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M2 Internship Proposal

Title: Towards simplified models of the self-aggregation of convective clouds

Internship short summary. Clouds are vital for modulating the Earth's radiation balance and therefore its climate. Their evolution in the context of climate change is uncertain, largely because the mechanisms governing the development of clouds and cloud systems are poorly understood. These complex mechanisms arise from the interaction between moist thermodynamics and fluid mechanics. The objective of this internship is to show that one of the fundamental mechanisms of cloud cluster development, convective self-aggregation, can be produced by a minimal representation of this thermodynamic-mechanical interaction.

Broader scientific context. Atmospheric convection corresponds to the vertical mixing of air in the troposphere. Adiabatic cooling in the updrafts of this convection causes the air to reach saturation and thus leads to cloud formation. Deep cloud convection, throughout the entire depth of the troposphere, is organized on various scales, from mesoscale convective systems (approximately 100 km horizontally) to global-scale disturbances (equatorial waves, Madden-Julian Oscillation). For many modes of organization, the mechanisms underlying their development are still poorly understood or debated.

The spatial organization of deep convection appears in its simplest form in various models of the atmosphere in a radiative-convective equilibrium configuration. In this configuration, the Earth's rotation is neglected and surface conditions and incoming solar flux at the top of the atmosphere are homogeneous horizontally. Most often, simulations are initiated with conditions that are also homogeneous horizontally and are run until a steady state is reached. In some cases, the models simulate sporadic deep convection throughout the domain. In other cases, these models simulate one or more regions of convection separated by dry regions without convection: this is known as self-aggregation, whereby convective clouds aggregate spontaneously, without any constraints imposed by initial conditions or boundary conditions.

This phenomenon appears both in kilometer-resolution model simulations based on the anelastic equations of the atmosphere and representing the main convective circulations, and in general circulation models based on primitive equations, in which convective circulations are represented implicitly by physical parameterizations. Self-aggregation is therefore a fundamental mechanism of spatial organization of atmospheric convection. Understanding this phenomenon is an important challenge for understanding the fundamental mechanisms of convection organization, and the proposed internship aims to contribute to this.

Internship objectives. The supervisors of this internship have developed a simple, quasi-analytical model based on primitive equations, which can be used to represent the various steady states (aggregated or non-aggregated) of radiative-convective equilibrium obtained with complex models (kilometer-resolution and general circulation models) and reproduces a large number of behaviors documented with these complex models [1]. The first objective of the internship is to develop an efficient numerical algorithm to solve the system of evolution equations in order to study the temporal evolution of the model variables towards their steady-state values and numerically validate the linear stability results obtained in [1]. Several secondary objectives are possible depending on the candidate's background and motivations:

- include into the model a representation of small-scale variability in the form of a stochastic forcing term in order to obtain a temporal evolution of the simple model similar to that of kilometer-resolution models;
- study (theoretically and/or numerically) two-dimensional versions of the model, especially the existence of steady-state solutions in rectangular domains with doubly-periodic boundary conditions, and if time allows their stability.

Prerequisites: good skills in scientific computing (Python), some basic PDE courses on hyperbolic equations, and a strong interest in an interdisciplinary project.

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Location: the internship will take place at the Centre National de Recherches Météorologiques, but regular meetings will be planed at the Institut de Mathématiques de Toulouse.

Dates: 5 months from March to July 2026.

References

[1] G. Bellon, A. Ribes, B. Meyssignac, O. Geoffroy, G. Faye and P. Noble. Convective self-aggregation as a two-regime damped gravity wave. Hal-05166602, (2025).