Supergranulation Scale Convection Simulations

Robert F. Stein,¹ Anders Lagerfjärd,² Åke Nordlund,² Dali Georgobiani,¹ David Benson,³ and Werner Schaffenberger¹

Abstract. Results of realistic simulations of solar surface convection on the scale of supergranules (48 and 96 Mm wide by 20 Mm deep) are presented. The simulations include the hydrogen, first and most of the second helium ionization zones. Horizontal magnetic field is advected into the domain by upflows at the bottom. Upflows stretch the field lines upward, while downflows push them down, thus producing loop like magnetic structures. The mass mixing length is 1.8 scale heights. Two thirds of the area is upflowing fluid except very close to the surface. The internal (ionization) energy flux is the largest contributor to the convective flux for temperatures less than 40,000 K and the thermal energy flux is the largest contributor at higher temperatures. The data is available for evaluating local helioseismic procedures.

1. The Simulation

Solar surface magneto-convection in a domain 24 Mm wide by 20 Mm deep and hydrodynamic-convection in a domain 96 Mm wide by 20 Mm deep was simulated by solving the conservation equations for mass, momentum and internal energy and the induction equation for the magnetic field. Spatial derivatives were evaluated using sixth order finite differences (Nagarajan, Lele and Ferziger 2003) with scalar variables defined at cell centers, and vector variables defined at cell faces, except for the electric current which is defined at the cell edges. Time advance was by a low memory, third order Runge-Kutta scheme (Kennedy, Carpenter and Lewis 1999). The calculations were performed on grids of 250², 500² and 1000² × 500 giving resolutions of 96, 48 and 24 km horizontally and 12-75 km vertically. Horizontal boundary conditions are periodic, while top and bottom boundary conditions are open. Div B = 0 is maintained to machine accuracy, but errors accumulate in a random pattern, so the magnetic field is cleaned every 30 sec solar time. f-plane rotation is included corresponding to a latitude of 30 deg.

A tabular equation of state which includes local thermodynamic equilibrium (LTE) ionization of the abundant elements as well as hydrogen molecule formation, was used to obtain the pressure and temperature as a function of log density and internal energy per unit mass. The radiative heating/cooling was obtained by solving the radiation transfer equation in both continua and

¹Michigan State University, East Lansing, MI 48824-2320, USA
²Niels Bohr Institute, Copenhagen, DK-2100, DK
³Kettering University, Flint, MI 48504, USA
The computational domain covers five orders of magnitude in pressure in the convective region, which is half the scale heights in the entire solar convection zone, even though the domain is only 10% of the zones geometric depth. It includes the hydrogen ionization layer and the first and most of the second helium ionization layers. The horizontal scale of the convection increases from granule size at the surface to supergranule size near the bottom of the computational domain.

2. Magneto-Convection

Two magneto-convection experiments have been initiated. Both start from a snapshot of hydrodynamic solar surface convection with dimensions 24 Mm wide by 20 Mm deep. In the first case, there is no initial magnetic field in the computational domain and horizontal magnetic field is advected into the domain by upflows at the bottom of the domain. It is found that the field strength evolves over a turnover time to a power law distribution roughly proportional to the square root of the mean density. In the second case, there is an initial horizontal field everywhere with its strength increasing with depth in accordance with an idealization of the distribution found in the first case, that is, as the square root of the density.

In both experiments, it is found that the magnetic field is stretched by the upflows to form loops with their legs anchored in the downflows (Fig. 1). This is similar to the results of Cheung et al. (2007, 2008), but occurring over a much larger width and depth range. This large range in depth means a large range in the horizontal scale of the convective motions from granules of the order of a Mm at the surface to small supergranules of the dimensions of the domain (24 Mm) near the bottom. This produces a hierarchy of loop structures.
When a loop like magnetic flux concentration emerges through the surface it alters the appearance of the granules. Fig. 2 shows a time sequence of temperature and magnetic field patterns at the level where the mean temperature is 5700 K. As more flux emerges the granules become larger and stretched in the direction of the field. The imposed field is in the x-direction.

3. Mixing Length

The mass mixing length is the inverse of the logarithmic derivative of the unidirectional (either up or down) mass flux. Figure 3 shows that over most of the computational domain except right near the surface the mass mixing length is 1.8 pressure scale heights. This is an easy, unambiguous, calculation to make for other stars as well to determine the appropriate mixing length.

4. Energy Fluxes

Most of the energy in the cooler part of the convection zone close to the surface where hydrogen is partially ionized is carried by the internal (ionization) energy flux. At temperatures above 40,000 K, this decreases and most of the energy is transported by the thermal energy flux (Fig. 3).

5. Driving and Damping

Convection on the Sun is driven primarily by radiative cooling in a thin boundary layer at the bottom of the photosphere where radiation begins to escape to space. Radiative cooling produces low entropy, over dense fluid that is pulled down by gravity. About 3/4 of the buoyancy work occurs in the downflows and 1/4 in the upflows, except close to the surface where it is approximately equal. Driving is maximal on the scale of the locally dominant scale of the convective motions.
6. Summary

Supergranulation scale convection simulations have shown how the combination of upflows and downflows produces loop like flux concentrations. It is found that the field strength approaches a distribution proportional to the square root of the density. It has also been possible to determine the mass mixing length \((1.8 H_P)\), and to show that most of the energy is transported as ionization energy below 40,000 K and as thermal energy above that temperature. Buoyancy driving is largest closest to the surface and occurs mostly in the downflows (75%).

Acknowledgments. The calculations were performed on the NASA High End Computing Columbia supercomputer and on the steno cluster of the Danish Center for Scientific Computing (DCSC/KU). Support for this project was provided by NASA grants NNX07AO71G, NNX07AH79G, NNX07AI08G and NNX08AH44G, NSF grant AST 0605738 and the Danish Natural Science Research Council. This support is greatly appreciated.

References

M. C. M. Cheung, M. Schussler, and F. Moreno-Insertis 2007, Astron. and Astrophys., 467, 703-719
A. Nordlund, Astron. and Astrophys. 1982, 107, 1–10