

Solar Surface Magnetoconvection

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Abstract.

Magnetoconvection simulations on meso-granule and granule scales near the solar surface are used to study small scale dynamo activity, the emergence and disappearance of magnetic flux tubes, and the formation and evolution of micropores.

From weak seed fields, convective motions produce highly intermittent magnetic fields in the intergranular lanes which collect over the boundaries of the underlying meso-granular scale cells. Instances of both emerging magnetic flux loops and magnetic flux disappearing from the surface occur in the simulations. We show an example of a flux tube collapsing to kG field strength and discuss how the nature of flux disappearance can be investigated. Observed Stokes profiles of small magnetic structures are severely distorted by telescope diffraction and seeing.

Because of the strong stratification, there is little recycling of plasma and field in the surface layers. Recycling instead occurs by exchange with the deep layers of the convection zone. Plasma and field from the surface descend through the convection zone and rise again toward the surface. Because only a tiny fraction of plasma rising up from deep in the convection zone reaches the surface due to mass conservation, little of the magnetic energy resides in the near surface layers. Thus the dynamo acting on weak incoherent fields is global, rather than a local surface dynamo.

1. Introduction

We model magnetoconvection in a small domain near the solar surface by solving the partial differential equations for mass, momentum and internal energy conservation and the induction equation for the vector potential. Our goal is to make a realistic representation of the solar surface (Stein & Nordlund 2000). Our domain is 6×6 Mm horizontally and extends from the temperature minimum, 0.5 Mm above continuum optical depth unity, to 2.5 Mm below the visible surface, using a grid $253 \times 253 \times 163$ grid points, which gives a horizontal resolution of 25 km and a vertical resolution of 15 km near the surface increasing

to 35 km at the bottom. The initial state was a snapshot of non-magnetic solar convection on which was imposed a uniform magnetic field: either a horizontal seed field of 1 G or 30 G, or a vertical field of 400 G. The boundary conditions are periodicity in horizontal directions, open boundaries for the fluid in the vertical direction, the magnetic field at the top tends toward a potential field. The magnetic bottom boundary condition for horizontal seed fields was that inflows advect in horizontal 1G or 30G field, while in outflows the vector potential is advanced in time from the induction equation with the current calculated using spline derivatives with the cubic spline condition that the third derivative is continuous. The magnetic bottom boundary condition for the vertical field was that the field tend toward the vertical. Rotation and coriolis forces are neglected, because on this small scale of mesogranulation, with a depth of only 3 Mm, the flows don't feel the rotation.

2. Three-dimensional Effects on the Mean Structure

The mean atmospheric structure is different in 3D than in 1D. There are two major reasons for this. First is a 3D radiative transfer effect. The temperature is very inhomogeneous near the surface of stars. In cool stars the dominant opacity source is H^- , which is very temperature sensitive – hot gas is much more opaque than cool gas. As a result, we only see the cool gas. Therefore, the average temperature, for a given effective temperature, is higher in 3D models than in 1D models and thus the scale height is larger and the atmosphere more extended. Second, convective motions produce a turbulent pressure which also contributes to the support of the atmosphere. The net effect of these two phenomena together is that atmosphere is raised about one full scale height in the 3D models compared to the 1D models.

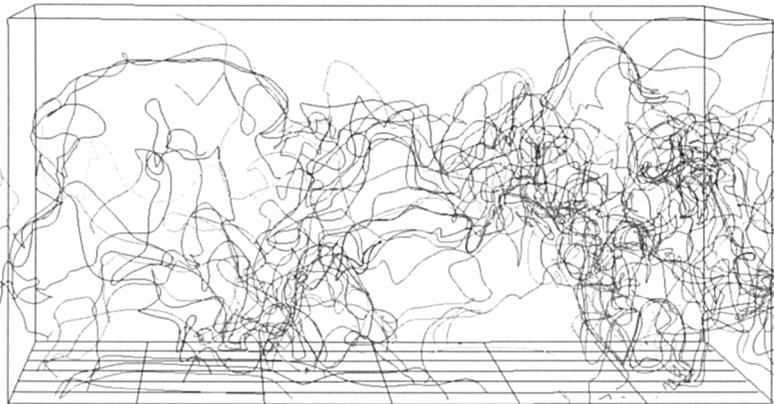


Figure 1. Selected magnetic field lines in a snapshot viewed from the side. Horizontal field is advected in by ascending flow at the bottom boundary. It gets advected, stretched and twisted by the convective motions.

3. Magnetoconvection

3.1. Magnetic Field Organization

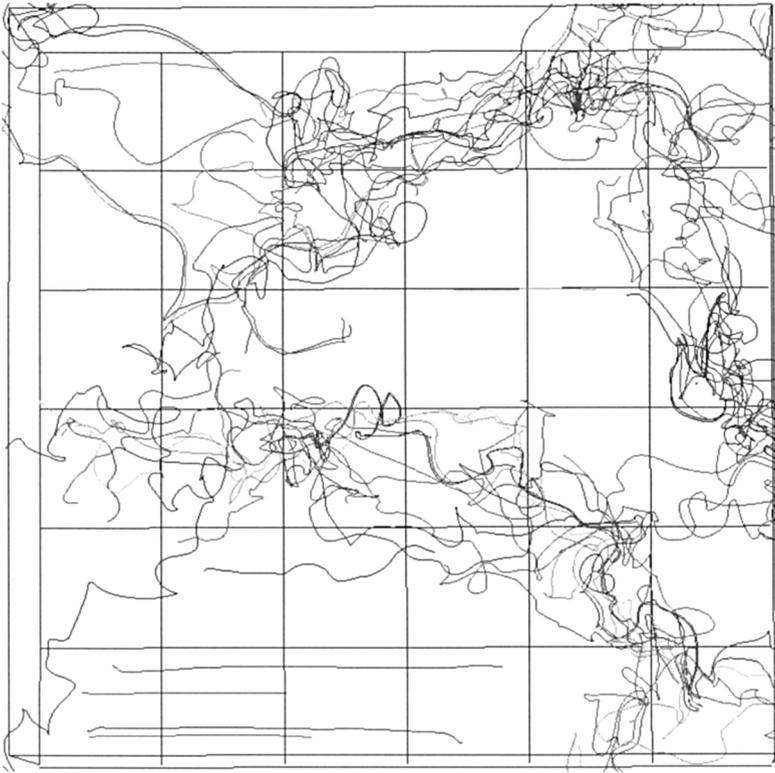


Figure 2. The same magnetic field lines as in Fig 1, viewed from the top. Squares at the bottom are 1×1 Mm. The magnetic field is advected into the computational domain by upflows in the interiors of the mesogranules and is swept out of the granules and mesogranules into the downflows in the mesogranule boundaries.

For the case of horizontal field advected in from the bottom, to date we have run an almost two hour sequence with a 1G field and a 30 min. sequence with a 30 G field. Figure 1 shows selected magnetic fieldlines for one snapshot for the 30G case. At the bottom there is horizontal magnetic field being advected into the computational domain by ascending fluid. Higher up are the twisted filed lines produced by the turbulent convective motions. It looks pretty chaotic. However, viewed from the top one sees that the the field is actually organized on a larger scale than the granulation (Fig. 2). It is being organized on the scale of the underlying mesogranules. The horizontal field is entering in the interiors of the mesogranules where there are the upflows. The overlying magnetic field has been twisted and stretched and swept out of the granules and mesogranules into the boundaries of the mesogranules, where the plasma is descending. This

produces a highly intermittent field with a stretched exponential distribution of field strengths, as has been found in the Boussinesq calculations of Cattaneo (1999) and as observed by, e.g. Harvey & White (1999) and Hagenaar (2001). This means that the stronger the field the tinier the fraction of the area it occupies. Fields stronger than 3 G, fill all the intergranular lanes and exist even inside some of the granules. Fields that are stronger than 30 G have been swept out of the granules into the intergranular lanes and even some the intergranular lanes have no field stronger than 30 G. Finally, fields stronger than 300G occur hardly anywhere in the domain (Fig. 3).

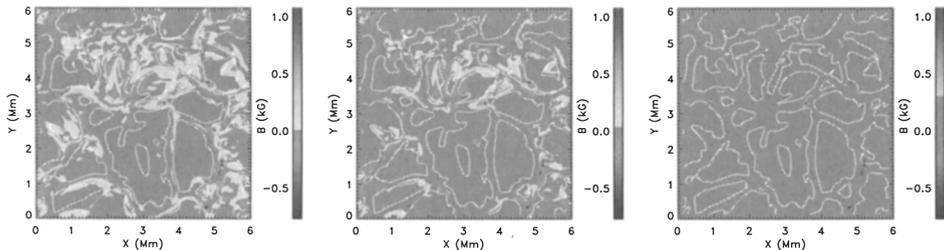


Figure 3. Image of magnetic field with superimposed zero velocity contours to outline the granules for the case of a 30 G uniform horizontal seed field. Field magnitudes less than 3, 30 and 300 G respectively are shown in gray. The magnetic field is concentrated into the intergranular lanes. It is highly intermittent, with strong fields occupying a tiny fraction of the total area.

3.2. Flux Emergence and Disappearance

In these simulation we see examples of flux emergence, merging, fragmentation, and cancellation. Figure 4 is a sequence of images at 10 sec. intervals showing a flux loop emerging on the right hand side and its foot points separating. New flux emerges sometimes inside granules, sometimes at their edges, and sometimes in intergranular lanes. Flux emerging inside granules is quickly swept into intergranular lanes by the diverging upflows of the granulation. Inside the intergranular lanes, the magnetic field is advected by horizontal flows (cf. Stein & Nordlund 1998). At the same time, on the left side, oppositely (vertical component) directed flux is coming together and partially annihilating. We still need to analyze this process to see what is actually occurring.

3.3. Stokes Profile Observations

Resolution has a tremendous impact on how one interprets observations. At low resolution (even with the old 47 cm Swedish Solar Telescope on La Palma) magnetograms show objects that look like round flux tubes (Fig. 5, left image). The new telescope with twice the diameter will reveal a much more complex structure (center image), while the simulations show that the actual situation is even more complex (right image). The topology of the observed field may be

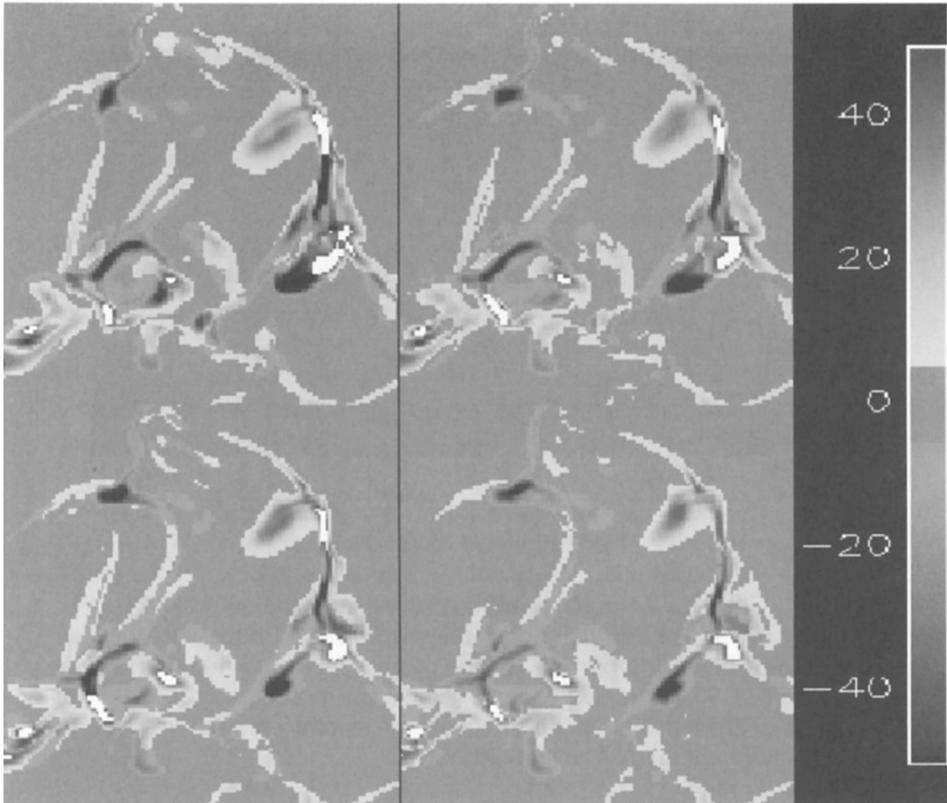


Figure 4. Four snapshots of the surface magnetic field magnitude at 10 sec. intervals (TL, TR, BL, BR) showing the emergence and footpoint separation of a magnetic loop on the right hand side and the disappearance of magnetic flux on the left hand side.

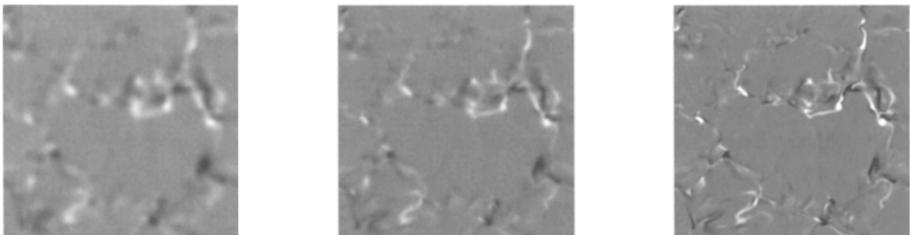


Figure 5. Stokes V image as it would be observed with perfect seeing at the old 47 cm Swedish Solar Telescope on La Palma (left), the new 97 cm telescope (center), and the image as obtained from the simulation (right).

dramatically altered at low resolution. Hence, high resolution observations are crucial for learning the actual solar magnetic field structure.

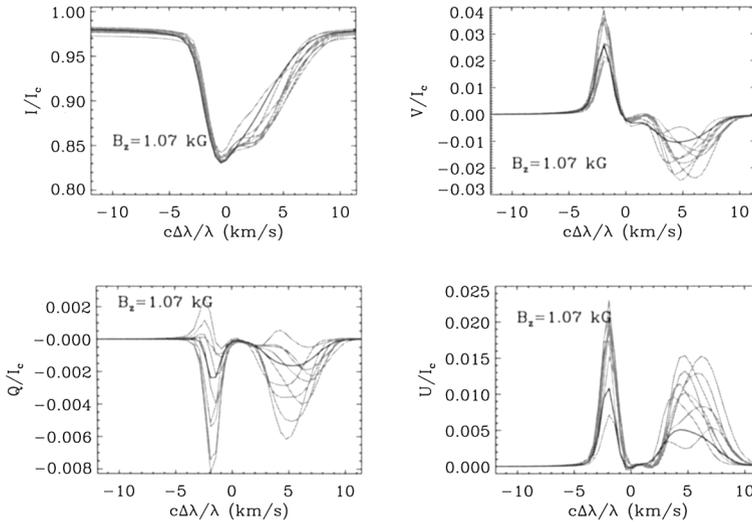


Figure 6. Stokes I,V,Q,U profiles for Fe I $\lambda 6302 \text{ \AA}$ as would be observed by the 97 cm Swedish Solar Telescope on La Palma with perfect seeing (thick lines) compared with the profiles for 9 individual grid cells covering 75×75 km region around the central point (gray lines). The profile is degraded by the finite telescope resolution with respect to what actually occurs in the simulation.

Stokes profiles are used to determine the vector magnetic field at the solar surface. Figure 6 shows the Stokes profiles for Fe I $\lambda 6302 \text{ \AA}$ as would be observed by the 97 cm Swedish Solar Telescope on La Palma with perfect seeing (thick lines). The light gray lines show the profiles from the 9 individual 25 km^2 pixels covering a 75×75 km region around the central point. The observed profile amplitudes are significantly degraded from what would be seen with infinite resolution. Observers should take this as a warning in interpreting their measured profiles.

3.4. Flux Tubes

How relevant is the concept of a “flux tube” for the weak, incoherent magnetic fields in the quiet Sun. Figure 7 shows strong magnetic field concentrations from a snapshot of the 1G simulation. There appear to be small magnetic loops extending up through the surface layers (about $1/7$ of the distance down from the top). However, figure 8 shows that the magnetic field lines go in and out of these loops and connect several of them. Thus, what might look like an individual flux tube is really part of a larger structure.

Sometimes, magnetic flux gets concentrated at the vertices of intergranular lanes and forms a “flux tube” (fig. 9). The “flux tube” is cooler than its surroundings and is being evacuated by downflows which are strongest at its periphery, in the intergranule lanes leading into the vertex. Near the surface and

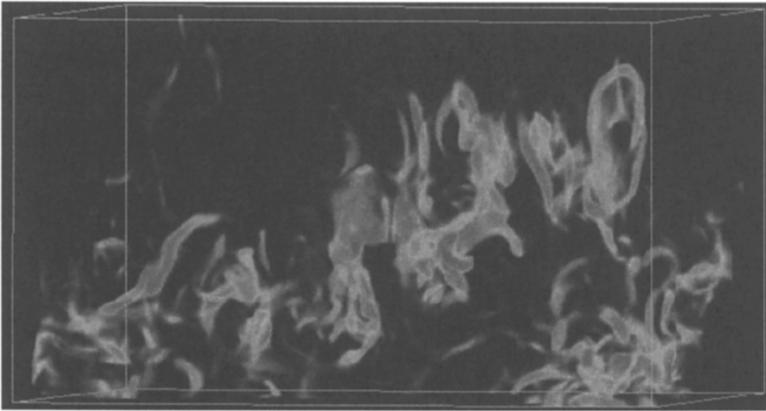


Figure 7. Strong magnetic field concentrations viewed from the side. The visible surface is about $1/7$ down from the top. Are the small loops with tops above the surface “flux tubes”?

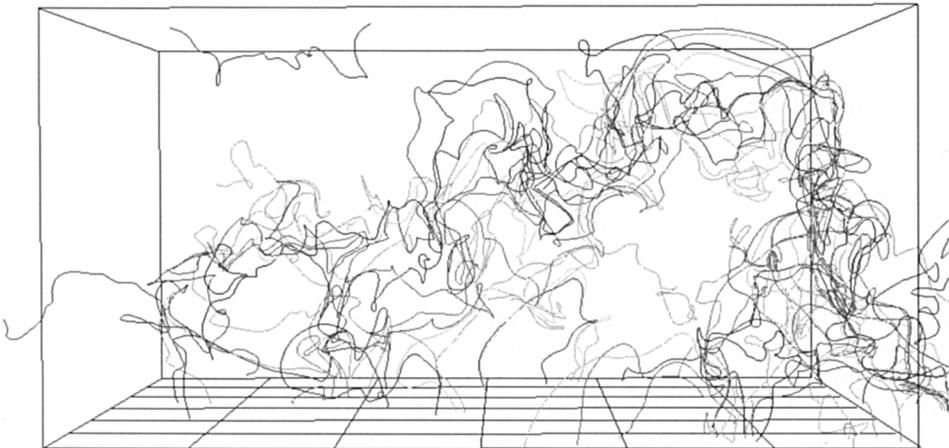


Figure 8. The same snapshot as in the previous figure, but now showing individual magnetic field lines. The magnetic field lines go into and out of individual strong field concentrations and connect over large regions of the simulation domain.

above the density inside the “flux tube” is already less than its surroundings, but at greater depth the density is still higher than its surroundings. Notice, that the individual magnetic field lines that are collected into the “flux tube” connect to several different locations below the surface.

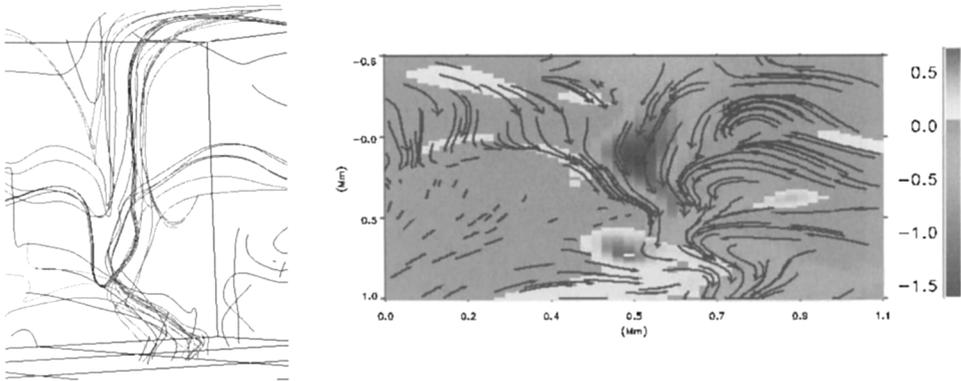


Figure 9.

(a) Magnetic field lines through a 1.5 kG “flux tube” that forms and gets partially evacuated in the 30G simulation. Near the surface the magnetic field lines form a flux tube bundle. Below the surface the field lines diverge in several different directions.

(b) Image of “flux tube” vertical magnetic field with fluid velocity vectors in the x - z plane. The tube is in the process of being evacuated by downflowing fluid. The density is less than its surroundings at and above the surface but greater than its surroundings below the surface.

4. Surface Dynamo?

For a dynamo to work there must be magnetic field amplification by stretching and twisting, diffusion to reconnect magnetic field lines and alter their topology, and recirculation to continue the process. Diverging upflows sweep the fluid into the downflows and concentrate the magnetic flux, but do not give rise to dynamo action. Vortical downdrafts stretch and twist the magnetic field to amplify it (as can be seen in the highly twisted magnetic field lines in Fig. 8). Resistive diffusion allows the magnetic field to diffuse through the fluid and to reconnect. The crucial question is whether the field is recirculated to be continually amplified.

Boussinesq simulations in a closed domain exhibit convection driven local dynamo action even in the absence of rotation and shearing motions (Cattaneo 1999, Emonet & Cattaneo 2001). The big difference between our simulation and those of Cattaneo and Emonet is that our simulation is stratified and has open boundaries. Magnetic flux is advected in through the bottom and can also be carried out through the bottom. At the top the field tends toward a potential field, so magnetic flux can also escape that way. The crucial question is how much recirculation there is within the near surface layers of the solar convection zone.

The magnetic energy grows linearly rather than exponentially and saturates at a small fraction of the kinetic energy (Fig. 10), because the magnetic field typically passes only once through this region of concentration and amplification by small scale convective flows. Unlike a Boussinesq fluid, the Sun is highly strati-

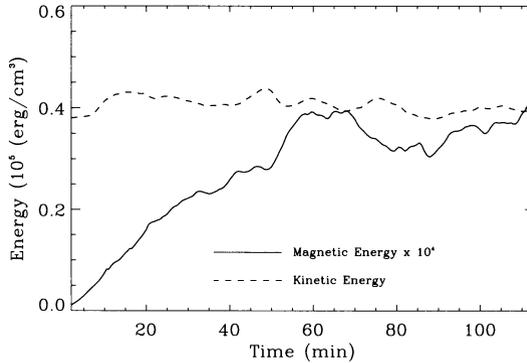


Figure 10. The magnetic energy increases linearly rather than exponentially, indicating that this is not dynamo action but one pass flux concentration and amplification. The magnetic energy saturates at a small fraction of the kinetic energy in about a turnover time for the largest (mesogranule) scale in the computational domain. (1G seed field simulation)

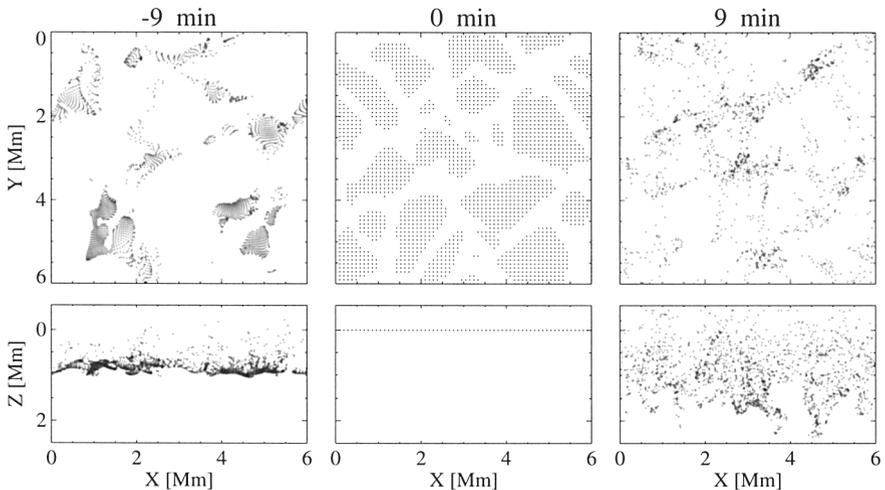


Figure 11. Fluid moving up at the surface and its location 9 min. earlier and later. Little of the fluid rising in the granules at the surface was near the surface 9 min. earlier. It comes from a small fraction of the volume at depth because the upflows are diverging and most ascending fluid turns over within one scale height and heads back down in a downdraft in order to conserve mass. The fluid that does reach the surface mostly descends in the fast downdrafts. Only a little gets recirculated and was close to the surface 9 min. earlier or remains close to the surface after 9 min.

fied and convection is asymmetric, with slow, nearly laminar, diverging upflows and fast, highly turbulent downflows. There is only a little local recirculation near the surface. Most of the fluid reaching the near surface layers turns over into downflows and is transported towards the bottom of the convection zone. This is illustrated by figure 11 which shows the history of fluid parcels that are moving upward at the surface at one instant. Nine minutes earlier they were mostly at a depth of 1 Mm and occupied a very small fraction of the horizontal plane. They occupied only a small fraction of the area because most ascending fluid must turn over within a scale height in order to conserve mass, so only a small fraction of the fluid at depth reaches the surface. They all come from approximately the same depth (1 Mm) because they were in upflows with fairly similar velocities. Hardly any of them came from near the surface, an indication of the lack of local recirculation. Nine minutes later most of the fluid has left the surface region, many in narrow downdrafts, and some has even descended to the bottom of the computational domain, because downflows are fast, converging and turbulent. Hardly any are left at or above the surface. Only a small portion of the fluid is recirculated to the near surface layers. This property is a consequence of the finite physical separation between the turbulent downdrafts and the small sub-volumes of the ascending flow that manage to reach the surface, and does not depend to any significant extent on the Reynolds number. Due to the lack of local recirculation, the magnetic energy grows linearly rather than exponentially because the magnetic field typically passes only once through the surface region where it is concentrated and amplified by small scale convective flows.

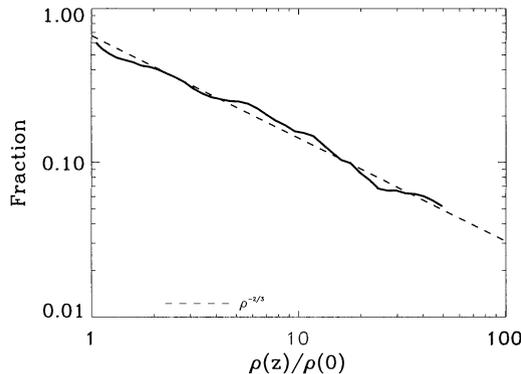


Figure 12. Fraction of fluid reaching the surface from any depth scales as $(\rho/\rho_{\text{surface}})^{-2/3}$.

Mass conservation requires that at any depth most upflowing fluid must turn over and head back down within about a scale height. Hence, only a tiny fraction of fluid starting up from the bottom of the convection zone makes it all the way to the surface. By tracing individual fluid parcels in time, we have found that the fraction reaching the surface from a depth where the density is $\rho(z)$ decreases as $(\rho(z)/\rho(\text{surface}))^{-2/3}$ (fig. 12). The weak incoherent magnetic

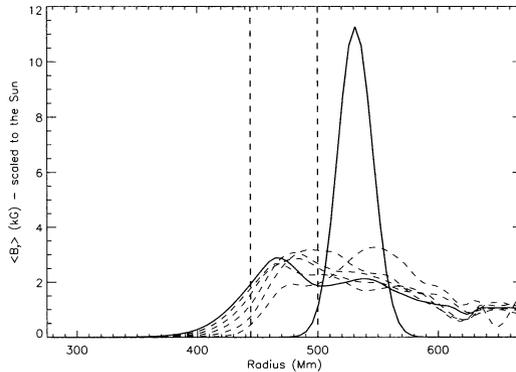


Figure 13. Magnetic flux initially in a thin layer in the convection zone gets redistributed throughout the convection zone, with most in the deeper layers (Nordlund et al. 2000). The right portion is the convection zone, the two vertical lines mark the undershoot layer, and the left portion is stably stratified.

field, unlike the strong coherent active region flux, is dominated by drag and advected by the fluid. Hence, most of the magnetic field will be located in the deeper parts of the convection zone. This has been verified by numerical simulations (Dorch & Nordlund 2001, Tobias et al. 2001). Magnetic field placed anywhere in the convection zone gets distributed throughout the convection zone and into the overshoot layer (fig. 13). The field strength increases with depth and its maximum lies in the overshoot layer, but most of the magnetic flux and energy is inside the convection zone, concentrated near the bottom. (In the Sun the tachocline is much thinner than it is in this toy simulation, so the amount of magnetic energy and flux in it is a small fraction of the total magnetic energy and flux.) The magnetic energy and flux near the surface is likewise small compared to the total magnetic energy and flux because it gets carried down to deeper layers by the downflows and only a little is brought back to the surface by the upflows.

Is there a surface dynamo? In the Sun, unlike simulations with closed boundaries and without stratification, there is little local surface recirculation. The recirculation is global. Surface magnetic fields are carried toward the bottom of the convection zone by downdrafts. The time scale at the bottom of the convection zone is long, months. Only a tiny fraction of fluid ascending from the bottom of the convection zone reaches the surface. Hence, much more flux and magnetic energy resides in the deep convection zone than near the surface and the energy added to flux that visits the surface is tiny compared to the global magnetic energy. These results lead us to conclude that there is no localized surface dynamo. Rather, there is a global dynamo in which a small fraction of weak, incoherent fields residing inside the convection zone is dragged to the surface, where it is shredded, concentrated, stretched and twisted by the small scale surface convective motions into the observed, incoherent, intermittent continually emerging, small scale surface field. This one-pass surface dynamo action

on granular and mesogranular (and probably supergranular) scales would distinguish these incoherent fields from the active region magnetic fields which represent another component of the global dynamo: strong, coherent fields that are buoyant and sufficiently large scale to feel the coriolis force, differential rotation and meridional circulation.

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5. Discussion

PISKUNOV: Do you see differences in field strength distribution on the surface and inside the box?

STEIN: The shapes of the distribution functions are the same at the surface and below but the extremes are larger deeper in the domain and the distributions are broader at depth.

PISKUNOV: Can you come up with a simple parameterized broadening function, which would describe the effects of convective motions?

STEIN: We know the variation with height of the time averaged rms velocities.

TITLE: The distribution function of ϕ does not have a constant slope. At $\phi < 5 \times 10^{19}$ m the slope steepens.

STEIN: I was not aware of that. It would indicate there are different mechanisms.

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