MCG-Rad: Monte-Carlo Global Radiative Forcings Computation

I. Pre-proposal's context, positioning and objectives

Radiative exchanges are the primary drivers of climate and climate changes. An accurate computation of the radiative flux is thus a necessary step for many scientific studies on climate change. For instance, radiative forcing is a metric which allows to estimate and to compare the amplitude of the various natural and anthropogenic perturbations on climate. Global indexes which are used for international negotiations such as the follow-up of the Paris agreement on climate change are also based on radiative forcing estimates. However, computing radiative exchanges at global scale with a reference model is a challenge that has still not be met. There are two major difficulties: first, the spectral dependence of gas properties for which absorption and emission is made by a large number (millions) of very sharp gas absorption lines; second, the interaction of the radiation emitted by gas with the complex and evolving 3D structure of clouds and aerosols.

The usual method to estimate radiative forcings and more generally radiative flux at the global scale is a multi step approach. Firstly the monochromatic radiative properties are computed using spectral data base. Secondly these properties are used by line-by-line models to compute the radiative exchanges for an ensemble of representative atmospheric profiles. These models are very expensive to run but provide results which are considered as references. Thirdly more simplified and less expensive models (narrow band or broad band models) are elaborated and validated against these reference results. Finally these models are used to compute the radiative exchanges and the radiative forcings at the global scale by a 4 dimensional integration (1 time and 3 space dimensions).

This approach as several limitations. The adjustment and validation of these simplified models is demanding, made only from time to time, creating a delay of several years between the improvement of a spectral database and its use for radiative forcings estimate. This validation is based on a sample of a few atmospheric profiles (one to a few tens), which is sufficient for clear sky conditions but questionable for cloudy conditions. Computation of radiative forcing for a large number of gases by changing the concentration of each gases individually requires a large amount of simulations.

The overarching objective of this project is to develop and implemented innovative Monte Carlo methods to accurately estimate the radiative flux and radiative forcings with a reference model that directly uses molecular-transition database and computes the radiative values at the global scale in one single step.

First breakthrough: *fast spectral-integration over millions of spectral lines.*

Since the origin of numerically-simulating radiative transfer, it was claimed that statistical approaches were the only practical way towards the simultaneous handling of all the optico-geometric complexity of radiation in 3D realistic systems. “Monte Carlo is the only numerical tool that passes infinite dimension”. The meaning of this sentence is quite clear for algebraic *linear* systems, for instance, and radiative transfer is indeed linear-transport physics. But linear-transport means that the extinction of a beam is exponential and the nonlinearity of this exponential-extinction (Beer law) is at the origin of severe difficulties. As far as the present project is concerned, the millions of absorption lines that we need to handle define the atmospheric-opacity and appear within the exponential, whereas the multiple scattering optical paths are “outside” the exponential (they define the line of sight along which Beer extinction is applied). Spectral integration and optico-geometric integration are therefore combined *nonlinearly*, and this nonlinearity is sufficient to cancel out large parts of Monte Carlo benefits.

But M. Galtier (Galtier et al. 2016, Eymet et al. 2013) and J. Dauchet (Dauchet et al. 2016) have recently proposed a way to bypass this nonlinearity without any loss in accuracy, and this proposition was shown to allow extremely fast simulations of top-of atmosphere fluxes. In few words, the main idea is to make use of “null colliders” (null-absorbers, null-scatterers) that one adds to the field in order to make it look homogeneous. But when a photon encounters one of these null-colliders, it simply continues its path as if the collision had no impact. The numerical solution remains identical, but in the underlying statistical formulation the line spectrum has been shifted from inside to outside the exponential.

The main consequence is that spectral integration is no-more specific, by comparison with integration over 3D paths, integration over the surface of the globe and integration over annual-scale time intervals: they are now all combined linearly and we can indeed benefit of Monte Carlo easily handling complex dimensions.

Galtier et al. established the practical feasibility of sampling molecular-transitions directly within the radiative transfer Monte Carlo; but the probability set they used was not optimized. This first set was "found" essentially by trial and errors. A truly efficient practice of line-sampling Monte Carlo will therefore require that we better understand the geometrical structure of the high-dimension space that we need to sample. This will required that the first phase of the present project be organized in such a way that two communities work together on the revisiting of Galtier et al.'s proposition. The implication of IRIT (computer graphics and multi-scale geometrical analysis in multidimensional spaces) and Meso-Star (computer graphics and complexity-engineering) answer this requirement.

Second breakthrough: *statistically combining spectral-integration with 3D-geometrical and annual-scale temporal integrations*

When addressing the practical question of implementing a Monte Carlo code that performs this combined integration, arises the question of making the best computer-science choices for fast tracking of multiple-scattering paths in complex 3D scenes (e.g. boundary-layer clouds) and efficient access to both spectroscopic and GCM-output data. Research groups in the main animation-studios of the cinema industry have received the proposition of M. Galtier and J. Dauchet with a strong and visible attention: 3 articles in the quite prestigious SIGGRAPH and EUROGRAPHICS conferences (Novák et al. 2014, Kutz, et al. 2017, Szirmay-Kalos et al. 2017) and the launching of Méso-Star[1], a start-up devoted to Monte Carlo handling nonlinearities in complex systems. This community organises its computer developments around open-source libraries and for atmospheric or thermal-engineering applications, we have already learnt how to make use of these libraries on a regular basis to achieve 3D-efficient and highly parallelized radiative transfer simulations. Altogether, advances on null-collisions by the physics community have nourished a computer-science community that in turn nourishes us with ready-for-use development environments[2].

The optimized sampling of a location at top of the atmosphere, of a time within the considered period, or a multiple-scattering path within a cloudy atmosphere are sources of no theoretical difficulty : they belong to the standard Monte Carlo practice. But the combined samplings of frequency, absorption species and molecular transitions is truly difficult and unexplored apart from Galtier's proposition. An intense spectral line far from the considered frequency can of course have more impact on the radiative transfer at this frequency than a closer but less intense one. But how can we organise this information considering that we deal with millions of lines and that they change with temperature, pressure and absorber amounts? How can we best pre-calculate and add to the molecular-database a limited number of parameters allowing a fast construction of well-adjusted sampling probabilities? Again, a first solution is already available and realistic simulations of top-of-atmosphere fluxes could be achieved in few seconds for a single atmospheric profile on very standard computers, but addressing large 4D files will require new developments and better adjustments. Good accuracy (0.1% requirement), and therefore variance reduction, is essential to the project. Reducing the variance will mean that our tools will be practically available to all climatologists, whatever their computer equipments.

Achievement: *a community-distributed reference radiative tool for climate and climate change analysis*

These breakthroughs will allow us **to design and realize a radiative transfer simulation tool that connects directly the output of a climate simulation to a molecular-transition database** such as the widely used GEISA (developed at LMD) or HITRAN. This tool will evaluate the radiative balance of the globe integrated over one or a few years of atmospheric profiles produced at high frequency (typically 3 hours) by meteorological centres or climate modelling groups. This evaluation at global scale with a reference model has never been achieved, is currently considered as infeasible within the existing resources and techniques, and will be a focal point in atmospheric radiative computation.

As within this project a major expected use of this tool will be to evaluate the impact of the changing absorber amounts, we will also make use of a general property of Monte Carlo methods: the ability to **evaluate parametric sensitivities** (or Jacobians) of a function in addition to the function itself (Roger et al. 2005). The practice can be quite difficult, in particular as far as numerical convergence is concerned, but M. Galtier has shown in his PhD work that sensitivities of top-of-atmosphere fluxes to gaseous abundances created no such convergence difficulties when using his line-sampling algorithm (unpublished at present date).

II. Project organization and means implemented

The project includes both consolidation of novel existing methods, development of new methods, software implementation of new techniques and use of these developments to advance climate science questions. It is a multidisciplinary project that gather experts in Monte-Carlo methods, radiative transfer, computer graphics, geometric modelling, spectroscopy data, climate modelling and climate change. This allows to build an end-to-end project, from fundamental developments to software tools for high performance simulations applied to climate challenges. The project will be divided in four tasks that will all start from the beginning and will have precise meeting points :

Task 0 : Management and outreach.

Task 1: Monte Carlo computation of radiative transfer directly from spectral database. Methodological development and implementation of the Monte-Carlo method: definition of the sampling strategy and required precomputing variables, parametric sensitivities.

Task 2: Computation of the climatological radiative flux and their parametric sensitivities. Computing the radiative forcing of atmospheric components and anthropogenic perturbations. Validation and assessment of the radiative forcing notably within the radiative forcing model inter-comparison project (RFMIP).

Task 3: Development and assessment of a radiative tool for the climate community. Recoding of Galtier's codes using the star-engine library[2]. Interfacing with GEISA/HITRAN. Interfacing with GCM outputs. Implementation of the sampling strategy and sensitivity algorithms of Task 1.

The project will be coordinated by Jean-Louis Dufresne (LMD/IPSL) expert in climate modelling, climate change studies and radiative transfer computation. He has been involved in more than 10 national and European projects, has been task leader in several of them, and has coordinated a large ANR project. He was head of the Climate Modelling and Climate Change team at LMD during 7 years (2004 – 2011), head of the IPSL Climate Modelling Centre during 8 years (2008-2016). He contributes to two radiative transfer inter-comparison projects, coordinates the IPSL contribution to the radiative forcing inter-comparison project (RFMIP) and candidates to be author of the chapter on « The Earth's energy budget, climate feedbacks, and climate sensitivity » of the next IPCC assessment report.

The consortium is composed of 3 internationally recognized laboratory and gathers scientists which expertises cover the whole chain of competency required to implement this ambitious project.

<u>Partner 1: LMD/IPSL, UMR 8539</u>
J-L Dufresne, C. Crevoisier, R. Armante: experts in climate modelling, radiative transfer, spectroscopy data and remote sensing, they aim at simulating and understanding climate variability and climate changes, at computing and observing from space radiation in order to better characterize current climate and better assess climate models.

<u>Partner 2: LAPLACE, UMR 5213</u>
R. Fournier, S. Blanco: experts in Monte-Carlo applied to engineering and atmospheric sciences, long and successful experience in using computer graphics tools for evaluation of path-statistics in complex 3D scenes (partnership with the Meso-Star[1] start-up, see hereafter).

<u>Partner 3: IRIT, UMR 5505</u>
M. Paulin, N. Mellado: experts in the field of computer graphics. From geometric modelling to realistic rendering, they aim at developing computationally efficient models and tools for light transport simulation, Monte-Carlo method and multi-scale modelling of discrete data.

These partners have been working together for more than a decade now. This fruitful and ongoing collaboration already resulted in co-supervised thesis, cosigned papers and the development of radiative transfer codes for the atmosphere of the Earth and other planets (Mars, Venus). Beyond this project, the partners have active collaborations with other national and international groups, ensuring a good connection with emerging tools and evolving questioning. For instance, the treatment of the 3D properties of cloud is not included explicitly in the present project, but Task 3 will directly benefit of the Monte Carlo codes developed in the frame of the ANR High-Tune and PNTS-2016-05 projects and dealing with radiative transfer in large eddy simulation (LES) clouds: although our line-sampling codes will here translate the boundary-layer cloud outputs of GCMs into simple-shape 3D clouds, they will be designed to also accept LES clouds as input.

Altogether, the complementary and relevant expertise to be gathered in this project, the theoretical foundations of our approach and the already existing software prototypes make us confident in our ability to achieve our main objectives and to make substantial progresses in the computation of radiative forcings.

III. Impact and benefits of the project

The community process of analyzing climate or climate-change with the outputs of general circulation models defines a need for computation of yearly integrated radiative forcing using the best accurate spectroscopic data. But this is assumed impossible because of computer power limitations and therefore accuracy compromises are made that strongly reduce the climatological significance of todays practice. We will solve this difficulty and **reach the required accuracy with non more than the typical computer equipment of climatology centres.** This is possible because we manage to translate gaseous radiative transfer into a linear integration problem that we solve using Monte Carlo, with an **ideal parallelization scalability** and ready-for-use **computer-graphics libraries** for path-tracking in complex 3D scenes (boundary layer clouds).

The initial proposition of Galtier et al. was not restricted to atmospheric sciences and most of the feasibility tests were oriented toward engineering questions, mainly heat transfer in combustion devices. One of the partners is deeply involved in such engineering projects and all the advances made here will immediately benefit to this neighbour community. In the 1960s, these two communities were working together on the modelling of radiative transfer in molecular gases. They have essentially split because of the impossibility to make a direct use of line-transition databases (that are still under common developments): they had to design approximate band-models and adjust them to their specific needs. We hope that a new start for a common radiative-transfer practice can be associated to the development of line-sampling Monte Carlo tools.

This last point means that we need to be very careful in our developments so that independent libraries can be reused by all communities dealing with molecular radiation. This will be achieved within the EDStar[3] environment, that is commonly developed by LAPLACE, RAPSODEE and Meso-Star[1]. These two last partners are not officially part of the present project, but they are directly concerned by its existence: RAPSODEE is a research laboratory involved in combustion heat-transfer and concentrated-solar engineering, in which gaseous radiation is essential; Meso-Star[1] is start-up applying computer graphics technologies to the engineering of complex systems. A contract between LAPLACE and Méso-Star engages Méso-Star to provide an engineering support to LAPLACE for the development of the EDStar platform via the star-engine library[3]. Therefore, the Meso-Star engineers will be effectively involved in the present project, which is a guaranty that all developments will be capitalized and designed in coherence with needs expressed outside the climatology community.

Still in direct relation with the EDStar plateform[3], the Occitanie Region already finances a teaching program (CLE-2017 project) addressed to researchers and engineers wishing to learn today practice of Monte Carlo. The present project will directly contribute to this teaching program.

IV. References related to the project

Dauchet, J. . et al. 2016: Monte Carlo and nonlinearities. arXiv preprint arXiv:1610.02684, https://arxiv.org/abs/1610.02684

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Roger, M. et al. 2005: Monte Carlo estimates of domain-deformation sensitivities. Phys. Rev. Lett. 95 (18). DOI: 10.1103/PhysRevLett.95.180601

[1]: Méso-Star: https://www.meso-star.com
[2]: Star-Engine: https://gitlab.com/meso-star/star-engine
[3]: EDStar: http://edstar.lmd.jussieu.fr/