Simulations of a Combined Convection Zone and Coronal System

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Abstract
We present recent results from a numerical simulation of a magnetized, compressible fluid confined to a spherical segment, spanning the solar convection zone, chromosphere, and corona. In this model, the bottom half of the simulation domain is convectively unstable, driven by an imposed heat flux at the bottom of the layer. This convective layer is coupled to a model chromosphere and corona, which are cooled and heated (respectively) to match a solar-like temperature profile. We are thus able to self-consistently model the dynamics associated with magnetic structures in the solar atmosphere as they evolve in response to subphotospheric, turbulent convection. We present simulations of arcade-like reconnection in the presence of supergranule-scale flows and discuss possible observational consequences.

Motivation and Background
The dynamic coupling between evolving magnetic structures visible in the solar corona and the vigorous fluid motions that inhabit the solar convection zone is just beginning to be understood. The turbulent convection below the photosphere continually redistributes the magnetic field, as magnetic structures are stretched, twisted, and otherwise reorganized in response to fluid motions. Such dynamics influence the structure and heating of the solar corona by advecting the photospheric footpoints of coronal magnetic loops, thereby causing changes in the coronal field topology that may ultimately trigger flares, coronal mass ejections, and other eruptive events.

In this paper, we present results of three-dimensional numerical simulations of fully compressible, magnetized fluids in spherical geometry. An initial large-scale bipolar magnetic field is imposed within localized spherical segments, simulating a fully emerged active region. Convection on the (approximate) scale of solar supergranulation is driven by imposing a temperature flux at the lower boundary of the domain. We investigate the resulting dynamics within our simulation domain.

Convection Zone Simulations...
Perspective views of the spherical segment domains are shown in Figure 1, illustrating the patterns formed by a magnetized compressible fluid. The broad convection cells have swept the magnetic field into the network of downflow lanes that separate neighboring cells. This morphology is typical of compressible magnetosconvection.

Figure 2 illustrates a rendering of the density field, wherein the gray-scale surface height is proportional to the density at the top of the layer. The corresponding velocities and magnetic field are represented by yellow and blue conical pointers.

...Coupled to a Coronal Layer
Using the fully convective simulations as a jumping-off point, we have extended the upper radial boundary of the simulation to include a passively heated layer above the convection, thereby approximating the corona of the sun. Such simulations enable the magnetic loops in the corona to evolve in a self-consistent manner as their respective footpoints are advected by fluid motions within the convection zone. The runs of temperature and density throughout the full domain of a prototype simulation are shown in Figure 3. The simulation is initialized so that a transition from high to low plasma occurs near the photospheric boundary. At present, the simulated coronal layer is passively heated to a fixed temperature equal to 10 times that of the photosphere. The simulation also includes a shallow, Newtonian-cooled chromospheric layer situated between the convection zone and corona.

Figure 4 illustrates the vertical velocity (center) and temperature gradients (left and right) superimposed on a three-dimensional representation of the magnetic field lines (blue), plasma streamlines (red), and density contours (green). The thermal energy in the convection zone is transported through the corona by propagating waves up to the upper boundary, where the density variations vanish. The bottom boundary is set by the solar photosphere, which is maintained at a constant temperature. The stratification of the convection layer is set by the polytropic index $n = 1.45$, while in the atmosphere matching exponentials are strung together in a piecewise fashion. The gas has a $\gamma = 5/3$. The magnetic field is assumed to be purely radial at both radial boundaries, while the latitudinal sidewalls are assumed to be perfectly conducting.

Numerical Model
We solve the fully compressible MHD equations for a non-rotating spherical segment:

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} - \mathbf{U} \times \mathbf{B}$$

The equations are non-dimensionalized using the depth of the convecting layer $d = R_s R_c$, and the state variables $\rho_e$, $T_e$, and $p_e$ at the upper boundary. Time is measured in units of the isothermal sound crossing time at the upper boundary, $\Delta t = \sqrt{R_s/(2\pi \rho_0)}$, where $R_s$ is the gas constant. The radial boundaries of the convecting layer are located at $R_s = 24$ and $R_s = 25$, and may be extended to include a model corona with an upper radius $R_s = 26$. The outer boundaries and imposed stress-free: the lateral sidewalls at $\theta_1$ and $\theta_2$ are assumed impermeable and stress-free, and the domain is periodic in longitude. A temperature gradient $\Delta T = 10$ is applied across the convection zone, while the upper boundary is held at constant temperature. The stratification of the convection layer is set by the polytropic index $n = 1.45$, while in the atmosphere matching exponentials are strung together in a piecewise fashion. The gas has a $\gamma = 5/3$. The magnetic field is assumed to be purely radial at both radial boundaries, while the latitudinal sidewalls are assumed to be perfectly conducting.

Conclusions and Future Work
- The simulation is initialized with a purely radial, bipolar magnetic field, which in the convection zone can then be advected by the ensuing fluid motions. In the low-$\beta$ atmosphere, the initial response is a pinching of the field lines, as the model chromosphere (Figures 4a-b) where the magnetic pressure force is the greatest. The net effect is to generate a downward plume within the approximate portion of the convection zone along the neutral line. Meanwhile, at the base of the convection zone immediately, the magnetic field pinches together in the corona, a response to the greater magnetic pressure force located there, forming an arcade-like structure in the simulated convection zone and U-loops in the model corona. Meanwhile, the fluid motions in the convection zone have advected the footpoints of the field away from the neutral line, generating currents (Figures 4c-d).

- As is typical for compressible convection, we find that the fluid within convection cells rapidly expels field to cell boundaries, even in regions where there is significant magnetic flux. We also find an enhancement in density surrounding the strongest magnetic field concentrations, which is likely a compressional effect as fluid parcels buffet the flux tube.

- Self-consistently coupling a low-$\beta$ environment (such as our model corona) to the layer of convection allows the investigation of topics such as: how emergent bipole affects the topology of the corona, how currents might be generated in coronal loop structures, how and where stresses build up that might lead to eruptive events, how helicity changes over time, etc.

- At present, our simulations are in the nascent stages, and thus we have not witnessed many of the dynamical events we expect to occur. Yet, we believe we have developed an environment in which to investigate many topics of current interest.

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