TARANG

1. About Tarang:

TARANG (synonym for waves in Sanskrit) is a speudo-spectral general purpose flow solver and has been developed for over 13 years. It is a parallel and modular C++ program with around 1,00,000 lines of code, and it can solve incompressible flows involving pure fluid, Rayleigh–Bénard convection, passive and active scalars, magnetohydrodynamics, liquid metals, rotating flows,etc. Tarang, at present, scales up to 196608 processors of Cray XC40 (Shaheen II of KAUST) for turbulence simulation of 40963 grid.

Tarang is an open-source code under General Public License (GPL), and it can be downloaded from http://turbulencehub.org. It is being used by around 15 research-groups across the world.

2. Research Groups Using Tarang:

Following are the research groups worldwide which use / have used Tarang.

- Prof. Mahendra Verma, Dept. of Physics, IIT Kanpur, India
- Prof. Sagar Chakrabarty, Dept. of Physics, IIT Kanpur, India
- Prof. J.K. Bhattacharjee, Dept. of Physics, Harish-Chandra Research Institute, Allahabad, India
- Prof. Rodion Stepanov, Institute of Continuous Media Mechanics, Perm, Russia
- Dr. Kacper Kornet, Dept, of Applied Mathematics and Theoretical Physics, University of Cambridge, UK
- Prof. Alban Potherat, Applied Mathematics Research Centre, Coventry University, UK
- Prof. Pinaki Pal, Dept. of Mathematics, NIT Durgapur, India
- Prof. Ravi Samtaney, Dept. of Mechanical Engineering, KAUST, Saudi Arabia
- Prof. Jai Sukhatme, Centre for Atmospheric and Oceanic Sciences, IISc Bangalore, India
- Prof. Krishna Kumar, Dept. of Physics, Indian Institute of Technology Kharagpur, India
- Prof. Alexandros Alexakis, Laboratoire de Physique Statistique, Paris, France
- Prof. Franck Plunian, Institut des Sciences de la Terre, Grenoble, France
- Prof Joerg Schumacher, Institut fuer Thermo-und Fluiddynamik, TU Ilmenau, Germany

3. Some Important Results from Tarang

i) **Hydrodynamic turbulence:** We simulate hydrodynamic turbulence using TARANG in a grid of 4096^3 resolution. We show that the numerical results match well with Pao's predictions ($E_u(k) \sim \exp(-k^{\frac{4}{3}})$) rather than Pope's predictions for both inertial and dissipative ranges. See Fig. (1)

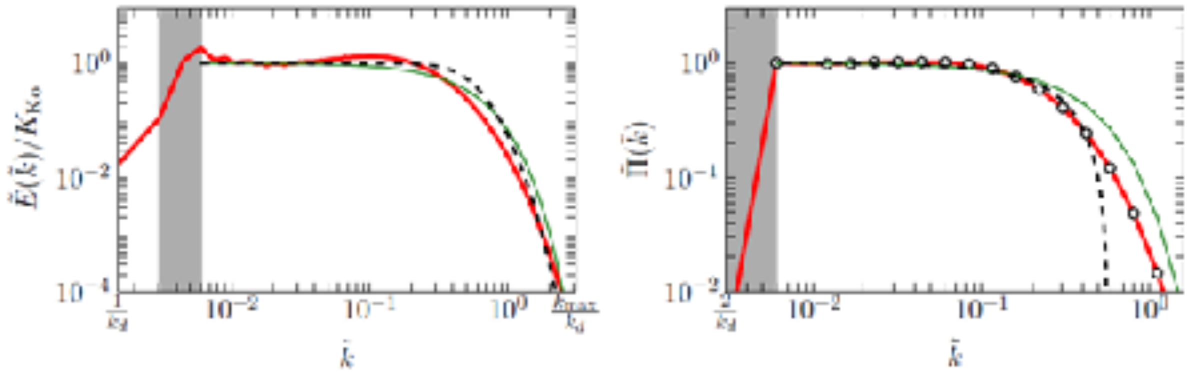

Figure 1: For hydrodynamic turbulence simulation with grid resolution of 4096^3: (Left) Plots of the normalized energy spectrum vs wave number, and (Right) plots of the normalized energy flux with wave number. The green solid line represents the model prediction of Pao, while the black dashed line represents that of Pope.

ii) **Rayleigh-Bénard Convection (RBC):** We simulate RBC for 4096^3 grid resolution – the highest ever employed for such studies. We study for Rayleigh-Number $\mathrm{Ra} = 1.1 \times 10^{11}$ - the largest for any spectral simulation. Using the simulation results, we show that turbulent thermal convection exhibits $E_u(k) \sim k^{-5/3}$, similar to hydrodynamic turbulence (1). See Figs. (2) and (3).

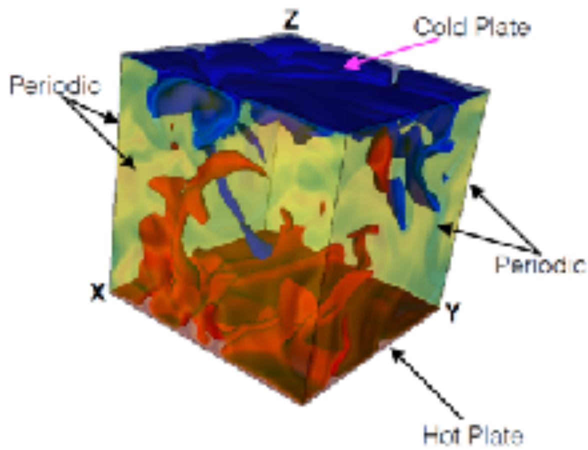

Figure 2: For RBC simulation on 4096^3 grid: Isocontours of two constant temperatures. The hot and cold structures of the flow are represented by the red and blue contours respectively.

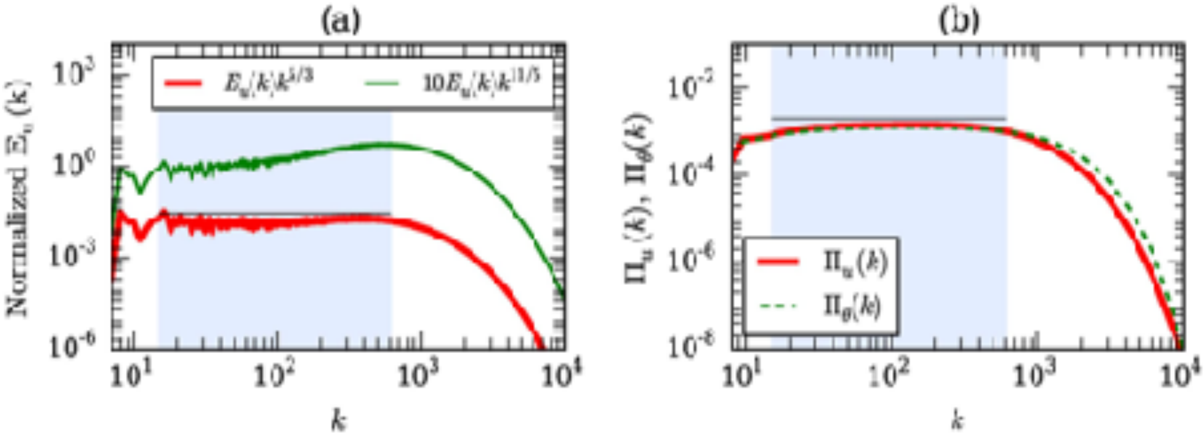

Figure 3: For RBC simulation with Pr = 1 and Ra = 1.1×10^{11} on 4096^3 grid: (a) Plots of normalized Kinetic Energy (KE) spectra for Bolgiano-Obukhov (BO) and Kolmogorov-Obukhov (KO) scaling; KO fits better with the data than BO scaling. (b) KE flux $\Pi_u(k)$ and entropy flux $\Pi_\theta(k)$. The shaded region exhibits the inertial range. Taken from Verma et *al.* (1).

iii) **Stably Stratified Turbulence (SST):** We simulate turbulent stably stratified flow for Froude number (Fr) = 10), Ra = 5×10^3 and Pr = 1. The numerical data fits better with Bolgiano-Obukhov (BO) scaling ($E_u(k) \sim k^{-11/5}$ than the Kolmogorov-Obukhov (KO) scaling, thus confirming the BO phenomology for SST turbulence (1). See Fig. 4.

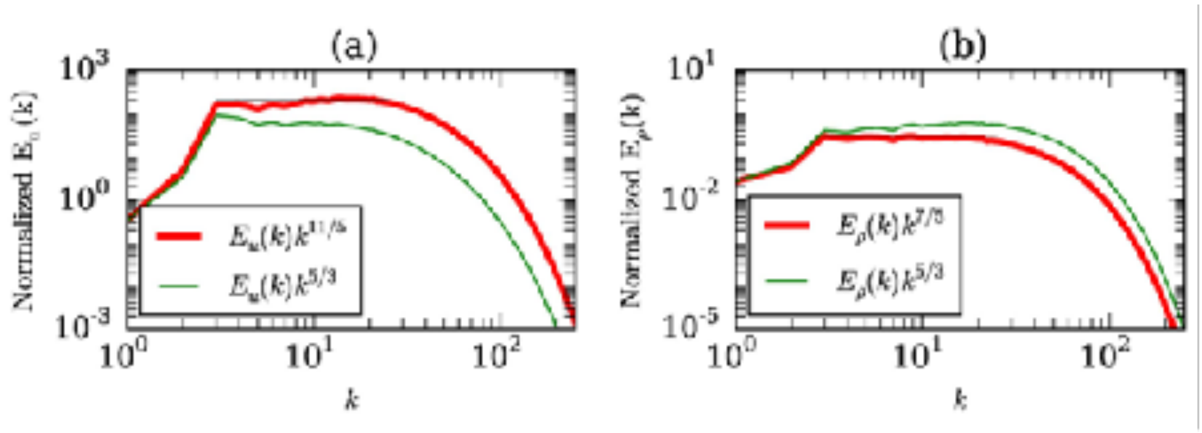

Figure 4: For the stably stratified turbulence with Pr = 1, Ra = 5×10^3, Fr = 10: Plots of (a) normalized kinetic energy and (b) potential energy spectra for Bolgiano-Obukhov (red) and Kolmogorov-Obukhov (green) scaling. Bolgiano-Obukhov scaling fits the data better than the Kolmogorov-Obukhov scaling. . Taken from Kumar et *al.* (2)

iv) **Rotating turbulence:** We simulate rapidly rotating decaying turbulence on 512^3 grid. We find that as the flow evolves in time, it becomes quasi-two dimensional with strong coherent columnar structures arising due to the inverse cascade of energy (3). See Fig. (5).

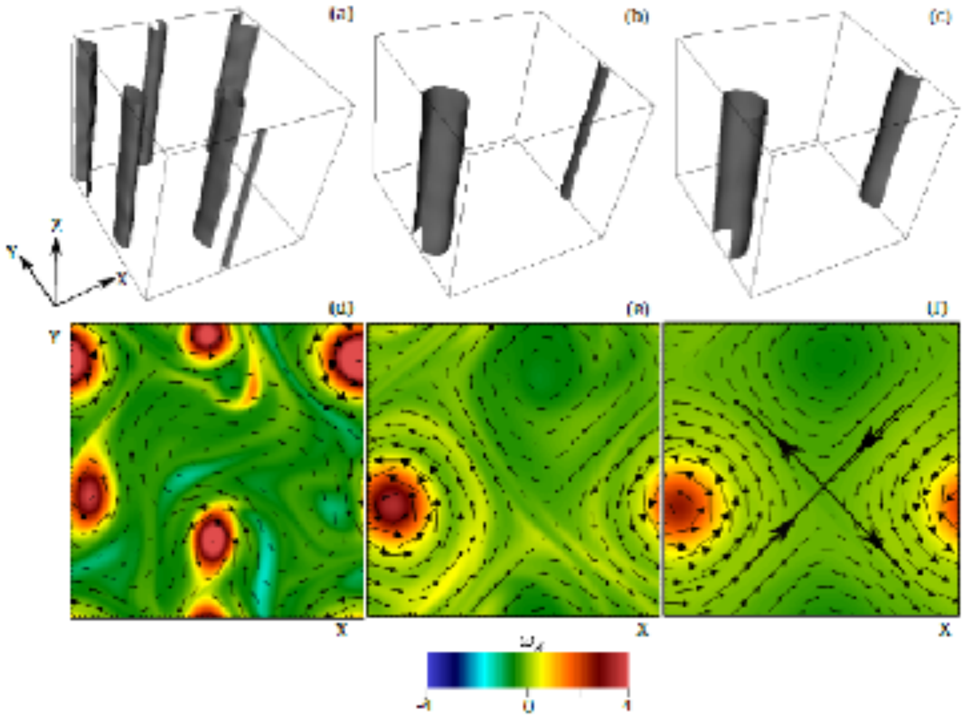

Figure 5: For the rapidly rotating decaying turbulence on 512x512x512 grid: The top panel exhibits the isosurfaces of the magnitude of vorticity $|\omega|$ at (a) $t = 49$, (b) $t = 98$, and (c) $t = 148$. The bottom panel shows velocity vector plot superposed with density plot for ω_z for the horizontal section at $z = \pi$ at (d) $t = 49$, (e) $t = 98$ and (f) $t = 148$. Taken from Sharma et *al.* (3).

4. Publications on Tarang

Number of publications from Prof. Verma's group: **30**

Number of publications from other groups: **14**

5. Tarang in Media

A key discovery observed by using Tarang was that the turbulence in Rayleigh-Benard Convection is better characterized by Kolmogorov's model instead of Bolgiano-Obukhov as was previously believed. This achievement has been highlighted in Nature India on 15th November, 2017. The details can be found in the following link:

https://www.natureasia.com/en/nindia/article/10.1038/nindia.2017.139

Reference

1. *Phenomology of buoyancy-driven turbulence: recent results.* **Verma, Mahendra Kumar, Kumar, Abhishek and Pandey, Ambrish.** s.l. : New Journal of Physics, 2017, Vol. 19.

2. *Energy spectrum of buoyancy-driven turbulence.* **Kumar, Abhishek, Chatterjee, Anando Gopal and Verma, Mahendra Kumar.** 2, s.l. : Physics Review E, 2014, Vol. 90.

3. *Statistical features of rapidly rotating decaying turbulence: enstrophy and energy spectra, and coherent structures.* **Sharma, Manohar Kumar, et al.** 2018, Physics of Fluids, p. In press.