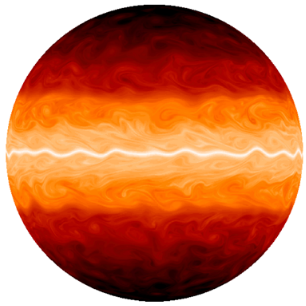
ABOUT THE HYPOTHESIS OF ABRUPT CLIMATE CHANGES: A STATISTICAL PHYSICS APPROACH

The hypothesis that climate may undergo an abrupt transition if global warming reaches some threshold is often discussed in the public debate. So far, there is however no clear scientific evidence, neither in favor, nor against the occurrence of such a scenario. Putting this question in the realm of science is a fascinating subject. The aim of this project is to study the possibility that the Earth's atmosphere may undergo an abrupt transition towards a state for which the equatorial belt would experience strong eastward jet velocities, a state referred to as superrotation. Such a bifurcation would drastically change the climate of the Earth at a global scale, changing the monsoon structure and the midlatitude weather, with unthinkable consequences on our civilisation. The inspection of planetary atmospheres in our solar system shows that several exhibit a strongly superrotating equatorial jet (e.g. Venus, Jupiter and Saturn), while others do not (e.g. the Earth). Moreover, while the paleoclimate evidence is still too scarce for a definitive answer, several authors have hypothesized that the Earth has experienced superrotation in the remote past.



Potential vorticity in a numerical simulation of a superrotating equatorial jet [8].

The hypothesis we want to test is that for some range of parameters, both a superrotating and conventional circulation can exist, and that random fluctuations of the dynamics may trigger a transition from one state to the other [5]. Dynamical mechanisms for a transition to superrotation have been suggested: they all involve equatorial waves, excited by hydrodynamic instabilities or resonant forcing [1]. However, addressing these issues with current atmospheric models faces several challenges. The main one is that it requires to run complex models with many degrees of freedom over unprecedented time scales. For this reason such a task has been considered impossible so far.

The most modern tools of statistical physics may help solving this issue. Statistical mechanics provides key tools in order to study complex systems. Its application to geophysical flows and climate dynamics has given impressive results during the last decade; for instance to explain the structure of coherent structures such as the Great Red spot of Jupiter [3, 4]. Recently, rare transitions between states with a different number of atmospheric jets, for Jupiter's troposphere, have been observed [2]. We have also used large deviation algorithms, based on statistical mechanics ideas, in order to study the probability of extreme heat waves over Europe [7].

We will use two key ideas from statistical mechanics in order to study superrotating equatorial jets. First, at a practical level, we will use a rare event algorithm that allows to gain several orders of magnitude compared to direct computation [6, 7], which allows to tackle problems that could not have been studied previously. Second, at a theoretical level, we will rely on large deviation theory, the key tool of modern statistical mechanics. Large deviation theory explains why bifurcations in a non-equilibrium context may have universal properties, why rare transitions in turbulent flows are described by Arrhenius laws, and why the dynamics of rare transitions is predictible.

The aim of this project will be to study the transition to a superrotating atmosphere in a simple atmospheric model. This project will involve numerical computations: although no specific training is required, the candidate should have an interest for numerical techniques. As the project will also involve modelling, and the use of statistical mechanical concepts, it should be of interest also for theoretically minded students. Another project, with a purely theoretical flavor, is also proposed.

References

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[3] F. Bouchet and A. Venaille. "Statistical mechanics of two-dimensional and geophysical flows". *Phys. Rep.* **515**, 227–295 (2012).

[4] C. Herbert. "An Introduction to Large Deviations and Equilibrium Statistical Mechanics for Turbulent Flows". In: *Stochastic Equations for Complex Systems: Theoretical and Computational Topics*. Ed. by S. Heinz and H. Bessaih. Springer, 2015. Chap. 3, 53–84.

[5] C. Herbert and F. Bouchet. "Rossby wave resonance, Hadley cell feedback and abrupt transitions to superrotation" (to appear).

[6] T. Lestang, F. Ragone, C.-E. Bréhier, C. Herbert, and F. Bouchet. "Computing return times or return periods with rare event algorithms". *J. Stat. Mech.* **043213** (2018).

[7] F. Ragone, J. Wouters, and F. Bouchet. "Computation of extreme heat waves in climate models using a large deviation algorithm". *Proc. Natl. Acad. Sci. U.S.A.* **115**, 24–29 (2018).

[8] R. K. Scott and L. M. Polvani. "Equatorial superrotation in shallow atmospheres". *Geophys. Res. Lett.* **35**, 24202 (2008).

Practical Information

- **Profile:** We are looking for candidates with a background in physics, in particular in nonlinear dynamics, statistical physics and fluid dynamics. No previous experience with numerical models of geophysical flows is required.
- **Location:** *Laboratoire de Physique de l'ENS de Lyon (UMR5672)*, Lyon, France.
- **Supervisors:** Corentin Herbert (CNRS, ENS de Lyon) and Freddy Bouchet (CNRS, ENS de Lyon).

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