Numerical Simulations Can Lead to New Insights

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Abstract.
Numerical simulations can lead to new insights into astrophysical processes that would be difficult to achieve otherwise. We present a few examples from our 1.5D radiation-magneto-hydrodynamic calculations and 3D convection calculations:

1. Magnetic field free regions of the chromosphere have enhanced emission without any increase in the average gas temperature.

2. Solar convection is driven non-locally by cool, turbulent, filamentary, downdrafts produced by radiative cooling in the surface boundary layer.

3. The lower part of the solar convection zone is slightly stably stratified.

1. Introduction
Numerical simulations can lead to new insights into astrophysical processes that would be difficult to achieve otherwise. We present a few examples from one-dimensional radiation hydrodynamic and three-dimensional magneto-hydrodynamic simulations of the solar atmosphere and convection zone.

2. Solar Chromosphere
To model dynamics of the solar atmosphere we solve the 1.5-dimensional conservation equations, the induction equation, the non-LTE radiative transfer equation, and the equations for atomic level populations. All quantities are a function of height and time only. We solve the equations implicitly on an adaptive mesh (Dorfi and Drury 1987) using Van Leer's (1977) second order upwind advection
scheme and Scharmer’s method for calculating the radiative transfer (Scharmer and Carlsson 1985).

These radiation hydrodynamic simulations of the solar atmosphere have radically changed our view of the solar chromosphere. They have shown that enhanced chromospheric emission, which corresponds to an outwardly increasing semi-empirical temperature structure, can be produced by acoustic waves without any increase in the mean gas temperature (Fig 1). Localized, brief periods of high temperature behind shocks lead to enhanced emission in the ultraviolet, where the emission is an exponential function of temperature. Integrated over time, the viscous shock dissipation is balanced by the radiative cooling and there is no increase in temperature. There is, however, an increase in radiation (radiative cooling). The semi-empirical chromospheric temperature rise is an artifact of temporal averaging of the highly non-linear UV emission. The Sun does not have a classical chromosphere in magnetic field free internetwork regions (Carlsson and Stein 1995).

![Figure 1. Time averaged (Mean) gas temperature in the simulation and the semi-empirical temperature that gives the best fit to the time average of the emergent intensity from the simulation. Also shown are: the minimum and maximum (range) temperatures in the simulation, the starting model temperature, and the semi-empirical model of Fontenala, Avrett & Loeser, 1993. The semi-empirical model giving the same intensities as the dynamical simulation shows a chromospheric temperature rise while the mean temperature in the simulation does not.](image)

3. **Solar Surface Convection**

To model convection we solve the three-dimensional equations of mass, momentum and energy conservation and the induction equation in non-conservative form on a non-staggered grid. We use a tabular realistic equation of state, including ionization energy. Radiative energy exchange is critical in determining the structure of the upper convection zone. Since the top of the convection zone occurs near the level where the continuum optical depth is one, neither the optically thin nor the diffusion approximations give reasonable results. We therefore include 3D, LTE radiation transfer in our model (Nordland 1982). We use a third order leapfrog predictor corrector in time (Hyman 1979) and calculate spatial
derivatives using compact third and sixth order fits to the functions (Lele 1992). The code is stabilized by a hyper-viscosity which removes short wavelength noise without damping the longer wavelengths. Horizontal boundaries are periodic, the top boundary is transmitting, and at the bottom boundary we specify the entropy of the incoming fluid, zero net mass flux and make pressure uniform over the bottom boundary (Nordlund and Stein 1990).

Such realistic simulations of convection near the solar surface have lead to a paradigm shift in our perception of convection. Convection is inherently non-local. It is driven from the surface boundary layer, on the intermediate scale of granulation, by radiative cooling which produces low entropy fluid that descends in the intergranule lanes and merges into filamentary downdrafts that penetrate through the convection zone (Figs 2 and 3). Most of the buoyancy work that drives the convection occurs in these overdense downdrafts. They drive both larger scale laminar cellular flows and smaller scale turbulent motions. This new paradigm replaces the older one of energy cascade from large scale driven eddies to smaller eddies.

Figure 2. Motion of fluid parcels. The location of fluid parcels which are moving upward through the visible surface at a given time, are shown 9 minutes earlier and later. These form the interiors of the granules. Nine minutes earlier, most of this fluid has come from about the same depth below the surface, but from a much smaller region of the horizontal plane, because the upflows diverge in order to conserve mass. Only a small fraction of fluid reaches the surface where it can cool by radiating to space. Nine minutes later, these fluid parcels are heading downward with large velocity and have converged into filaments.

Shear at the edges of the downflows creates vorticity and turbulence in the downdrafts (Fig 4). Ascending fluid, in contrast, has a very low level of fluctuations, because it diverges and overturns as it rises in order to conserve mass as it enters lower density layers. Hence, the upflows are laminar and entropy neutral (Nordlund and Stein 1995).

4. Solar Interior Convection

To model the deep layers of the solar convection zone we use a three-dimensional magneto-hydrodynamic code that solves the equations for conservation of mass,
Figure 3. Entropy fluctuations. They occur primarily as low entropy, filamentary, downdrafts, descending through nearly uniform, entropy neutral ascending fluid and are produced by radiative cooling of fluid that reaches the surface.

momentum and internal energy in conservative form together with the induction equation for the magnetic field, on a staggered mesh. An ideal equation of state is used (Stein, Galsgaard and Nordlund 1993). Radiation transfer is treated in the diffusion approximations using a Kramer’s type opacity. In order to reduce the thermal relaxation time, we increase the energy flux to $10^7$ times the solar value, so this is a “toy model”.

Simulations of such highly idealized models of the deep layers of the solar convection zone have revealed that the entropy structure in the bulk of the convection zone is slightly stable, due to the gradual transition from radiative to convective energy transport (Fig 5). The radiative flux decreases with increasing height, because the Kramer’s opacity increases with decreasing temperature. This heats both the ascending and descending gas. As a result, the entropy of the ascending fluid increases with height and the entropy of the descending fluid increases with depth (the entropy of descending fluid also increases with depth due to entrainment). Given the intermittency of cool, descending fluid, the median and average entropy increases slightly with height, producing a slightly stable entropy gradient (Fig 5 and 6). It is also clear from Fig 6 that entropy fluctuations injected into the ascending fluid at the bottom boundary layer of the convection zone are much smaller than the those injected into descending fluid by radiative cooling in the top boundary layer of the convection zone (Nordlund and Stein 1995).

5. Conclusion

We have called attention to three significant new insights into the structure of the solar chromosphere and convection zone arising from the analysis of numerical simulations: the lack of a chromospheric gas temperature increase in magnetic field free regions, the non-local driving of convection on intermediate scales arising from radiative cooling at the top boundary layer of the convection zone, and the slightly stable stratification of the bulk of the convection zone.
Figure 4. Vorticity. It is produced by the shear of overturning flows and occurs primarily in the intergranule lanes and the filamentary downdrafts. Upflows, in contrast, are very laminar and free of vorticity because the upflow diverges and all fluctuations get smoothed out quickly.

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References

Figure 5. The total energy flux and the fluxes that contribute to it (enthalpy, radiative, kinetic energy and viscous) are shown for a toy solar model along with the mean entropy. Entropy decreases rapidly with height near the top boundary of the convective layer (very unstable) due to radiative cooling. In the bulk of the convection zone the mean entropy is nearly constant, but increases slightly with height (slightly stable) because radiation heats the fluid and increases its entropy.

Figure 6. Histogram of entropy fluctuations at each depth. The minimum entropy, corresponding to the coolest downdrafts, increases toward the bottom of the convection zone. The entropy contrast decreases with depth because ascending, entropy neutral, fluid overturns and mixes with the entropy deficient descending fluid. The median entropy (the darkest band) decreases slightly with depth in the bulk of the convection zone, because radiation heats the fluid.