SUPERGRANULE SCALE CONVECTION SIMULATIONS

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ABSTRACT

Results from a realistic supergranulation scale simulation of solar convection are presented. The size of horizontal cellular structures increases gradually and continuously with increasing depth. There is no preferred size except for granulation. Broad upflows at larger depths sweep aside the more closely spaced downflows above, merging them into larger downflows at larger depths. The convection excites a rich spectrum of oscillations in the simulation that closely match those observed by SOHO/MDI. The velocity spectrum can be separated into convective and oscillation mode contributions using a phase speed of 6 km/s in the $k - \omega$ plane. The horizontal velocities are almost exclusively convective. The vertical velocities are primarily convective at small scales and oscillatory at large scales. To reduce noise, velocity power for each time should be averaged, rather than calculating the spectrum of the time-averaged velocities—the latter introduces spurious features.

Key words: Sun: convection, supergranules.

1. INTRODUCTION

We have realistically simulated solar surface convection on supergranules scales (48 Mm wide by 20 Mm deep). Realism is achieved: by using an equation of state that includes ionization and excitation of hydrogen, helium and the other abundant elements, by calculating the radiative heating/cooling assuming Local Thermodynamic Equilibrium, and by solving the Feautrier equations for the intensity along a vertical and four inclined rays that rotate in angle each time step, using a multigroup binning of the opacity and source functions. The simulations were bootstrapped from narrower domains where they were relaxed for 3.6 turnover times and have been run for 65 hours (solar time), which is 1.4 turnover times at the 48 Mm wide size. The results of these simulations are being made available on the MDI data base in FITS format.

2. CONVECTION MORPHOLOGY

Convection has a cellular pattern in horizontal planes, with compact upflows surrounded by more or less continuous downflow lanes. The size of the upflows increases continuously with depth (Fig. 1). How does this come about? It is the result of mass conservation. Most of the fluid moving upward at a given depth has to turn over and head back down within a scale height. As a result, the horizontal size of the upflows is the order a scale height which increases with increasing temperature at larger depths [1],

$$r = 2HV_{\rm horiz}/V_{\rm vert}\ , \qquad (1)$$

where r is the horizontal size of the upflow, H the scale height, $V_{\rm horiz}$ and $V_{\rm vert}$ the horizontal and and vertical flow velocities in the diverging upflow. Mass conservation takes care of itself by acting through the pressure. If there is insufficient pressure to push enough mass out horizontally, then density increases in the upflow until the pressure is raised sufficiently to expel it.

The result of mass conservation is that the upflows diverge horizontally. This diverging flow sweeps the smaller scale downflows above sideways, merging them into larger, more widely spaced downflows (Fig. 2). The upflows also decelerate, halt and disperse weaker downflows from above that are trying to beat their way down against the strongest upflows. Above the boundaries of the larger cells at depth, where the fluid is moving downward, there is no resistance to the downflows above, so it is here that the downflows collect and penetrate to large depths.

3. VELOCITY SPECTRUM

The velocity spectrum is $\sqrt{kP(k)}$, where $P(k)$ is the velocity power and k the wavevector. This has the advantage that its units are velocity and it is independent of the units of k. It increases approximately as a power law from giant cells down to granular scales and then decreases for still smaller scales (Fig. 3). The morphology from granules to giant cells is self similar. Granules are the only distinct scale of motion, although there is a small increase in amplitude at supergranule scales.

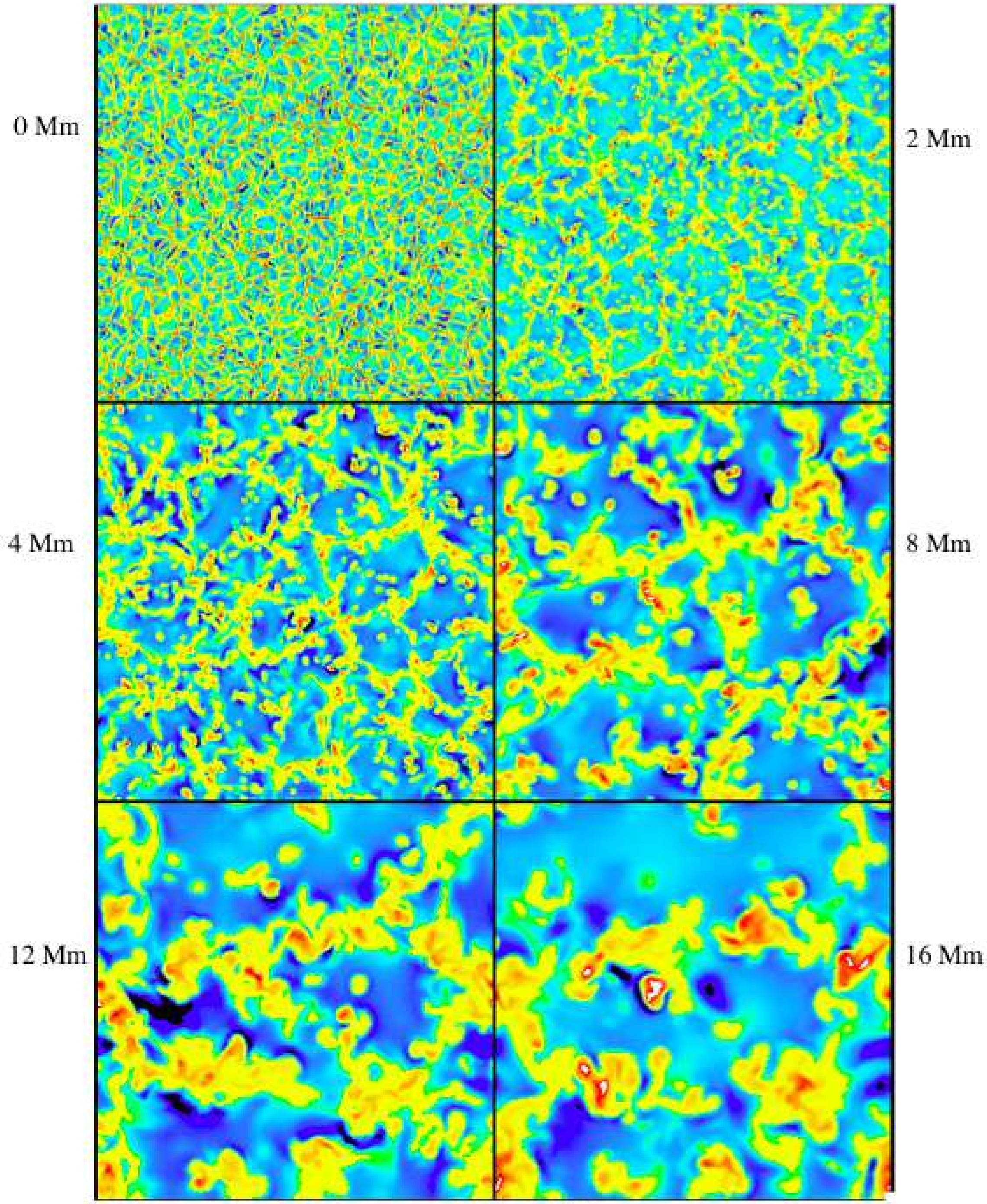

Figure 1. Vertical velocity in horizontal planes at the surface and 2, 4, 8, 12, and 16 Mm below the surface from a simulation snapshot. Note how the horizontal scale of the structures increases continuously with increasing depth from granules at the surface to supergranules at 12 or 16 Mm.

A subsonic/supersonic filter can be used to separate the convective and oscillatory contributions to the spectrum (Fig. 3). At and above the visible surface the horizontal velocity is almost exclusively convective in origin, while the vertical velocity is due to both convection and oscillations. At granular scales the convective motion dominates the vertical velocity, while at large scales the oscillation motion dominates.

It matters how the spectrum is computed in order to reduce the noise (fig. 4). The appropriate method for reducing noise in the spectrum is to average the individual velocity power spectra for each time, then multiply by the wave vector and take the square root. Some have first

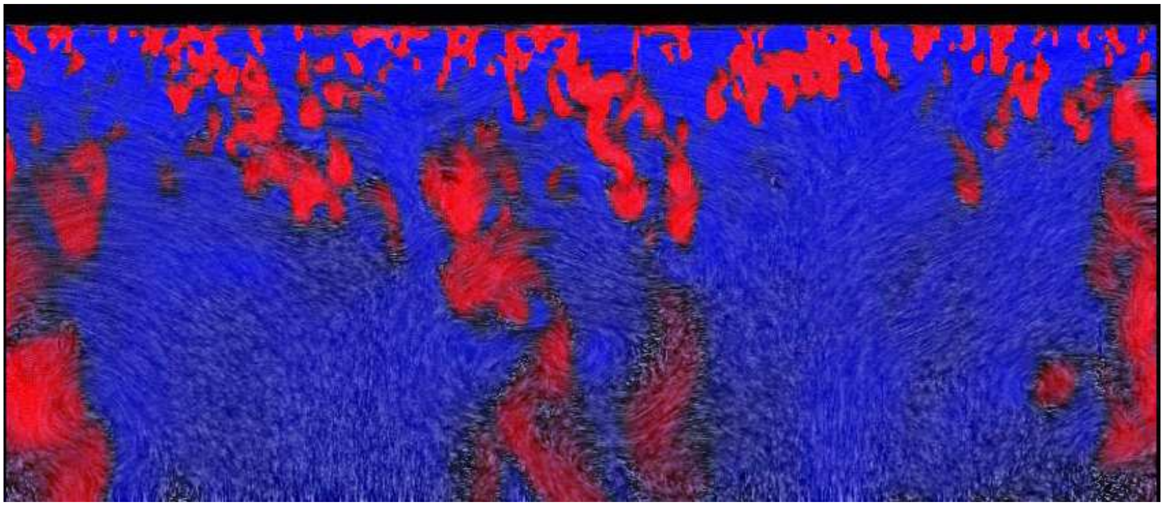

Figure 2. Velocity in a vertical slice. At the top there are many downflows. Some of these get swept sideways and merged by the diverging upflows from below. Some downflows get halted by the upflows. As a result, there are fewer, larger, more widely spaced downflows deeper into the convection zone.

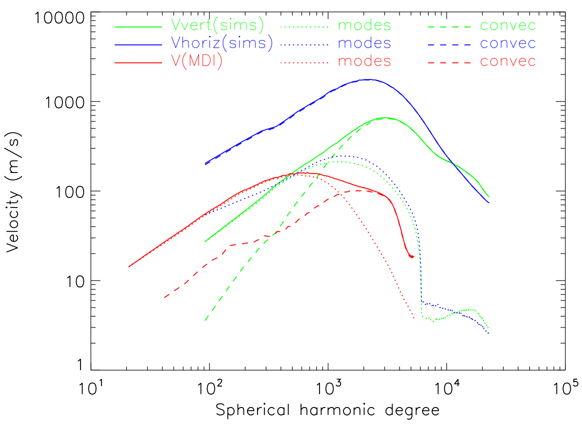

Figure 3. Velocity spectrum of simulation horizontal and vertical velocity at a height of 200 km above $\tau_{500} = 1$ and MDI high resolution line of sight (LOS) velocity. The total velocity (solid lines) and its oscillation (dotted lines) and convection (dashed lines) contributions are shown. The horizontal velocity is almost entirely convective in origin. The vertical and LOS velocities are primarily convective at granulation scales and oscillation modes at large scales. There is a slight increase in power at supergranulation scales in the convective component of the MDI velocity power.

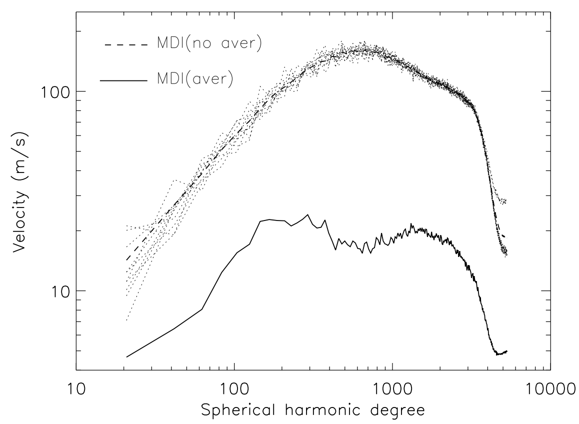

Figure 4. Velocity spectrum, the square root of the average of the velocity power spectra times the wave vector, for MDI high resolution data. The spectra for 10 individual times are shown dotted. The velocity spectrum from the average of the individual power spectrum is shown dashed. It is smooth because it is the ensemble average of many noisy realizations. The spectrum of the time average velocity is shown solid. It is the spectrum of only a single realization so it is noisy. It's shape is distorted and unphysical features have been introduced.

averaged the velocity over time and then calculated the power spectrum of the average velocity. This approach gives a spectrum of only a single realization so it is noisy. This method also reduces the power at scales that change over times shorter than the averaging interval, which produces a distorted flattened spectrum, and introduces artificial features (Fig. 4). The appropriate way to make larger scale features visible in the presence of larger amplitude smaller motions is to filter in Fourier space, removing both high frequency and large wave vector power.

4. OSCILLATIONS

These simulations have a large enough computational domain both horizontally and vertically and extend for a long enough duration so that they possess a rich spectrum of f- and p-modes (Fig. 5). They allow us, for the

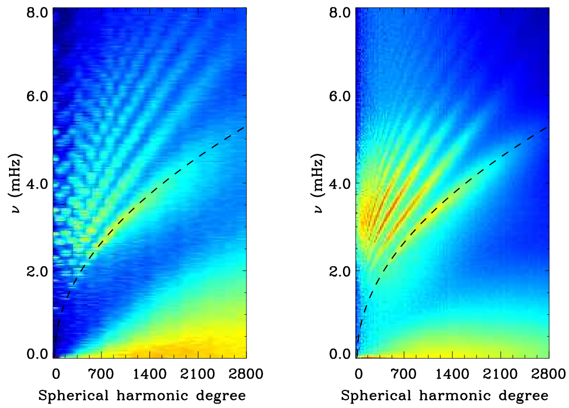

Figure 5. The power spectra ($\ell - \nu$ diagrams) for the simulated vertical velocity (left) and the Doppler velocity from the MDI high-resolution observations (right). The dark curve represents the theoretical f-mode. The simulation has a rich spectrum of $f-$ and $p-$ modes, but is sparser than the Sun because of the size of the computational domain.

first time, to test the inversion methods used in local helioseismology and also to evaluate how close the realistic simulations are to the Sun. Such tests are particularly important for the local helioseismology methods, which are based on simplified models of wave propagation. For this purpose, the simulation results are being made available on the MDI data base. They are in FITS format, one directory for each time step (at one minute intervals), one file per variable.

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