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Phenomenology and High-Rayleigh Number Simulations of Horizontal Convection

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The degree to which the ocean circulation can be regarded as "buoyancy-driven" is a long-standing question. Theoretical studies show that pure horizontal convection in a Boussinesq fluid is non-turbulent at high Rayleigh numbers, but it is an open question as to what this result implies for the deep circulation in the limit of high Rayleigh number. Furthermore, does the presence of a small amount of mechanical forcing at the surface change the phenomenology completely and completely nullify the results?

To investigate these questions we perform high resolution numerical simulations of horizontal convection at Rayleigh numbers between 10^6 and 10^{11}. Various scaling arguments of kinetic energy dissipation rate, buoyancy variance dissipation rate and thermocline depth are investigated. Without mechanical forcing, the maximum non-dimensional stream-function is consistent with the previous estimates and it obeys a 1/5-power law with Rayleigh number. The depth of the thermocline is also consistent with prior scalings. The numerical results for buoyancy variance dissipation rate are lower than the theoretical upper bound, but decrease with $\kappa^{3/5}$ rather than the suggested $\kappa^{1/3}$. Interestingly, the deep circulation decreases with increasing Rayleigh number, and the penetration of the circulation becomes independent of the aspect ratio of the tank.

We also employ several different mechanical stirring experiments to mimic the effect of wind on the circulation. The results indicate that the kinetic energy dissipation rate and buoyancy variance dissipation rate increase with the strength of the mechanical forcing, and even at the highest Rayleigh numbers the deep circulation is significant. The circulation in the domain appears to increase when the frequency of the forcing is in resonance with the buoyancy frequency of the flow.