulated solution. This is an ongoing research and a domain which still needs to be built or formalized. The fact that tuning was not considered so far as a real scientific question in the community of climate modelers, and that it was often even hidden in the model description despite its central role in model performances is one of the main illustrations of this. And of course, teaching is central if wanting to build this hybrid science, for dissemination but also just for formalization of the question itself. This will be promoted in particular in the Master 2 UMPC/OCAOS modelling course, leaded by F. Hourdin and in the Master 2 OASC/UPS, as well as in series of doctoral schools on modelling co-organized by F. Hourdin. The code evaluating spectrally and temporally integrated 3D radiation is open-source and will be documented and distributed to the community via the EDStar platform (http://edstar.lmd.jussieu.fr/). In the next two years, the platform will be extended with a set of e-learning tools concerning statistical-engineering of complex systems (project accepted in phase 2 of Contrat de collaboration Laboratoire-Entreprise, CLE-2016). The IR3C cloud-simulation examples of Task 3.1 will be made interactive and included to this set.

8 References:

In the list of references below we have highlighted in blue persons from the CNRM Partner, in turquoise persons from the LMD Partner and in purple persons from the LAPLACE Partner.

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