Computational methods for approaching slow manifolds, tracking extreme events, and understanding multi-scale dynamics

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Abstract: Fluid dynamics and plasma physics present a dazzling array of problems with very wide scale separation in both space and time. Such problems are typified by turbulence, which can exhibit factors of 10^{12} between the largest and smallest spatial scales and 10^{13} between the fastest and slowest dynamical times. These problems, and many others, are modeled using partial differential equations. I will present a series of strategies for accurately and expediently solving the relevant model PDEs in order to extract physical insight into a wide variety of systems. I will focus on the solution to a pair of geophysical and astrophysical problems involving turbulent convection, magnetic fields, and rotation. In particular, I will discuss the application of a new class of model PDEs called Direct Statistical Simulation, applicable for a broad class of problems with anisotropic flows. These methods solve for a cumulant hierarchy rather than the field variables directly and provide new insights into non-linear multi-scale interactions. In doing so, I will also address the not insignificant but often overlooked challenge of putting new discoveries in applied mathematics into the hands of practitioners in a wide variety of disciplines. I will highlight the use of the Dedalus Project, a flexible toolkit for solving almost arbitrary PDEs that my collaborators and I have developed.