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SPECTRALLY-CONSISTENT REGULARIZATION OF TURBULENT RAYLEIGH-BÉNARD CONVECTION

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The incompressible Navier-Stokes (NS) equations form an excellent mathematical model for turbulent flows. In primitive variables they read

$$\partial_t \boldsymbol{u} + \mathcal{C}(\boldsymbol{u},\boldsymbol{u}) = \mathcal{D}\boldsymbol{u} - \nabla p\,; \qquad \nabla \cdot \boldsymbol{u} = 0, \tag{1}$$

where $\boldsymbol{u}$ denotes the velocity field, p represents the pressure, the non-linear convective term is defined by $\mathcal{C}(\boldsymbol{u},\boldsymbol{v}) = (\boldsymbol{u}\cdot\nabla)\,\boldsymbol{v}$, and the diffusive term reads $\mathcal{D}\boldsymbol{u} = \nu\Delta\boldsymbol{u}$, where ν is the kinematic viscosity. However, direct simulations at high Rayleigh numbers (Ra) are not feasible yet because the convective term produces far too many relevant scales of motion. Hence, in the foreseeable future numerical simulations of turbulent flows will have to resort to models of the small scales. The most popular example thereof is the Large-Eddy Simulation (LES): the (unresolved) subgrid stress (SGS) tensor is approximated in terms of the resolved velocity (filtered velocity). Many SGS models have been proposed in the last decades (see [1], for instance). Alternatively, regularizations of the non-linear convective term basically reduce the transport towards the small scales: the convective term in the NS equations is replaced by a smoother approximation [2]. In our previous works (see [3, 4] and reference therein), we restricted ourselves to the $\mathcal{C}_4$ approximation [2]: the convective term in the NS equations (1) is then replaced by the following $\mathcal{O}(\epsilon^4)$-accurate smooth approximation $\mathcal{C}_4(\boldsymbol{u},\boldsymbol{v})$ given by

$$\mathcal{C}_4(\boldsymbol{u},\boldsymbol{v}) = \mathcal{C}(\overline{\boldsymbol{u}},\overline{\boldsymbol{v}}) + \overline{\mathcal{C}(\overline{\boldsymbol{u}},\boldsymbol{v}')} + \overline{\mathcal{C}(\boldsymbol{u}',\overline{\boldsymbol{v}})}, \tag{2}$$

where the prime indicates the residual of the filter, *e.g.* $\boldsymbol{u}' = \boldsymbol{u} - \overline{\boldsymbol{u}}$, which can be explicitly evaluated. Therefore, the only additional ingredient is a self-adjoint linear filter, $\overline{(\cdot)}$, whose filter length, ϵ, is determined from the requirement that vortex-stretching must stop at the smallest grid scale [4]. Altogether, the method constitutes a parameter-free turbulence model that has already been successfully tested for a variety of natural and forced convection configurations (see [2, 3, 4], for instance).

In the present work, we propose to investigate the scaling of heat flux (Nusselt number), thermal and kinetic boundary layer thickness as functions of Ra in turbulent Rayleigh-Bénard (RB) convection (horizontal fluid layer heated from below and cooled from above, as in Figure 1). To do so, a direct numerical simulation (DNS) beside the regularization modeling will be performed, where the results of the DNS will assess the validity of the regularization technique. Afterward the last will be used to carry out a simulation of turbulent RB convection at higher Ra number, that can be a link to the extensive numerical and experimental works available in RB convection problem, such as [5, 6]. Moreover the statistical behavior of the sensitive small-scale turbulent components, namely the thermal and kinetic dissipation rates, will be analyzed since these terms play a main role in the heat transport mechanism within the boundary layers and the bulk in fully developed turbulent flow.

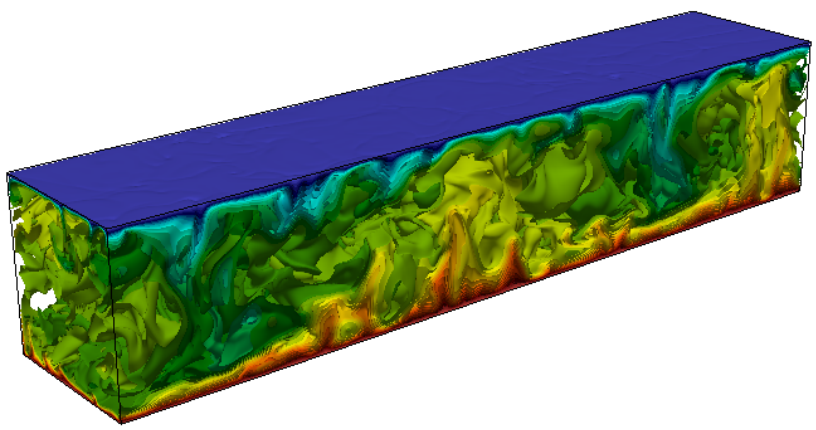

Figure 1: Instantaneous isotherms of turbulent Rayleigh-Bénard convection extracted from a DNS at $Ra = 3.5 \times 10^7$ and $Pr = 0.7$.

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