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Making Waves in the Sun

Named from the Greek word photos (light), the photosphere is the deepest part of the sun that can be seen by the naked eye. Observations of the photosphere reveal that the solar surface rotates differentially with a 26-day period at the equator and a 31-day period at 60 degrees latitude. Helioseismic inversions, a technique that utilizes propagating sound waves within the Sun to probe its interior structure and dynamics, indicate persistence of this mean surface-flow pattern down to the base of an unstably stratified turbulent convection zone, encompassing the outer 200,000 km directly beneath the photosphere. At this depth, the latitudinal variation of rotation rapidly decreases and vanishes to a state of solid body rotation in a stably stratified interior, encompassing the inner 500,000 km. The thin, radially sheared transition zone between the unstable and stable regions of the solar interior is called the tachocline.

The upper portion of the tachocline is characterized by coupled shear and penetrative overshoot that act to force deeper stably stratified motions. The lower tachocline lies in the stably stratified interior, and it is believed to be crucial for magnetic-flux storage and release, and therefore critical for the solar dynamo that operates on the 22-year sunspot cycle. The lower tachocline is characterized by stably stratified and sheared MHD instability, turbulence, and waves.

The detailed dynamical behavior of the tachocline region is currently poorly understood. Important and basic questions, like "What determines the thickness of the tachocline?" remain unanswered. Current theoretical ideas suggest anisotropic mixing processes govern tachocline thickness, but demonstration of the basic processes (never mind quantitative description!) remains wanting.

Candidate physical phenomena that participate in the dynamics of the tachocline begin with down-welling fluid from the convection zone. Such convective overshoot disturbs the upper portion of the stable interior and is thought to generate gravity waves that propagate downward. The shear in the tachocline may induce overturning and breaking of the gravity waves, resulting in local patches and layers of anisotropic turbulence and mean-flow acceleration. Furthermore, strong magnetic fields influence the evolution, dynamics, and anisotropic mixing of the region.

Characterizing the nature of the resulting inhomogeneous and anisotropic mixing and mean-flow-generation mechanisms are challenging problems. Headway is made piecemeal, as researchers attack specific aspects of the problem. New techniques and algorithms must be developed and implemented. Without the availability of resources like those at SDSC, progress in modeling this important region of the solar interior would be impossible.

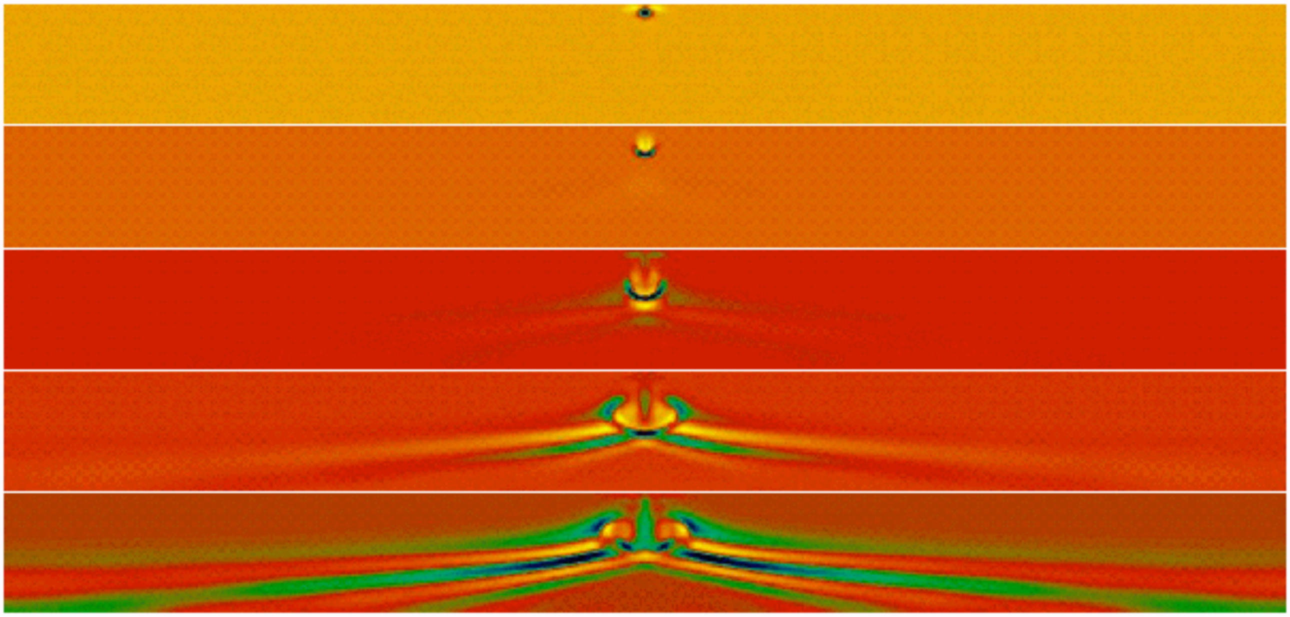

Figure 1: Time series depicting the generation of gravity waves in a stable layer from the impact of a thermal plume from above. The top half of the numerical domain is shown. (Click on image for larger view.)

Figure 1 shows a pseudo-spectral simulation of an isolated, heavy plume descending from a modeled solar convection zone. The calculation is accomplished by evolving the spectra using a mixed implicit/explicit third-order Runge-Kutta timestepping method. Images of the temperature time derivative are shown; perturbations caused by the head of the plume appear initially as the small blue region near the top of the domain. When the plume impacts the underlying stable layer, gravity waves are generated and propagate downward. The gravity waves can be seen as slanted lines in the lower half of the domain.

Near the lower boundary in the simulations, a sponge layer employing Rayleigh damping and Newton cooling is used in an attempt to circumvent unwanted reflections of gravity waves back into the domain interior. Such sponge layers have been used with acceptable results to minimize the impact of reflected waves on convection-zone dynamics; however, the damping such near-boundary layers provide is imperfect, and wave reflections, albeit of much lower amplitudes than would occur in their absence, do indeed result. Unfortunately, dynamics in the stable region are much more sensitive to reflected waves than in the convection zone, and stable-layer analysis is therefore restricted to only very short times immediately after plume impact.

The same problem exists for other boundary techniques we have tried, including the wave-transmitting conditions proposed by Klemp and Durran (1983, *Mon. Weather Rev.*, Vol 111, pp 430-444) and modifications of both the damping layer and the transmitting boundary techniques. We are currently implementing a new boundary technique we have developed that makes use of so-called Perfectly Matched Layer (PML) methods developed over the last few years in the fields of computational electromagnetics and ideal-fluid acoustics (e.g., Abarbanel, Gottlieb and Hesthaven, 1999, *Journal of Computational Physics*, Vol 154, pp 266-283). Preliminary test results are extremely promising and will allow diagnosis of gravity waves generated throughout the evolution of plume overshoot, not simply the earliest times, as is the case now.

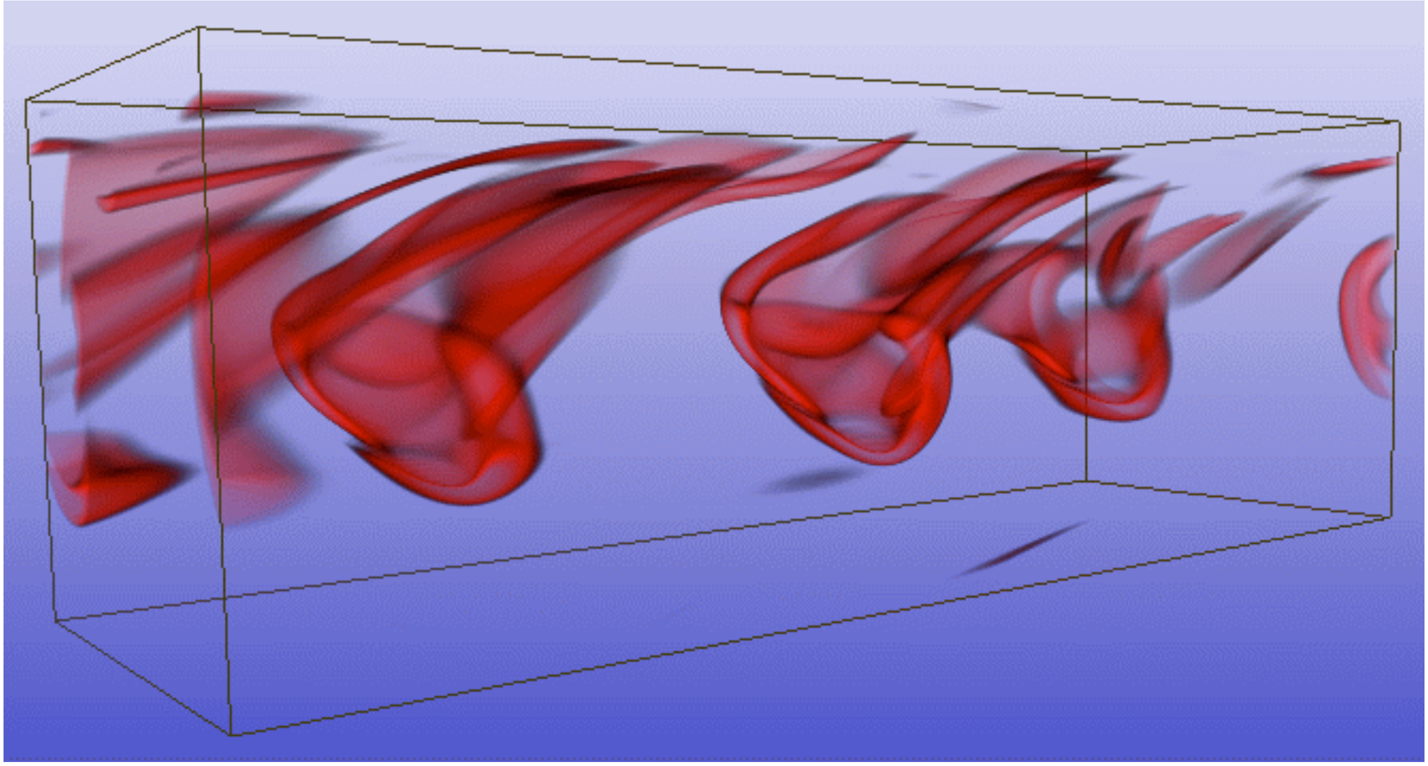

Figure 2: Coherent vortex-loop structures which appear spontaneously during gravity-wave breaking. Vorticity magnitude shown in red outlines hairpin like features which become entangled and instigate the transition to small-length-scale turbulence.

Figures 2 and 3 show work on another component of our program, the breaking of gravity waves generated by plume impacts. This simulation includes only the stable region of the solar interior. Large-amplitude gravity waves propagate downward, then break as small-length-scale 3-D perturbations grow to nonlinear amplitudes. During intermediate times (Figure 2, middle panel of Figure 3), coherent structures in the form of three interleaved vortex loops interact and instigate the transition to smaller scales of motion. Both figures show the magnitude of fluid vorticity. Figure 3 shows a 3-D volume rendering of the coherent vortex-loop structures, while Figure 2 shows the evolution in a vertical 2-D slice. The time depicted in the middle panel of Figure 3 is the same as that used in Figure 2.

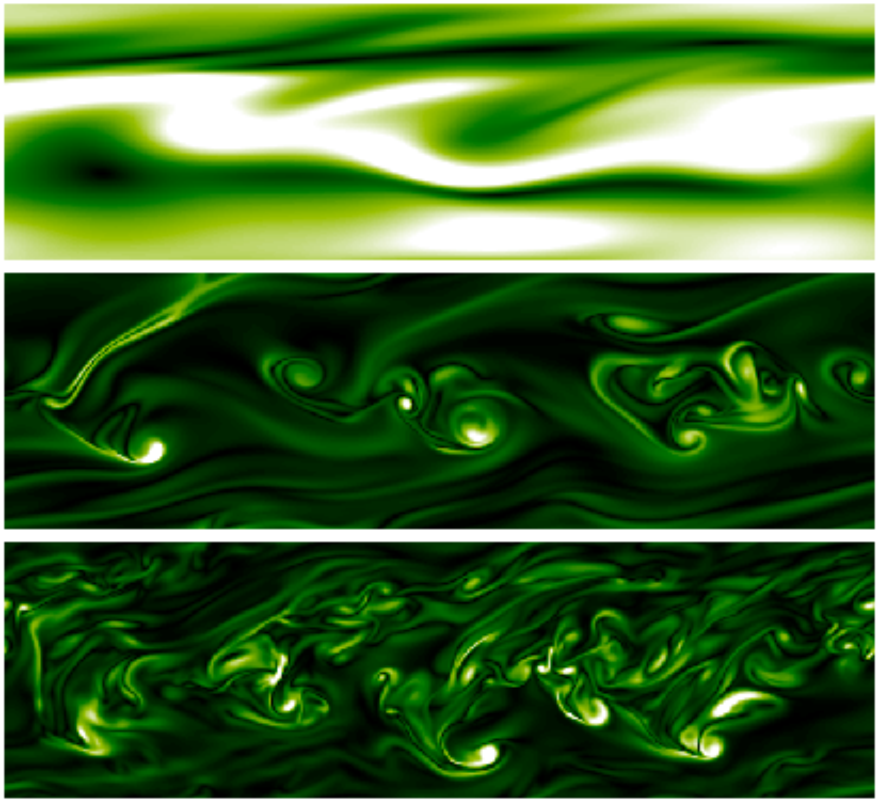

Figure 3: Time sequence of vorticity magnitude for a breaking gravity wave and subsequent generation of small-length-scale turbulence.
(Click on image for larger view.)

Ongoing and current work concentrates on the effects of shear and poloidal and toroidal magnetic fields as well as improved lower boundary conditions for the coupled stable/unstable layer simulations.

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