SKIN-FRICTION FIELD IN TURBULENT CONVECTION

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Abstract The dynamics of the boundary layers of temperature and velocity are the key to deeper understanding of turbulent transport of heat and momentum in thermal convection. Here, the structure of the skin friction field at the bottom and top plates of a Rayleigh-Bénard convection setup is investigated. We therefore analyze data obtained in direct numerical simulations of Rayleigh-Bénard convection in a cylindrical cell of aspect ratio $\Gamma = 1$. Our analysis is focused to critical points of the two-dimensional skin friction field at the walls. We analyze the statistics of the critical points and relate them to the thermal plumes which detach from the wall and move up into bulk.

INTRODUCTION

Studying Rayleigh-Bénard convection can give valuable information about properties of thermally driven turbulence, a flow phenomenon which appears in many applications in nature and technology. One central question in this setting is that of the mechanisms of turbulent transport of heat and momentum. As in all other wall-bounded flows, boundary layers do form. In turbulent convection, boundary layers of the temperature and velocity coexist. Understanding their detailed dynamics and linkage is essential for deeper insights into the turbulent transport as a whole. In this work we go directly to the wall and analyze the patterns of the wall stress and the temperature gradients as well as their dynamical relation. The wall stress forms a two-dimensional vector field at the plate consisting of two non-vanishing components of the nine-component velocity gradient tensor A_{ij}. Critical points (or zero points) are found for the resulting two-dimensional vector field which is termed skin friction field. Properties of this field have been studied recently in plane shear flows (see e.g. Refs. [1, 2]). There, they have been found partly around the edges of an evolving large-scale structure. We apply and extend these ideas to Rayleigh-Bénard convection and want to unravel their role in the plume detachment.

NUMERICAL MODEL

Our analysis is based on direct numerical simulations (DNS) of the Boussinesq equations of thermal convection in a closed cylindrical convection cell. At all walls no-slip boundary conditions are applied for the velocity field. The top and bottom walls are isothermal, the side wall is thermally insulated. We apply a spectral element method in the simulations in order to resolve the gradients of velocity and temperature accurately [3]. More details on the numerical scheme and the resolutions can be found in Ref. [4].

RESULTS

The velocity gradient tensor A_{ij} holds information about the local topology of the turbulent flow. It is defined as $A_{ij} = \partial u_i/\partial x_j$, where $u_i = (u_x, u_y, u_z)$ are the velocity components and $x_j = (x, y, z)$ the space directions. Tensor invariants of A_{ij} for an incompressible flow follow to [5]:

$$P = -A_{ii} = 0\,, \quad Q = -\frac{1}{2}A_{ij}A_{ji} \quad \text{and} \quad R = -\frac{1}{3}A_{ij}A_{jk}A_{ki}\,. \tag{1}$$

The invariants Q and R provide a topological classification of the local turbulent flow: while Q separates regions dominated by strain from those dominated by vorticity, R classifies the dominance of stretching or compression [5]. A similar procedure is now applied to the skin friction field. The two-dimensional skin friction field is defined as

$$s_i = (s_x, s_y) = \left(\frac{\partial u_x}{\partial z}, \frac{\partial u_y}{\partial z}\right)\,, \tag{2}$$

where z is the direction normal to the wall. When multiplied with the dynamic viscosity μ this field results in the two components of the wall stress field. Figure 1 shows field lines of the skin friction field for an instantaneous snapshot obtained at the heating plates of two DNS of turbulent convection at different Prandtl numbers (see the top row of the figure). The figure demonstrates the existence of zero points of the vector field. In the vicinity of these zero points, we can now apply the same concepts that have been used originally for A_{ij} (see e.g. [1] for more details). We expand the skin friction field as $s_i = A_{i3} + \mathcal{A}_{ij}x_j$ around the critical points where $A_{i3} = 0$ and $\mathcal{A}_{ij}$ contains second order derivatives. Similar to the plane shear flow case, we identified dominant pairs of saddles and nodes. The nodes can be sources or sinks. Their probability distribution will be analyzed with respect to varying Prandtl and Rayleigh numbers. The inspection of the bottom row of the figure shows a correlation of these zero points with regions of a very small vertical temperature

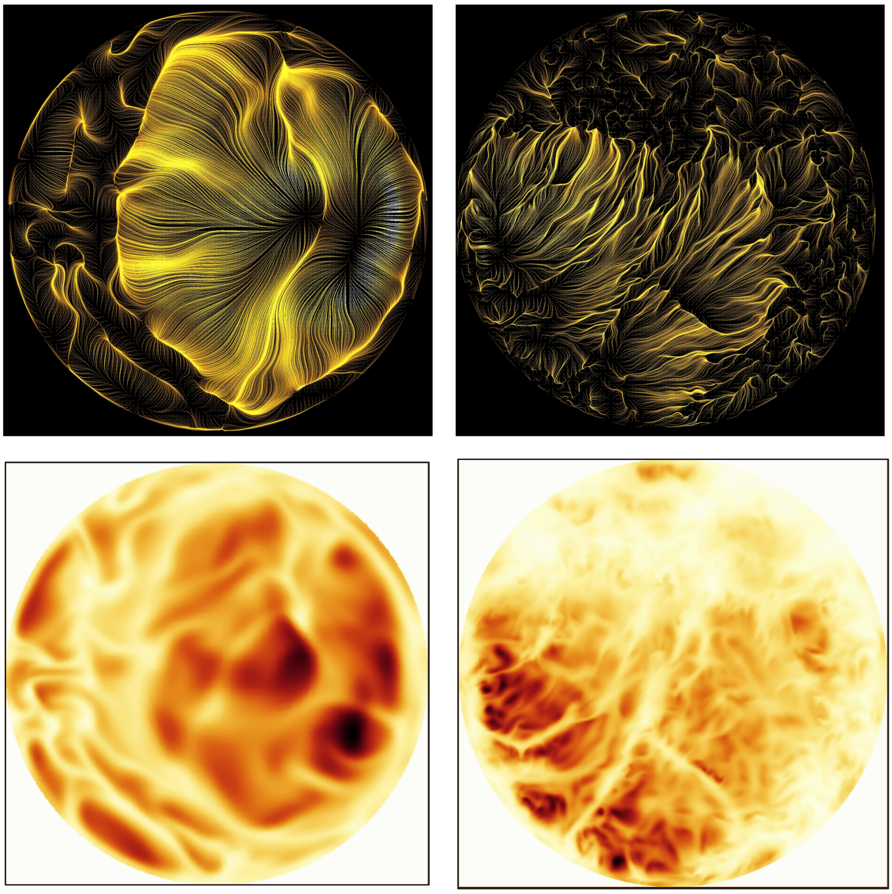

Figure 1. Field lines of the skin friction field (top row) and the vertical temperature derivative (bottom) taken at the wall of the cylindrical convection cell at $z = 0$. The left column shows convection in air at a $Pr = 0.7$, the right column in a liquid metal $Pr = 0.021$. Both data records are obtained at $Ra = 10^8$. The largest magnitude of the temperature derivatives is found in the dark colored regions. The brightest regions are the lowest magnitude and hence are regions of plume detachment.

derivative. This observation can be condensed in a model that relates the plume detachment to the zero points. Our approach makes contact to the recent analysis of fluctuating local thermal boundary layers which was reported in [4].

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