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The GASpAR code for geophysical turbulent flows

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We present a status report on the Geophysical Astrophysical Spectral element Adaptive Refinement (GASpAR) code developed within the Geophysical Turbulence Program at NCAR.

Turbulent flows are ubiquitous, and as manifestations of one of the last outstanding unsolved problems of classical physics, they form today the focus of numerous investigations; they are linked to many issues in the geosciences, *e.g.,* in meteorology, oceanography, climatology, ecology, solar–terrestrial interactions and fusion, as well as dynamo effects generated by convection, compositional gradients or thermospheric winds and leading to geomagnetic variations through atmosphere-ionosphere coupling.

Nonlinearities prevail in turbulent flows when the Reynolds number $\Re$ —which measures, as a control parameter, the amount of active temporal or spatial scales in the problem— is large; the number of degrees of freedom increases as $\Re^{9/4}$ for $\Re \gg 1$ in the Kolmogorov (1941) framework, and for geophysical flows, often $\Re > 10^8$. The ability to probe large $\Re$, and to examine in detail the large-scale behavior of turbulent flows, depends critically on the ability to resolve adequately such a large number of spatial and temporal scales, or else to model them, or a combination of both.

One intriguing observation concerning turbulent flows, such as in the atmosphere and the oceans, resides in the departure from normality in the probability distribution functions. The origin of these fat wings is not understood; they appear in many nonlinear problems with a wide range of excited scales. One does not know yet what structures are key to our understanding the statistical properties of turbulent flows (*e.g.,* vortex sheets, spirals or filaments, shocks or fronts, blobs, plumes or tetrads, knots, helices, tubes or arches). The link between structures and non-Gaussian statistics is the basis for the notion of intermittency which plays a role *e.g.,* in reactive flows, in convective plumes, in combustion, in the heating of the solar corona or in the chemistry of the interstellar medium because nonlinear interactions alter local chemical contact rates. It may also be at the origin of the random reversal of the magnetic field of the Earth. However, intermittency is not included explicitly in models of these processes; furthermore, it is not clear whether the overall statistics of the flow at large scale will be affected by this omission, or if so, how intermittency should be incorporated.

Theory demands that computations of turbulent flows reflect a clear scale separation between the energy-containing, inertial (self-similar) and dissipative ranges. Convergence studies on compressible flows show that to achieve the desired scale separation between the energy-containing modes and the dissipation regime, it is necessary to compute on regular grids of at least 2048^3 cells (Sytine *et al.*, 2000).

Today such computations can barely be accomplished. A pseudo-spectral Navier-Stokes code on a grid of 4096^3 regularly spaced points has been run on the Earth Simulator (Isihara *et al.*, 2003) but the Taylor Reynolds number is still of the order of 500, still very far from what is asked for in geophysics. Adaptivity seems to be needed, provided thesignificant structures of the flow are indeed sparse so that their dynamics be followed accurately although such structures are embedded in random noise.

We have built an object-oriented code, GASpAR, that is flexible enough to be applicable to a wide class of turbulent-flow and other multi-scale problems. The computational core is based on spectral element operators, which are represented as objects. The formalism accommodates both conforming and nonconforming elements, and their associated data structures for handling inter-element communications in a parallel environment. Dynamic adaptive mesh (nonconforming h-type) refinement is provided for, and its suitablity for turbulent flow models will be examined. The first application of the code will concern the Hwa-Kardar (1989) equations, which arise when writing the dynamical version of self-organized criticality. These equations can serve as a model of solar flares when viewed as overlapping avalanches (Liu *et al.*, 2003).

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