Chapter 6

CONCLUDING REMARKS

We have presented the results of two complementary studies, one observational and the other theoretical, of turbulent convection of supergranular scales of motion within the upper solar convection zone in order to better understand the dynamical role of such convection in shearing layers within the sun. Complex convective patterns possessing a wide range of spatial scales are evident both in observations of supergranular outflows visible at the solar surface as well as in global numerical simulations of turbulence within thin spherical shells, and are likely to influence the dynamics of the deeper convection zone below as well as the more tenuous photosphere, chromosphere, and corona above. We now briefly summarize our findings from both studies, and conclude with a discussion of future directions in §6.2.

6.1 SUMMARY OF RESEARCH PRESENTED IN THIS THESIS

Chapter 3 describes an observational study entailing the characterization of cell sizes and evolution associated with solar supergranulation, as determined from the life histories of several thousand supergranules individually identified by their horizontal outflow signatures. The near-surface horizontal flow fields were measured by applying correlation tracking methods to mesogranular flow structures within a time series of MDI full-disk ($2''$ pixels) line-of-sight velocity images of the solar photosphere. This time series contains over 8000 images separated by one minute, sampling a $45°$-square region of quiet sun for a duration of about six days, and represents the first study of solar supergranulation at such high combined temporal and spatial resolution. Sites of strong horizontal outflow were identified as supergranules using a pattern recognition algorithm, from which the life history of all cells in the six-day dataset was recorded.

We find that supergranular outflow cells in this quiet sun region have a broad range of sizes, distributed in an approximate Gaussian fashion, with typical length scales of 14–20 Mm after image smoothing effects are accounted for. The supergranular pattern appears to be surface-filling, with individual cells separated by a connected network of thin convergence lanes that covers the entire field of view. The complex evolution of the supergranular pattern is embodied in the wide spectrum of cell lifetimes, ranging from time scales as long as several days down to the temporal resolution limit of 6 hr. Such evolution typically occurs via merging and splitting of individual supergranules, coupled with the emergence and disappearance of the associated interstitial convergence lanes. In other instances, segments of the convergence lane network are observed to be advected laterally as existing supergranular outflows grow or contract.

The supergranular pattern can therefore be characterized as an evolving network of thin convergence lanes separating broad outflow cells, and is most likely the surface manifestation of vigorous overturning motions occurring in the near-surface layers directly below the photosphere. In addition, the hierarchy of fluid motions in the upper convection zone is not limited to supergranular scales of motion, but also encompasses the smaller-scale patterns of mesogranulation and granulation as well as larger scales such as banded zonal flows and weak meridional currents. To elucidate the role such dynamics may play within the upper solar convection zone, we have constructed detailed three-dimensional numerical simulations of a compressible fluid, confined to thin rotating spherical shells positioned near the top of the solar convection zone.

The simulations presented in Chapter 5 constitute the highest resolution simulation of solar-like convection within a spherical shell computed to date. Spherical harmonic modes with $\ell \leq 340$ are explicitly resolved, allowing structures of order 10 Mm to be realized within the simulations. In all cases, a four-fold angular periodicity was used to reduce the computational workload. Solar-like stratification, thermal forcing, and differential rotation profiles are imposed on the fluid, in order to approximate the conditions present in the layers where solar supergranulation is thought to be driven. The ASH computer code, operating in a massively parallel computing environment, is used to advance in time the anelastic equations of motion. These equations allow us to include the effects of compressibility, yet filter out acoustic waves which would otherwise severely limit the size of the computational time step. The dynamical effects of turbulent motions not explicitly resolved in these simulations are accounted for by simple parameterizations of energy and momentum transport included in the anelastic equations.

The simulations suggest that convection on multiple scales may be a natural consequence of a compressible fluid experiencing a rapidly changing stratification. Convection within both shallow and deep shell cases having identical stratification near their respective upper boundaries (both located at 0.98 R) show a prominent network of narrow downflow lanes having a length scale of about 200 Mm near the top of each shell. The broad regions in between contain rising fluid that is further segmented into more localized sites of fast upflows each measuring about 15–30 Mm across, or about equal to the horizontal scale associated with solar supergranulation. With depth, the network of fast downflows becomes less uniform, forming plume-like structures that extend the full depth of each shell, while the small-scale upflows evident near in the upper layers gradually disappear altogether to form broad regions of upwelling fluid.

In all cases studied here, the latitudinal dependence of the differential rotation within these thin shell simulations reflects the angular velocity profile Ω imposed at the lower boundary. Negative radial gradients of angular velocity persist throughout each domain, and are maintained by the transport of angular momentum by the convective motions. Reynolds stresses associated with such motions, in particular the broad regions of upflowing fluid and the surrounding network of downflows, are found to transport angular momentum inward, balancing the outward transport achieved by diffusion. These dynamics may be interpreted as the tendency for radially moving fluid parcels to partially conserve their angular momentum per unit mass as they move radially throughout the shell, and are likely induced by the influence of rotation on the convective motions. These results suggest that the dynamical effects of rotation, while relatively weak given the short overturning time scales associated with the convection, are still strong enough to create the necessary velocity correlations that account for the observed angular momentum transport.

These simulations suggest that the upper shear layer of the sun may behave similarly, with the network of narrow downflow lanes associated with the supergranulation pattern facilitating the inward transport of angular momentum. Such transport would than contribute to the decrease of angular velocity with radius, as seen in helioseismic inferences of Ω. As a result, the depth of the upper shear layer may be loosely related to the radial extent of convection associated with the supergranulation pattern visible at the surface.

6.2 FUTURE OUTLOOK

The research presented in this thesis represents a detailed look at the intricate convection within the upper shear layer of the solar convection zone. We have sought to understand what scales of convection are driven, what determines the depth of the shear layer, and what are the dynamical effects of this convection in maintaining the shear layer. Since both the observational project and numerical simulations can be viewed as initial building blocks toward such understanding, we now present some possible future directions this research might take.

The correlation tracking algorithm outlined in §2.3 used to determine the supergranular flow field was shown to have systematic errors on the order of 10% for shifts between 0.005 pixels and 0.05 pixels. The magnitude of such errors suggest that the algorithm can be made more accurate by using an interpolation scheme of a higher order, thereby reducing the systematic errors generated by the algorithm.

We have left unexplored the large body of work regarding pattern formation in turbulent systems. The ever-changing near-surface velocity field appears to evolve in a remarkably ordered fashion, especially given the level of turbulence that must be present a short distance below. Consequently, it may be possible to create an evolving field of cells using a rule-based system that produces statistical area and lifetime distributions similar to those of solar supergranulation, thereby isolating the important length and time scales operating within the system.

The mean differential rotation and meridional circulation profiles deduced from the large-scale flow study of §3.4, wherein correlation tracking was applied to the supergranular flow field, contain a large degree of scatter. Determining these mean flows within many additional regions available to MDI will likely reduce this scatter.

The supergranular flow field has been shown to readily advect small-scale emergent magnetic flux toward convergence lanes, thereby concentrating the flux on relatively larger scales. This behavior is common to regions of quiet sun, such as the 45°-square field presented here. A logical extension of this research is therefore to investigate the effects of more intense magnetism on supergranular flows, such as within active regions and near sunspots. The character of supergranulation is likely to change under the influence of stronger magnetic fields, as the stabilizing effects of such magnetism affects the overturning motions associated with the convectively unstable fluid.

The numerical models possess several attributes that are drastically different than the upper solar convection zone. Foremost, the sun does not possess an impermeable lower boundary in the middle of its convection zone. Allowing mass to pass through the lower boundary would be more realistic, as the current simulations require the convective overturning motions as well as any large-scale meridional circulations to close within the confines of the thin shell domains. As an alternative to allowing permeable boundaries, we are in the process of constructing a simulation of the entire convection zone with a spatial resolution adequate to deal with a surface layer containing the small-scale convective structures seen in the simulations presented here. It will be interesting to see if a shearing boundary layer near the top of these domains forms naturally.

As computing technology increases, it will become possible to construct simulations of fluid with even higher spatial resolution, which in turn would allow convection at higher R_a and R_e to be studied. Whereas attaining solar values of R_a and R_e within simulations of convection is unlikely in the foreseeable future, it is of great interest to see whether the dynamical trends presented here also operate within more turbulent flows.

We recognize that the representation of sub-grid scale (SGS) effects in these simulations, achieved by simply enhancing the thermal and molecular diffusivities, greatly simplifies their true effects. As more coherent small-scale structures form within more turbulent fluid, the inaccuracies associated with using a simplified SGS treatment are likely to grow. It has been shown that small-scale features in the flows will not only dissipate momentum and heat, but are also able to advectively transport these quantities. More sensible treatments of the SGS terms in the ASH code would capture more of the dynamical effects associated with fluid motions not explicitly resolved.

The advent of continuous imaging of the solar surface carried out at high spatial and temporal resolution has led to remarkable ways to probe the dynamics of the intensely turbulent convection zone. Such efforts will be carried to new levels with the planned Solar Dynamics Observatory mission, and likewise the upgrades to GONG will provide uninterrupted Doppler imaging from the ground. The continuous rapid advances with massively parallel computing architectures will enable even more detailed simulations of turbulent convective fluids analogous to the solar convection zone. We thus foresee complementary paths coupling major observational and theoretical efforts in studying the complex evolving dynamics within the solar convection zone.