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Foreword / *Avant-propos*

Geophysical and astrophysical fluid dynamics in the laboratory / *Dynamique des fluides géophysiques et astrophysiques au laboratoire*

Foreword to the special issue: Geophysical and astrophysical fluid dynamics in the laboratory

Avant-propos du numéro spécial : Dynamique des fluides géophysiques et astrophysiques au laboratoire

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Abstract. This special issue brings together 19 review articles addressing a broad range of problems in geophysical and astrophysical fluid dynamics, reflecting both the current state of the art and ongoing research, with a special focus on the contribution of laboratory experiments. This foreword outlines the general context and key challenges of the field, and places the individual contributions in perspective.

Résumé. Ce numéro spécial réunit 19 articles de revue couvrant un large spectre de problématiques en dynamique des fluides géophysiques et astrophysiques, reflétant à la fois l'état de l'art et les recherches en cours, avec un accent particulier sur l'apport des expériences en laboratoire. Cette préface présente le contexte général et les principaux défis du domaine, et met en perspective les différentes contributions.

Keywords. Geophysical fluid dynamics, Astrophysical fluid dynamics, Laboratory experiments.

Mots-clés. Dynamique des fluides géophysiques, Dynamique des fluides astrophysiques, Expériences de laboratoire.

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1. Introduction

Geophysical and Astrophysical Fluid Dynamics (GAFD) encompasses all types of flows occurring in any natural system, from Earth's atmosphere and oceans to the interiors of planets and stars, and even toastrophysical structures such as accretion disks. These systems involve a wide

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range of fluids—air, water, liquid metals, plasmas—and span extensive spatial and temporal scales. Despite this diversity, GAFD research is unified by a common set of governing equations and a shared methodological framework: the construction of simplified models that isolate fundamental physical mechanisms. This special issue explores how laboratory experiments contribute to advancing our understanding of these generic mechanisms.

GAFD often involves extreme flow regimes and complex coupled physics that challenge numerical and theoretical approaches. While computational tools have advanced rapidly, particularly with the emergence of data-driven techniques, laboratory experiments remain indispensable. They give direct access to real systems, inherently including all physical effects, boundary conditions, and spatial and temporal scales, without relying on parameterizations or closure models. Laboratory experiments allow systematic exploration of parameter space and sustained operation in extreme regimes, thereby yielding statistically converged data. Laboratory flows emerge directly from the fundamental equations with no a priori, and can thus reveal rare, serendipitous and unexpected behaviors. These strengths coexist with inherent drawbacks: quantitative measurements are always challenging and limited, and experiments are constrained by practical restrictions on e.g. geometry, scale separation, and working fluid properties.

2. Topics overview

This special issue provides an overview of the state of the art and ongoing research in experimental GAFD. The 19 review articles highlight the breadth of physical processes accessible in the lab and underline the universality of the mechanisms across planetary and astrophysical contexts. The contributions demonstrate that progress stems from both large-scale experimental platforms and small-scale analog models.

Convection is a classical and long-standing research topic in fluid mechanics, with particular features in GAFD. Natural systems are often expected to operate in so-called ultimate regimes, where diffusive effects become negligible. While the existence of such a regime remains a subject of debate in the context of Rayleigh–Bénard convection, a radiatively driven convection setup has recently demonstrated an ultimate regime in a novel configuration [1]. Rotation plays a dominant role in GAFD, and its influence on convection has been studied experimentally for over seventy years, remaining a very active area of research [2]. Furthermore, many natural systems—including oceans, gas giants, and stellar interiors—feature multiple buoyancy sources, leading to complex double-diffusive convection regimes that are especially prone to laboratory investigation [3].

Phase-change dynamics are fundamental across planetary layers but remain challenging to parameterize due to complex interactions between fluid mechanics and out-of-equilibrium thermodynamics. Laboratory investigations address phenomena ranging from planetary surface ablation [4] to core crystallization processes [5]. The resulting solid boundary topographies, spanning multiple scales, increase the complexity of GAFD flows and offer a valuable platform for controlled experimental studies [6].

Multiphase flows pose major challenges for numerical modeling and are ubiquitous in natural systems. Experimental studies target applications ranging from marine plastic transport [7] and dune morphodynamics [8] to soil erosion [9] and metal-silicate differentiation during planetary accretion [10].

Stratification and rotation are fundamental components of GAFD, driving instabilities such as baroclinic modes [11]. They govern complex flow regimes including jet dynamics [12] and mixing in stratified turbulence [13]. They also sustain internal waves—gravity and inertial, respectively—that share many characteristics but exhibit key differences [14]. Internal waves play a central role in geophysical and astrophysical dynamics, particularly through their nonlinear interactions that sustain wave turbulence [15] and generate mean flow oscillations, exemplified by the quasi-biennial oscillation [16].

Magnetohydrodynamics (MHD) is a central component of GAFD, yet remains particularly challenging to investigate experimentally. Ambitious laboratory setups, often pushing the limits of current technology, have been developed to explore MHD phenomena. The dynamics of accretion disks has been a subject of intense experimental effort [17]. Dynamo action remains a long-standing goal, with several past attempts yielding limited success. Nonetheless, notable progress includes the laboratory-scale observation of magnetic field reversals [18]. New experimental platforms are now entering the arena offering new opportunities for exploration [19].

3. Conclusion

This special issue is intended for researchers in GAFD, scientists from adjacent disciplines, and early-career or prospective students. It also aims to foster dialogue across traditionally compartmentalized fields—including atmospheric sciences, oceanography, deep geophysics, planetology, astrophysics, fluid mechanics, and nonlinear physics. Finally, it highlights the role of experimental GAFD as a powerful tool for education and outreach, thanks to accessible and illustrative setups that make complex processes tangible for students and the broader public.

In conclusion, laboratory experiments remain a cornerstone of GAFD. They complement observations, theory, and numerical simulations, providing unique access to physical insight. This role is increasingly critical as we seek to understand the changing dynamics of our planet and the surprising behaviors emerging from newly explored planetary and stellar systems.

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