Turbulent Convection in large-aspect-ratio Cells

Convective turbulence is created in a fluid which is heated strongly from below. The resulting complex interplay between buoyancy and gravity is present in many systems, reaching from astro- and geophysical flows to chemical engineering and indoor ventilation (see e.g., [1]). Frequently the lateral extension of convective turbulence exceed the vertical one by orders of magnitude. For example, atmospheric mesoscale layers and the Gulf stream evolve on characteristic horizontal lengths of 500 to 5,000 km in combination with vertical heights of about 1 to 5 km. The resulting aspect ratios are then 100 to 1,000.

The massively parallel supercomputing facilities which are available today allow us to study how the flow structures and the transport properties in convective turbulence change when the convection cell is successively extended in both horizontal directions, while keeping the vertical one fixed. Theoretically, this opens the possibility for the formation of pancake-like large-scale circulation patterns or bigger clusters of hot and cold temperature blobs. But is convective turbulence seizing this opportunity? Indeed, a very recent work by Hardenberg et al. [2] indicates that such structures can be formed. However, the lateral Grid resolution and the degree of convective turbulence were still moderate in this simulation. Systematic numerical studies on the geometry dependence of turbulence are rare, since they become extremely numerically expensive. In particular, the large lateral Grid extensions for the flat cells require computational resources which have become available with the advent of the Blue Gene systems.

Another important open question in this context is the dependence of transport properties on the aspect ratio. We can expect that the turbulent dispersion of tracer particles, such as aerosols in the atmosphere or phytoplankton in the upper ocean, will be different for the lateral and vertical directions. Recall that convective turbulence is inhomogeneous and anisotropic. Planets and stars rotate at different angular frequencies, i.e. in addition to the buoyancy and gravity effects Coriolis forces appear. The effect of rotation on the structure formation and the tracer transport is a further question which will be investigated in our massively parallel high-resolution simulations of turbulent convection.

Parallel Computation

Our direct numerical simulations solve the Boussinesq-Navier-Stokes equations by a pseudospectral method. At the core of this numerical scheme is the Fast Fourier Transform (FFT), which allows for the calculation of different terms of the nonlinear partial differential equations, either in physical or in wavenumber spaces, and also for rapid switching between the spaces. The classical parallel implementation of three-dimensional FFTs uses a slabwise decomposition of the simulation domain. For a simulation with N^3 Grid points, the method allows a parallelization on up to N processors. The rather small memory size per core on Blue Gene and the large difference in the number of vertical and horizontal Grid points require so-called volumetric FFTs which decompose the three-dimensional volume into iproc × jproc pencils and allow for a parallelization degree of N^2. The prime requirement for a simulation with a large Grid is that the FFT algorithm should also be scalable, i.e. increasing the number of CPUs to solve the problem should also substantially decrease the time-to-answer [3]. Figure 1 shows the scaling properties of our simulation code for an increase in the number of CPUs by more than two orders of magnitude (see inset). The main figure illustrates also that different decompositions iproc × jproc of the total CPU number alter the performance significantly.

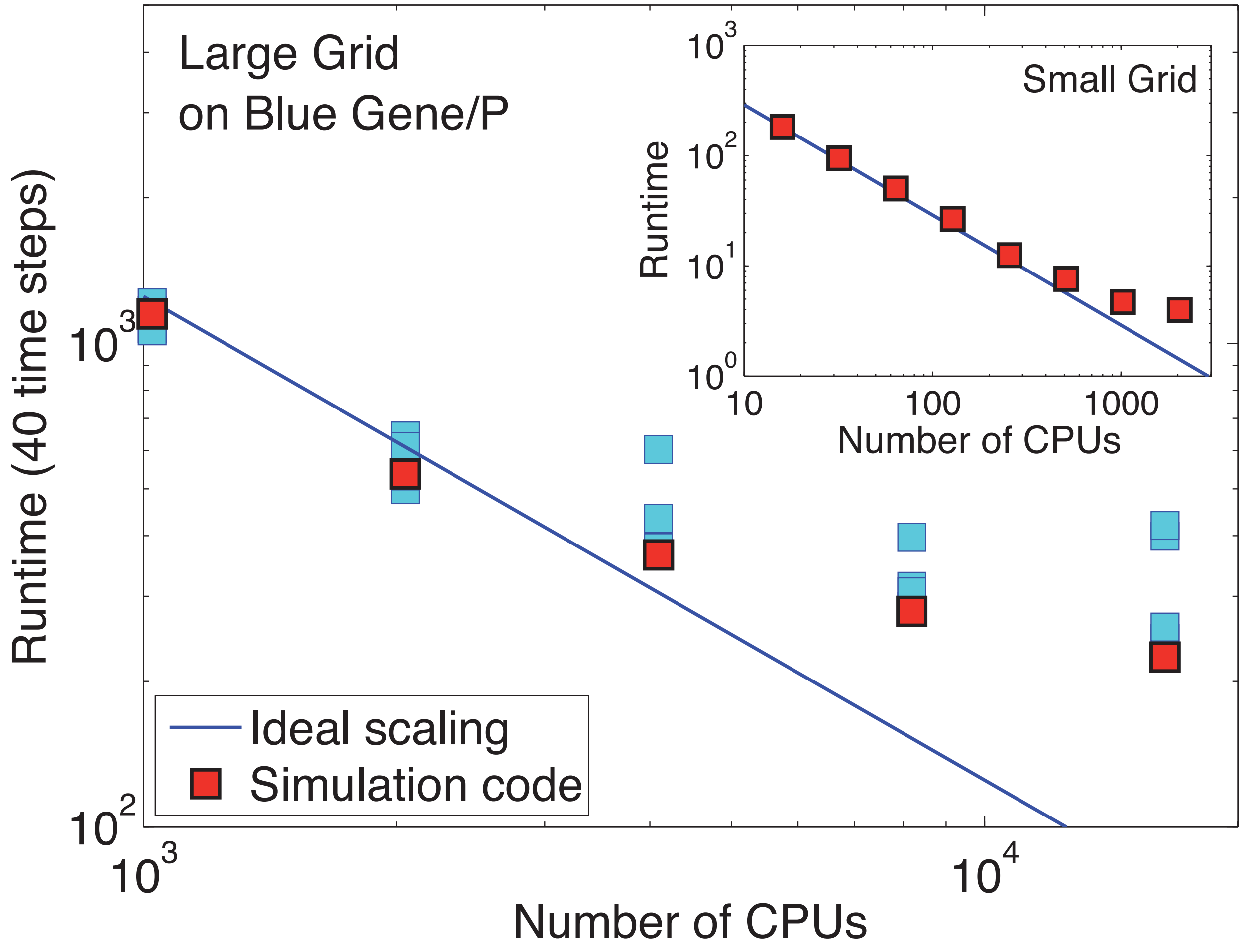

Figure 1: Strong scaling tests of the production code. The cyan boxes mark different decompositions iproc × jproc for a given total number of CPUs. Inset: The number of CPUs has been varied from 16 to 2,048 on a smaller Grid.

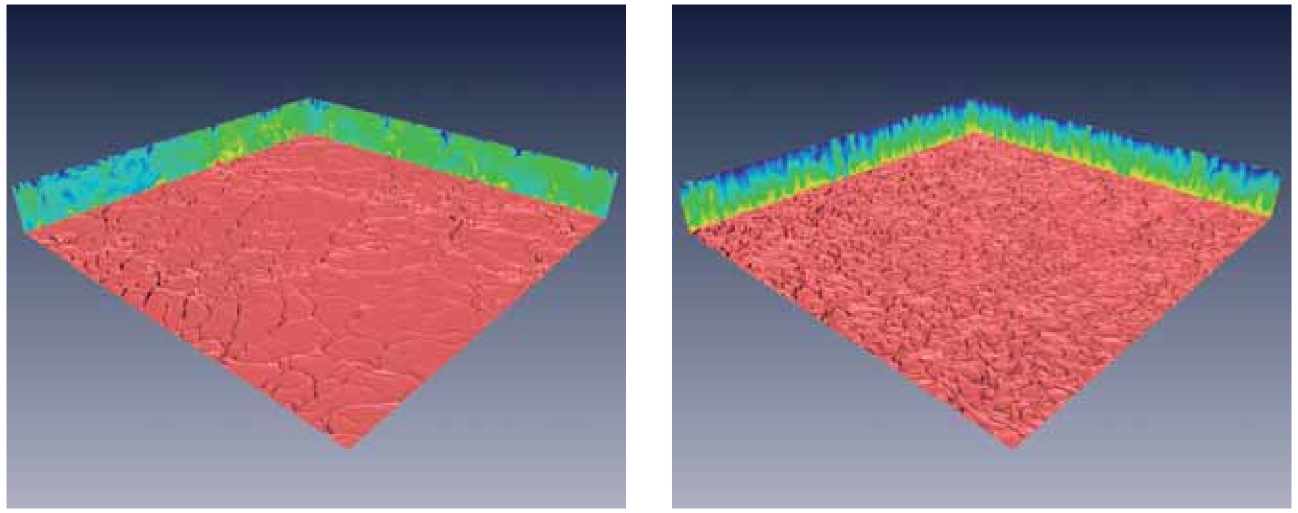

Figure 2: Snapshot of temperature field. An isosurface close to the heating plate and contour plots at two side planes are shown. Left: No rotation. Right: Strong rotation about the vertical axis.

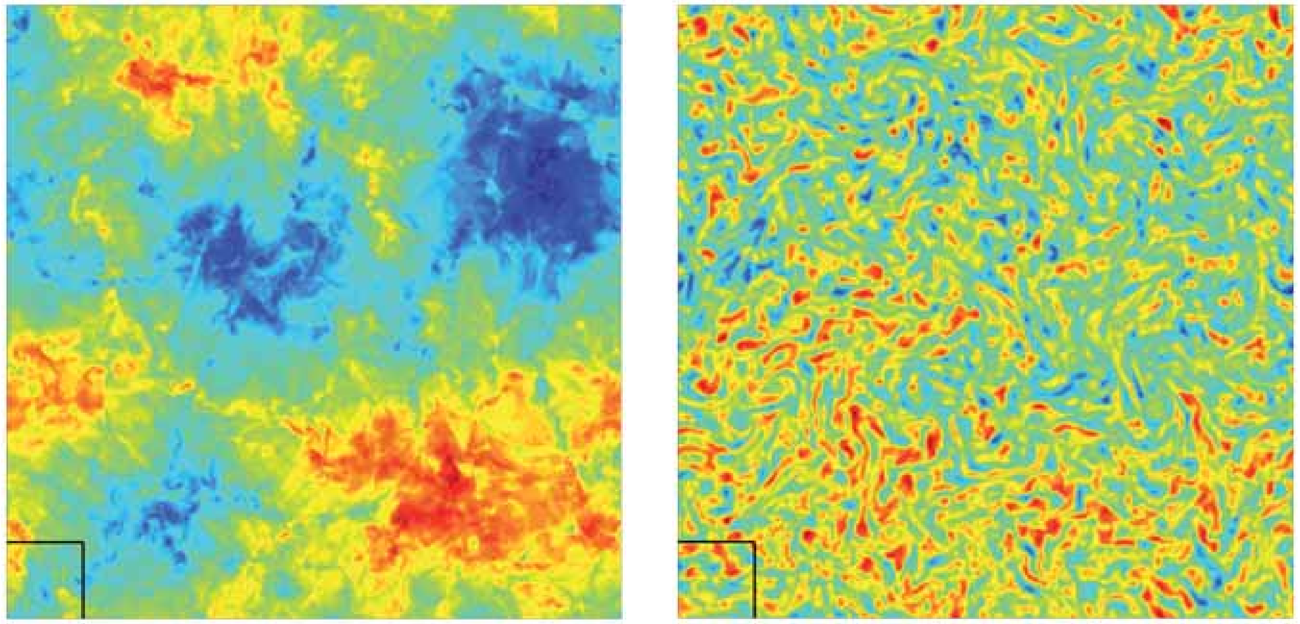

Figure 3: Contours of the vertically averaged temperature field. The black box is the aspect ratio of one cell. The vertical direction points out of the plane. Left: No rotation. Right: Strong rotation.

Results and Outlook

Figure 2 shows two instantaneous snapshots of the full convection cell at an aspect ratio 8. In both cases, the computational Grid contains 2,048×2,048×257 points. The production jobs for these parameter sets were run on 1,024 CPUs. An isosurface of the temperature close to the heating plane is shown. In addition, contour plots of the temperature on two side walls are displayed. The left picture for the non-rotating case indicates the formation of large-scale patches which are visible as ridges of the isosurface. They are known as thermal plumes which detach permanently from the thermal boundary layers at the top and bottom planes. These characteristic elements of convective turbulence can also be seen in the side planes. The situation changes drastically when strong rotation is present. The vertical transport of heat is arranged in columnar structures. Strong rotation prohibits thus the formation of large-scale lateral patterns in our convection cell.

Figure 3 (left) highlights large-scale temperature patterns which have been formed for the non-rotating case. Contours of the vertically averaged temperature at one time instant are shown (red=hot; blue=cold). The figure also underlines clearly that the structures would not be observable in a cell of aspect ratio one which is indicated by the black box. The strong rotation case (Figure 3 right) reflects again the vertical columnar arrangement of the turbulence as shown in Figure 2. An open question, that we are going to study in the future, is whether the large-scale filaments in the non-rotating case prevail when the driving of the turbulent motion by the vertical temperature difference becomes stronger.

As said before, an important aspect for our better understanding of convective turbulence is to unravel the local mechanisms of the transport of heat through the cell. The preferential choice is then to “go with the flow”. This so-called Lagrangian description provides exactly this perspective on the turbulent fluid motion. The velocity and temperature fields are monitored from a local frame of reference which is co-moving with a tracer particle along the streamline. Here, we advect simultaneously up to 1,5 million of such tracers with the flow equations. In convective turbulence, it turns out that this motion becomes qualitatively different in the lateral directions compared to the vertical one. The lateral dispersion is found to be similar to isotropic turbulence and reveals the famous Richardson dispersion law [4].

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