OCEAN DYNAMICS AND MODELING

HYPOP: I'm part of the Climate Ocean and Sea Ice Modeling (COSIM) team at LANL. In this role, I presently work on the developement of HYPOP, a hybrid vertical coordinate version of POP (Parallel Ocean Program.) The latter, developed at LANL from GFDL's modular ocean model is one of the most widely used z-coordinate OGCM and is the ocean component of NCAR's Community Climate System Model.

POP vs MICOM: Prior to being part of the HYPOP model development team, I was involved, in the COSIM effort to characterize and understand the differences in the representation of the thermohaline circulation (THC) in POP and Miami Isopycnic Coordinate Ocean Model (MICOM.) These two OGCMs are based on the same governing equations but adopt fundamentally different formulations and numerical techniques. The main difference is that POP uses depth as the vertical coordinate while MICOM uses potential density as the vertical coordinate. The interplay of numerics and physics could not be better illustrated than in the way POP and MICOM finally represent ocean circulation. The specific setup consists of a global domain, bulk forcing through a Kraus-Turner mixed layer with specified atmospheric climatology (no restoring boundary conditions), and a simple ice model (`public.lanl.gov/balu/micom.html`.)

Besides my involvement in COSIM, I have maintained an independent set of research interests in GFD in general and 'dynamics of ocean circulation' in particular. I have had them funded mostly through small one or two PI projects. Oceans are an important component of the earth's climate system and many issues of climate change are closely tied to transport processes in the oceans. Transport in the oceans is primarily acheived by (1) the surface-intensified wind-driven circulation and (2) the buoyancy-driven Thermo-Haline Circulation (THC) I'm working on specific aspects of these component modes using both realistic Ocean General Circulation Models (OGCMs) and their more idealized counterparts, as briefly described below.

MESOSCALE EDDIES (50-100 kms) play a vital role in large scale ocean circulation, but cannot be adequately resolved in long term simulations and must therefore be parameterized. In separate studies of wind-driven and buoyancy-driven components, I use idealized eddy-resolving models of ocean basins in an effort to understand eddy-induced transport processes and to investigate and develop parameterizations of these processes (`public.lanl.gov/balu/Turb.html`.)

GULF STREAM SEPARATION: Idealized studies of flow past a cylinder on a β-plane by Tansley and Marshall (2001) imply that the Reynolds number of the vertically-homogeneous flow may play an important role in the separation of Western Boundary Currents (WBC). By simulating the vertically-homogeneous flow in the world oceans using realistic topography and coastlines, I'm hoping to shed more light on this aspect of WBC separation.

THC DYNAMICS: I'm using MICOM in the global setup previously mentioned to study the role of Ekman drift at the latitudes of the ACC in determining the rate of formation of deep water in the North Atlantic.

LARGE EDDY SIMULATION (LES) is a powerful computational tool that has come to play a central role in the investigation of turbulent, three dimensional, fluid flows that are of both scientific and engineering importance. However, the use of these ideas in climate modeling, i.e., in the modeling of atmospheric and oceanic turbulence is severely lacking and does not extend beyond the most elementary ideas of eddy viscosity. We also note that very different physical phenomena underlie the mesoscale turbulence of the atmosphere and the ocean, as compared to the much smaller scale three dimensional turbulence that is previously referred to. In recent work, we have investigated the use of a class of LES models in modeling mesoscale turbulence in idealized Geophysical Fluid Dynamics (GFD) problems and demonstrated the viability of some of these models in reproducing important aspects of both eddy-driven mean circulation and eddy-induced variability at coarse resolutions that resolve only the largest of the eddy scales. I plan to extend this LES work to more realistic ocean circulation problems, both by implementing these LES schemes in OGCMs, and investigating a hierarcy of test problems involving both wind-driven and buoyancy-driven circulation. (`public.lanl.gov/balu/les1.pdf`)

DYNAMICAL SYSTEMS APPROACHES: With a view to better understanding low-frequency variability of the climate system, I use dynamical-systems ideas and tools in analysing the dynamics of the atmosphere-ocean system, in a fashion complementary to the usual methods of analysing such systems. For example, in a recent article, we point out the important role played by global bifurcations (as opposed to local bifurcations) in explaining the variability arising in models of the wind-driven double gyre circulation in the oceans (`public.lanl.gov/balu/Dynsys.html`.)

iPOP: Long-term changes in climate are crucially controlled by the global ocean. However, because of limitations inherent to the numerical techniques that underlie present day ocean models, state-of-the-art climate change simulations resolve the oceans only very coarsely. Rather than evolve the strongly-coupled multiple-scale ocean system on the fastest time scale, as is done in present day models, with this project, one is able to evolve the dynamics on the long time scales of interest through a series of quasi-steady states wherein the fast scales are continually equilibrated. In collaboration with Mark Taylor, we have implemented recently developed, sophisticated, fully-implicit integration techniques in a version of POP. This is intended to make possible long-term simulations of ocean circulation at high resolutions and should serve as a prototype for the next generation of climate-ocean models. (`public.lanl.gov/balu/iPOP`)

FLUID DYNAMICS RESEARCH INTERESTS

COARSE-GRAINED FLUID DYNAMICAL MODELS: Given the finite resolution of computations, two classes of problems in fluid dynamics invariably run into numerical difficulties: First is the category of fluid interfaces which are thought of as infinitesimally thin. This will be discussed in a separate section below. Second, in nonlinearly cascading flows, various dynamical quantities (e.g., enstrophy in two- and three-dimensions) continually flow down to the small scales and something has to be done about it. In a purely dissipative regularization of the small scales, one appeals to the presence of viscosity in nature and therefore simply dissipates whatever arrives at the smallest resolved scales. The downside of this is that the viscosity chosen is usually orders of magnitude greater than in the physical process under consideration and more often than not is determined by the ability to run the numerical code stably. On the other hand, one could implement inviscid dispersive processes at the smallest resolved scales to represent the rectified action of rapid subgrid-scale processes, in addition to the (now subsidiary) dissipative processes necessary to balance the input of energy and enstrophy in forced flows. This line of investigation has been very rewarding in that the equations governing such models have also proved useful in describing vortex methods wherein the velocity field is mollified (vortex-blob method) and have previously arisen in the study of viscoelastic fluids (`public.lanl.gov/balu/Turb.html`.)

PHASE FIELD MODELING OF INTERFACES: The numerical modeling of fluid-fluid interfaces as sharp discontinuities is fraught with problems in that the grid spacing places a limit on the resolution and in the face of sharp gradients at grid scales, most numerical schemes perform poorly. However, that interfaces have non-zero thickness was realized (as early as the late nineteenth century) by Lord Rayleigh and gradient theories were proposed by van der Waals and Korteweg. But it has been only in the past few years that this mesoscopic, free energy-based description of an interface has been used to computational advantage in simulating interfaces, somewhat in analogy with the use of artificial viscosity to capture shocks. After having demonstrated the feasibility of using such an approach in realistic fluid dynamical situations, I'm now interested in using this technique in various problems and hybridizing it with various other numerical flow simulation schemes. (`public.lanl.gov/balu/Diffuse_interface.html`)

KINETIC THEORY AND DISCRETE-VELOCITY MODELS: While in highly rarefied regimes (large Knudsen numbers Kn), Monte Carlo techniques can be used to effectively solve the Boltzmann equations, hydrodynamic equations like Euler equations or Navier-Stokes equations can be used to describe fluid flow in much denser regimes ($Kn \ll 1$). In the intervening transitional regimes ($Kn = O(1)$), however, the numerical stiffness of the Boltzmann equations make them very expensive to be used effectively. There is therefore considerable incentive in employing, say the Navier-Stokes approximation as far outside the fluid dynamical regime as may be physically justifiable. Towards this end, we have identified "moment realizability criteria" entirely in terms of quantities inherent to the Navier-Stokes approximation and which can be used to montinor the internal validity of such simulations. Thus, problem regions of the flow can be flagged to suggest alternative descriptions and avoid large errors in momentum and energy fluxes.

For the same transitional regimes, there have also been suggested various descriptions intermediate between the Navier-Stokes and Boltzmann approximations. They typically consist of equations describing the evolution of a larger set of moments (of the single particle distribution function) than just the mass, momentum, and energy and such approximations are termed "higher-order moment closures". There are, however, few cases in which their utility in the transitional regimes has been established. It is in this context that discrete-velocity models have a valuable role to play. With their typical small set of allowable velocities, exact solution of the model Boltzmann equations is possible without recourse to Monte-Carlo like techniques and thus a clear evaluation of the utility of "higher-order moment closures" may be obtained.

Besides serving as a testbed for various closures, discrete-velocity models are an excellent pedagogical tool for most concepts of classical kinetic theory. Their rich structure can infact be exploited to motivate and emphasize the use of some constructs which are perhaps not well appreciated in the classical context. An example is the use of Legendre transforms and conjugate variables to ease the analysis and formulation of various closures: Navier-Stokes approximation via the Chapman-Enskog expansion is best done for the discrete-velocity models using these conjugate variables and so are some of the "higher-order moment closure" schemes in classical kinetic theory. (`public.lanl.gov/balu/DKT.html`)

My other research interests in fluid mechanics include

- Nonhydrostatic effects in shallow fluid flows and associated wave equations (`public.lanl.gov/balu/obstacle.html`, `.../nonhydro/nonhydro.html`)
- Analysis and effective computation of systems with multiple time scales (`public.lanl.gov/balu/moa.html`)
- Bifurcation structure and Low-dimensional dynamics in pdes describing various flows
- Lattice Boltzmann and Lattice Gas methods for pdes
- Time series analysis, Singular Spectrum analysis, Principal Orthogonal Decomposition