Dynamics of Rotating Penetrative Convection and Rotating Double-Diffusive Systems

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Abstract

This work presents numerical and experimental investigations regarding rotating penetrative convection and rotating double-diffusive systems under thermal or salty stratification. The focus is on how convection driven by thermal instability interacts with a stably stratified region, producing internal waves. These waves result from nonlinear interactions between convective motion and stable density gradients. As convection overshoots into the stratified layer, complex feedback loops arise, leading to wave generation. In rotating systems, Coriolis effects further modify the dynamics, giving rise to inertial-gravity waves in the stably stratified region, and different elongated vortex patterns in the convective zone, that can change how convection overshoots and how it drives internal waves.

Our experimental setup, named *CROISSANTS (Convective ROtational Interactions with Stable Stratification Arising Naturally in Thermal Systems)*, is found at the Physics Laboratory of the Ecole Normale Supérieure (ENS) de Lyon. The experiment is mounted on a rotating table and investigates the dynamics of rotating systems using water with a temperature gradient. The temperature ranges from approximately 30 °C at the top of a 30 cm-high cubic cavity and decreases to 0 °C at the bottom. Since water exhibits a density inversion between 0 °C and 4 °C, the system naturally develops convection at the bottom, beneath a stably stratified region that extends from the convective interface to the top of the cavity. Measurements using Particle Image Velocimetry (PIV), Schlieren techniques, and Laser-Induced Fluorescence (LIF) captured the convective and wave motions in both vertical and horizontal planes. In non-rotating cases, a novel transition in the growth pattern of the convective interface was observed. In rotating systems, this transition was absent, as the Coriolis force altered the structure of convection and its interaction with the stably stratified zone. Numerical simulations complement the experiments, exhibiting similar behavior to the observed experimental results.

These results provide insights into phenomena related to geophysical and astrophysical flows. In the Earth's atmosphere, internal gravity waves are excited in the stratosphere by convective motions from the troposphere. In the oceans, similar processes occur where convection and double diffusion generate waves in stratified regions. In the astrophysical context, these interactions are relevant to planetary and stellar interior applications, where convection can drive waves in stably stratified layers such as the radiative zone of stars or the (possibly existing) stratified layer at the Earth's external core, where rotation effects are even more significant due to the small Rossby numbers, of the order of 10^{-5} to 10^{-4}. This indicates that rotational forces dominate over inertial forces, highlighting the importance of better understanding the effects of rotation in the dynamics of penetrative convection and wave interactions. Understanding these processes provides a framework for interpreting how convective motion transfers energy across scales, impacting large-scale magnetic fields and planetary evolution.