THE LARGE-SCALE CIRCULATION IN TURBULENT RAYLEIGH–BÉNARD CONVECTION IN AN ASPECT RATIO 1 CELL AT LARGE RAYLEIGH NUMBERS

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Abstract We present temperature measurements in turbulent Rayleigh–Bénard convection (RBC) over the Rayleigh number range $3.0 \times 10^{13} \lesssim Ra \lesssim 1.3 \times 10^{14}$ and at constant Prandtl number Pr ≈ 0.8. The RBC sample, known as the High-Pressure Convection Facility (HPCF) of Göttingen, is an upright cylinder of aspect ratio $\Gamma = 1.00$. Using three horizontal rows of thermistors at different heights in the sample, we determined the orientation angle of the large-scale circulation (LSC) plane. Results identify a well established single-roll LSC with a periodic "torsional" mode with a frequency f_C. The values of f_C are consistent with the frequencies f_L obtained from power spectra $P(f)$ of temperature time series taken at mid-height of the sample. The non-dimensionalized frequencies $\tilde{f}_C$ are well described by a power law: $\tilde{f}_C \propto Ra^{\zeta_f}$ with $\zeta_f = 0.46 \pm 0.01$. In contrast: No evidence for a LSC has been observed in similar experiments using a $\Gamma = 0.50$ cell [1].

MEASUREMENT

We investigated the large-scale circulation (LSC) in turbulent RBC by performing measurements on the cylindrical cell with aspect ratio $\Gamma = D/L = 1.00$, with diameter $D = 1.12$ m and length $L = 1.12$ m, of the High-Pressure Convection Facility of Göttingen [2]. As was done at smaller Ra [3], this cell, called HPCF-IV, was equipped with three sets of eight thermistors, each set spaced uniformly in the azimuthal direction, mounted at a radial position 1.0 mm from the side wall. The three sets were located in the horizontal planes at $z = L/4$, $z = L/2$ and $z = 3L/4$, with the bottom plate set to $z = 0$ m. The planes are, respectively, indicated by the indices b, m and t. The LSC orientation angles $\theta_{b,m,t}(t)$ were calculated from the first-order Fourier mode of each set of thermistors as function of time [4]. The difference in the orientation angle between the bottom and the middle set as function of time, $\theta_b(t) - \theta_m(t)$, is shown as the red curve in figure 1*(a)*. Likewise, the angle difference between the middle and the top set, $\theta_m(t) - \theta_t(t)$, is shown in blue. Next, we calculated the normalized cross-correlation function $C_{t,m}^{b,m}$ between those angle differences as a function of the time lag τ. An example is shown by the black solid circles in figure 1*(b)*. In order to accurately determine the fundamental frequency f_C, we fitted an enveloped cosine wave. That fit is shown as the solid red line in figure 1*(b)*.

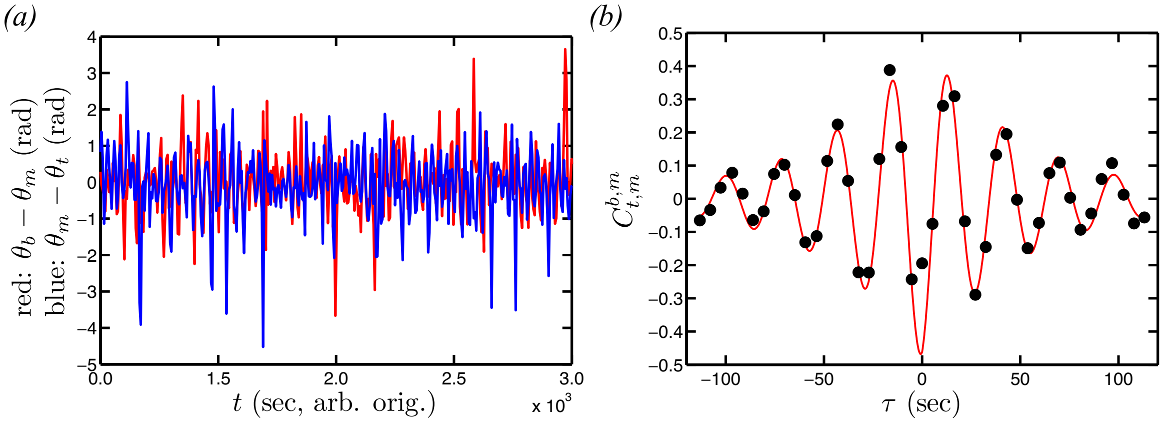

Figure 1. *(a)* Small window of the time series of the LSC orientation angle differences between the bottom and middle thermistor set (red curve) and the middle and top thermistor set (blue curve). *(b)* The normalized cross-correlation function between the time series of panel *(a)* as function of the time lag τ (solid circles). In order to accurately determine the fundamental frequency f_C we fitted an enveloped cosine wave to the correlation function (solid red line). The data in both panels were taken at $Ra = 1.15 \times 10^{14}$.

RESULTS

An important result is that $C_{t,m}^{b,m}(\tau)$ oscillates and is negative for $\tau = 0$, showing that the azimuthal orientations of the LSC plane at $z/L = 1/4$ and at $z/L = 3/4$ are anti-correlated. This indicated that the orientations are out of phase by an angle close to π. Thus there exists a torsional oscillation of the LSC circulation plane, as first found in Ref. [5] for smaller Ra and Pr near 4. We repeated the above procedure for different fixed Rayleigh numbers, resulting in the data points shown as solid circles of figure 2. Here, we have non-dimensionalized the frequency by using the diffusive time scale L^2/ν, with ν the kinematic viscosity, resulting in $\tilde{f}_C = f_C L^2/\nu$. Fitting the data to a power-law results in $\tilde{f}_C = 0.14 Ra^{\zeta_f}$ with $\zeta_f = 0.46 \pm 0.01$, indicated by the solid red line. Interestingly, when retrieving the non-dimensional frequency $\tilde{f}_L$ associated with the LSC by means of power spectrum, $P(f)$, analysis of fast temperature time series taken at a single point in space inside the RBC cell (indicated by the open circles), one obtains the same scaling within the measurement uncertainty. The data fit the picture of a single-roll LSC and with a "torsional" mode as part of its stochastic dynamics. Contrary to similar experiments on a $\Gamma = 0.50$ cell, which yielded no evidence for the existence of a LSC [1], we found a well developed single-roll LSC for $\Gamma = 1.00$ for Ra up to 1.3×10^{14}.

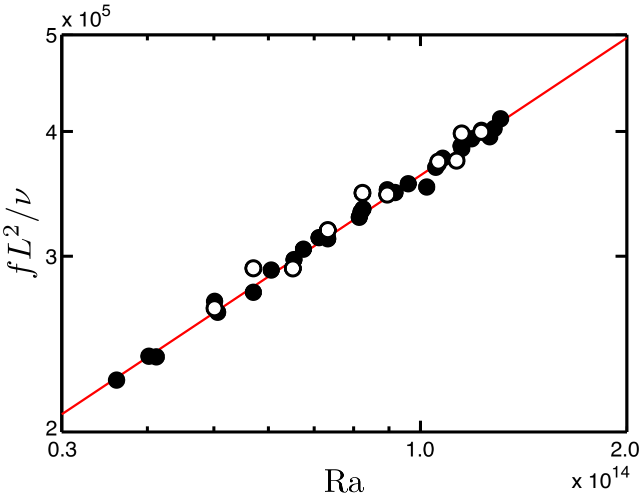

Figure 2. The non-dimensional frequency $\tilde{f} = fL^2/\nu$ associated with the LSC versus the Rayleigh number. Closed circles: the frequency $\tilde{f}_C$ as obtained from the cross-correlation function $C^{b,m}_{t,m}$. Open circles: the frequency $\tilde{f}_L$ as obtained from the single-point frequency power spectrum $P(f)$. A power-law fit to the cross-correlation data results in $\tilde{f}_C \propto Ra^{0.46}$ as indicated by the solid red line.

References

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