

## Chapter 1

### INTRODUCTION: THE DYNAMIC SOLAR CONVECTION ZONE

Our sun is the nearest star to earth and the most massive object in the solar system. Most of this mass is concentrated near its center (the *core*), where the matter is hot and dense enough to permit the fusion of its abundant supply of hydrogen into helium. The energy produced via these thermonuclear reactions slowly diffuses through the *radiative interior* until it enters the *convection zone*, a layer roughly 200 Mm (where 1 Mm equals 1000 km) thick occupying about the outer 30% of the sun by radius. In this region, the entropy and temperature gradients are superadiabatic and therefore unstable to convective overturning motions; thus, it is energetically favorable for fluid to rise buoyantly by extracting energy from the ambient thermal field. Once the heat reaches the surface of the sun (the *photosphere*), it escapes through the tenuous *solar chromosphere* and *corona* and into outer space.

The focus of this thesis is the dynamics within the upper layers of the solar convection zone. The convection zone as a whole contains fluid motions that vary over widely ranging yet distinct length and time scales, all of which interact in complex ways. In this introductory chapter, we first examine in §1.1 what has been learned about the convection zone from observations of the photosphere, including from results of helioseismic inversions. In §1.2 we describe the current state of numerical modeling efforts which elucidate some of the dynamical processes present when compressible fluids are subject to rotation and stratification. Finally, we develop and motivate the research

presented in this thesis in §1.3.

## 1.1 OBSERVATIONS OF THE SOLAR SURFACE

### 1.1.1 Differential Rotation of the Surface and Interior

Observations of the solar photosphere show that the sun possesses a *differential rotation* in which the equatorial regions rotate faster than the poles. Measurements of Doppler shifts of photospheric absorption lines (Howard & Harvey 1970; Snodgrass & Ulrich 1990) indicate that the surface plasma at the equator has a rotation period of 25 days, while in the polar regions it is about 33 days. Alternatively, measuring the rotation rate of sunspots and other surface features as they rotate across the disk of the sun (Ward 1966; Howard et al. 1984; Snodgrass & Ulrich 1990; Zappalà & Zuccarello 1991) also show a similar differential rotation profile, except that these rotation rates are found to be faster than the plasma rate by a few percent at each latitude. This systematic difference in rotation rates most likely indicates that the sub-surface layers rotate faster than the surface, as the magnetic features reflect an average of angular velocity as weighted over their radial extent.

The existence of approximately  $10^7$  resonant acoustic modes of oscillation makes it possible to probe the solar interior in some detail using *helioseismology* (e.g. Ulrich 1970; Gough & Toomre 1991). Helioseismology involves the measurement and analysis of the oscillation frequencies of these normal modes, as measured at the surface, in order to infer properties of the medium through which the waves have traveled. Waves of different frequencies provide information over a range of depths and latitudes, from which it is possible to construct detailed maps of structure and large-scale flows within the interior of the sun. For example, inversions of *global modes* are used to infer the dependence of density, pressure, temperature, and sound speed with both radius and latitude, whereas their rotational splittings provide estimates of the angular velocity

field throughout much of the sun, as shown in Figure 1.1 for example.

Over the last seven years, two major research efforts have provided nearly uninterrupted observations of the solar photosphere from which the oscillation frequencies can be measured. The Global Oscillation Network Group (GONG) operates a series of six identical Doppler imaging instruments distributed approximately equally in longitude around the earth. The data from the six observing sites are subsequently combined to form one continuous dataset on which helioseismic inversions can be performed. In a complementary fashion, the Michelson Doppler Imager (MDI), one of several instruments on board the Solar and Heliospheric Observatory (SOHO) spacecraft, also provides continuous observations of the line-of-sight surface velocity field. From its vantage point in space, MDI does not suffer from atmospheric seeing effects and weather-related interruptions which can affect the data from the GONG project. On the other hand, the ground-based GONG instruments are more accessible and can be upgraded as more advanced instruments become available. Together, the virtually uninterrupted coverage and high temporal resolution of the data provided by both projects enables the precise measurements of oscillation frequencies necessary for detailed helioseismic analyses.

Global helioseismic inferences of angular velocity deduced from both GONG and MDI data indicate that the surface differential rotation pattern of fast equatorial rotation relative to the poles largely holds throughout the bulk of the convection zone, such that radial gradients of angular velocity are small (Thompson et al. 1996; Schou et al. 1998). Figure 1.2 shows that there exists a layer of radial shear, known as the *tachocline* (Spiegel & Zahn 1992), located at the interface between the bottom of the convection zone and the stably stratified radiative interior underneath. Much recent attention has focused on the tachocline region, as it is thought to be the seat of the global solar magnetic dynamo. In the near-surface layers, helioseismology also reveals the existence of another shear layer occupying the outer 35 Mm or 5% of the sun. This upper shear layer contains negative radial gradients in angular velocity, lending credence

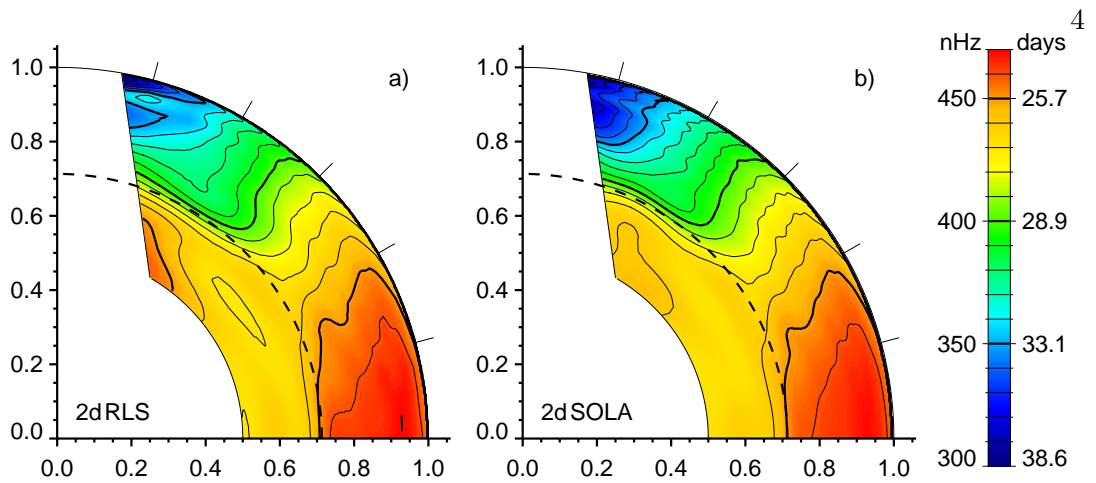


Figure 1.1: Average rotation rates  $\Omega/2\pi$  as a function of radius and latitude inferred from two different helioseismic analyses applied to MDI velocity images. (adapted from Fig. 5 of Schou et al. 1998).

to the notion that subsurface fluid layers rotate faster near the surface, much as was inferred by comparing the tracer and spectroscopic rotation rates.

### 1.1.2 Dynamics in the Near-Surface Layers

High-resolution observations of the photosphere indicate that the upper shear layer contains several spatially coincident yet distinct modes of convection. White light images show a mottled pattern known as *granulation* (e.g. Bray et al. 1984; Roudier et al. 1991), representing the tops of near-surface convection cells, called *granules*. The granulation pattern is observed to cover the entire visible surface, with individual granules being recognizable for about 5–10 minutes and typically measuring about 1 Mm across. In addition, images of the line-of-sight velocity field reveal larger scales of convection such as *mesogranulation* (measuring 5 Mm across, existing for several hours) (November et al. 1981) and *supergranulation* (25–30 Mm, 1 day) (Leighton et al. 1962), which also cover the visible surface of the sun while coexisting with the granulation pattern.

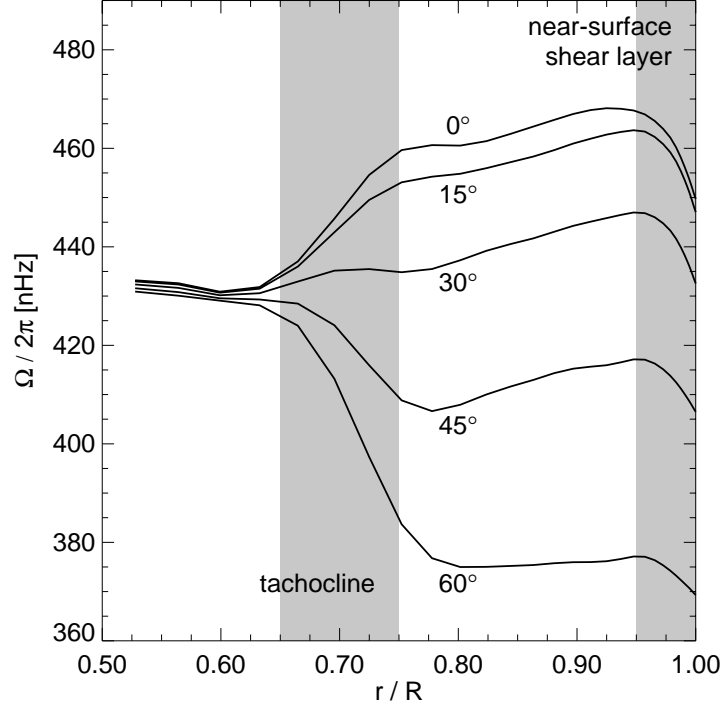


Figure 1.2: Average rotation rates  $\Omega/2\pi$  inferred from the helioseismic inversion of over 4 years of GONG data using the RLS technique (adapted from Howe et al. 2000). Shear layers (*shaded*), evidenced by variations of  $\Omega$  with radius, are observed near the base of the convection zone as well as near the surface. The gradients of  $\Omega$  in that near-surface shear layer at high latitudes is somewhat sensitive to the inversion method and data sets used (e.g. see Fig. 1.1 and Schou et al. 1998).

*Time-distance* and *ring-diagram* techniques are two examples of *local helioseismology*, in which helioseismic analyses are applied to more localized regions of the sun. Both methods have revealed flow patterns in the near-surface layers having a spatial scale larger than that of supergranulation. By partitioning the visible surface into smaller sections, it is possible to infer the dependence with position and depth of quantities such as temperature and average flow velocities by measuring the oscillation frequencies of high-degree modes. Time-distance analyses indicate that persistent poleward meridional flows of order  $20 \text{ m s}^{-1}$  occupy at least a 20 Mm-deep layer below the photosphere (Giles et al. 1998). The return flow, which must be located at a level

deeper than to which the time-distance analysis is sensitive, has not yet been detected. Synoptic maps of the horizontal velocity field inferred from ring-diagram analyses show extended regions of organized flow patterns evolving on time scales on the order of one day, while longer temporal averages show banded zonal flows which propagate toward the equator over the course of several years (Haber et al. 2000). The ring-diagram analyses have revealed that the meridional circulations can possess an evolving double-celled structure with latitude in the northern hemisphere, while that in the south is single-celled (Haber et al. 2001).

In response to these various motions, small-scale magnetic elements present in the photosphere are observed to be systematically advected by granular and supergranular flows (Berger et al. 1998; Hagenaar et al. 1999). As a result, individual filaments of emergent flux interact frequently with other magnetic elements, either merging with or annihilating other elements, depending on polarity. At the same time, larger regions of intense magnetic field, including sunspot pairs and plage regions, can persist for time periods ranging between a few days and several months. Sunspots in particular form regular patterns which cycle every 22 years as indicated by the timing, latitude, and polarity of emerging sunspot pairs. At the beginning of each sunspot cycle, pairs first appear in mid-latitude regions with an approximate east-west orientation. Sunspot pairs in the northern hemisphere generally have the opposite polarity of pairs in the southern hemisphere, but throughout each cycle the polarity remains the same for a given hemisphere. As the cycle progresses, pairs emerge in increasing numbers at latitudes progressively closer to the equator. After about 11 years, the sunspots at the equator become fewer in number while the next cycle begins as sunspots reappear at mid-latitudes. The spots of the new cycle have their polarity reversed from the spots of the previous cycle, making the total cycle time about 22 years.

We have described several ordered phenomena, such as differential rotation, supergranulation, and the 22-year magnetic cycle, which coexist with the quickly evolving

and highly turbulent fluid motions within the convection zone. A detailed picture of how such persistent flows and magnetic fields interact with the more intermittent fluid motions is just beginning to emerge. Dynamical effects which are not yet accessible to observations can only be examined with the aid of analytical models and numerical simulations of turbulent convection, which we now review briefly.

## **1.2 SIMULATIONS OF TURBULENT CONVECTION**

### **1.2.1 Mean-Field Hydrodynamic Models of the Convection Zone**

With the rapid advancement of computer technology, especially over the past two decades, theoretical modeling of turbulent convection is now playing an increasingly larger role in gaining a better understanding of convection zone dynamics. Solar observations not only provide many clues toward such understanding, but also serve as goals to which the theoretical models strive to attain.

Due to the complexity and vigor of the turbulence within the convection zone, not all dynamically relevant scales of motion can be explicitly resolved in the same simulation. The most widely adopted approach is to assume a separation of scales, whereby large-scale or long-lived phenomena of interest, such as the differential rotation, are typically represented by globally averaged quantities. Perturbations superposed on these mean quantities thus describe more local phenomena. Such scale separation is achieved by filtering the relevant physical equations in space or time, and then solving only the averaged equations. Obtaining a solvable set of equations requires one to somehow approximate how the dynamics of the unresolved scales of motion affect those scales which are explicitly resolved. Given the usually intricate dependencies between large- and small-scale dynamics of a turbulent system, however, it may not be clear what treatment of the small-scale effects is appropriate. Furthermore, it may not even be clear that an appropriate dividing line between small- and large-scale motions exists,

since the very nature of turbulence is that it is characterized by a wide range of scales of motion. Despite these limitations, such scale-separation treatments are widely used to investigate the intricate dynamics occurring within the solar convection zone.

The broad class of *mean-field models*, which typically contain only at most a few resolved large scales of motion, provided the first theoretical picture of convection zone dynamics. Such calculations suggested that the effects of unresolved motions are likely to make important contributions to large-scale dynamics. For example, velocity correlations associated with turbulent eddies, commonly known as *Reynolds stresses*, were found to be very effective in transporting angular momentum throughout the convection zone and are therefore likely to play an important role in achieving the solar differential rotation profile. By adjusting the functional forms of the Reynolds stress terms it was possible to obtain models which compare favorably to the observed solar surface rotation, meridional circulation, and temperature profiles (Durney & Roxburgh 1971; Kitchatinov & Rüdiger 1993). However, other choices led to very different profiles, and there is no evident basis for preferring some functional forms over others. Many of these models also produced cylindrically symmetric angular velocity profiles in the interior, a result now contradicted by helioseismic inferences. One notable exception is the model of Kitchatinov & Rüdiger (1995), which was able to produce an interior differential rotation profile similar to that inferred from helioseismic inversions. The main drawback of the mean-field approaches continues to be the ad hoc parameterization of small-scale effects.

### 1.2.2 Multi-Mode Hydrodynamical Simulations

The continual advancement of computing technology has enabled simulations of three-dimensional systems that explicitly resolve a diverse spectrum of size scales, rather than only the largest few. Several recent compressible convection simulations exhibit rich structures, such as narrow downflow plumes and concentrated vorticity fields co-

existing with large-scale circulation (e.g. Brummell et al. 1995), suggesting that the gross parameterizations of small-scale dynamical source terms typically employed in mean-field treatments are physically inappropriate. However, the disparity between the largest and smallest size scales of motion in the convection zone continues to present severe challenges for modeling, as local dissipative processes operate on size scales that are at least a factor of  $10^6$  smaller than the depth of the convection zone itself. Current computer technology can explicitly resolve only  $10^3$  size scales in each of the three physical dimensions when memory, data storage, and time-stepping limitations are considered. In terms of the *Reynolds number*  $R_e$  (ratio of inertial to dissipative forces), the largest current models have  $R_e = 10^4$ , which is much lower than the value of  $R_e = 10^{12}$  thought to exist within the solar convection zone. Values of other nondimensional parameters of these simulations, such as the *Rayleigh number*  $R_a$  (ratio of buoyancy driving to dissipative forces), *Taylor number*  $T_a$  (ratio of Coriolis to viscous forces), and *Prandtl number*  $P_r$  (ratio of viscous to thermal diffusion) are similarly removed from the parameter regime applicable to the actual sun. As a result, issues of scale separation and closure still exist, although to a lesser degree than in mean-field models since these more detailed simulations explicitly resolve a much broader range of scales. Three-dimensional models serve as useful analogs for the real convection zone because many physical effects relevant to the dynamics on a global scale are present to some degree.

Solar convection zone simulations have employed several different strategies to cope with the disparity of scales. One approach seeks to study the global dynamics of a spherical system by approximating the convection zone as a fluid confined to a rotating spherical shell. The available computational degrees of freedom are used to explicitly model the largest scales of motion, while net contributions resulting from motions occurring on sub-grid scales are approximated.

We now discuss global simulations of convection in rotating spherical shells. Un-

like mean-field models, the largest size scales associated with convection are now explicitly resolved in these simulations. The first extensive research in this area was performed by Gilman (1977, 1978a,b), who modeled a Boussinesq fluid (where the fluid is largely incompressible except for density perturbations coupled with gravitational effects) at  $Re \approx 100$ ,  $T_a = 10^5$ , and  $Pr = 1$ . Simulations having Rayleigh numbers between  $10^4$  and  $10^5$  were computed for various combinations of temperature and velocity boundary conditions. For  $Re \lesssim 5 \times 10^4$  these models exhibited solar-like surface differential rotation profiles, with zonal velocities faster at the equator than at mid- to high latitudes. Such differential rotation was achieved by the equatorward transport of angular momentum by Coriolis forces and Reynolds stresses working against diffusion. For  $Re \gtrsim 5 \times 10^4$ , the transport of angular momentum away from the equator by poleward meridional flows became strong enough to reverse the sense of the differential rotation profile, such that the angular velocity of equatorial latitudes became slower than at higher latitudes.

Compressibility was later included into these spherical shell models (Glatzmaier & Gilman 1981; Glatzmaier 1984, 1985; Gilman & Miller 1986) via the *anelastic approximation*, first adapted from meteorology to the stellar context by Gough (1969). These anelastic models exhibited convective structures possessing a wide range of spatial and temporal scales. The most prominent velocity structures that emerged were the so-called *banana cells*, visible as fluid rolls elongated in latitude oriented perpendicular to the equator. For the more highly stratified models that were considered, a necessary condition for surface differential rotation was that the rotational influence, characterized by  $T_a$ , must be large enough to allow angular momentum to be deposited in equatorial regions by Coriolis-driven Reynolds stresses. In addition, the unresolved motions need to transport heat more efficiently than momentum, suggesting a  $Pr$  less than unity. However, the solutions with strong enough rotation to produce a surface equatorial acceleration also had the angular velocity nearly constant on cylinders aligned with the axis of rotation, which we now know is not the case within the actual solar convection

zone.

The advent of high-performance, massively parallel computing platforms provides access to more turbulent regimes, allowing simulations with much lower diffusivities (and thus higher  $R_e$  and  $R_a$ ) to be carried out. The models of Miesch et al. (2000) and Elliott et al. (2000) represent the most turbulent simulations of a global variety performed to date. In these simulations, combinations of flow parameters and boundary conditions were found which produced a more solar-like differential rotation, breaking the tendency for a cylindrically symmetric angular velocity profile. The increased turbulence in these simulations was accompanied by a breakup of the banana cell structures and a more complex evolution of convective structures than found in the earlier, less turbulent simulations. As the driving was increased, however, the rotation profiles tended to revert back to being aligned on cylinders. In these simulations the level of turbulence is still substantially lower than in the actual sun, and it remains to be seen how even more turbulent driving affects the dynamics within these systems.

Parallel computing opportunities have also permitted local studies of the turbulent dynamics of rotating fluids. In contrast to the scale-separation approach, this strategy distributes the computational degrees of freedom over the smallest scales of motion, thereby precluding the need for parameterizing unresolved effects. As a result, the computational domains are more restricted in overall size, and are usually Cartesian rather than spherical, but do not include any sub-grid scale approximations found in the global simulations described earlier. However, any large-scale structures that do form are limited by the size of the domain and thus may not be representative of a larger system. Because the combined effects of small-scale motions at or near the scale of dissipation have a significant effect on the global dynamics, these models are still of great interest.

Turbulent, compressible fluids in a Cartesian domain have been modeled by Cattaneo et al. (1991), with effects due to rotation later included by Brummell et al. (1996,

1998). Rotational effects on an  $f$ -plane are included by inclining the axis of rotation with respect to the thermal stratification, effectively representing different latitudinal positions on a sphere. These models are characterized by a more laminar thermal boundary layer at the upper surface covering a deeper turbulent interior. Of interest in the solar case is the behavior at  $P_r < 1$ , where compact plumes of downwelling fluid span the full vertical extent of the fluid layer. These coherent downflows, however, contribute little to the overall vertical transport of energy as their upward heat flux is largely balanced by the downward transport of kinetic energy. The primary energy transport is therefore accomplished by the smaller-scale, more turbulent motions of the system. Simulations with a moderate rotational influence were found to drive a mean flow (although it is rather modest when compared to the kinetic energy of the convection), owing to the tilting of downflowing structures toward the rotation vector.

Another class of local simulations designed to provide insight into granular convection in the near-surface layers has been performed by Stein & Nordlund (1998, 2000). The fully compressible fluid equations are solved, including the effects of ionization and radiative transfer which are important for the near-photospheric layers. Their domain is a  $6 \text{ Mm} \times 6 \text{ Mm}$  wide and  $3 \text{ Mm}$  deep Cartesian box, which is large enough to contain many granules but only encompasses a relatively shallow layer of convection near the surface of the sun. However, these models do produce some extremely realistic results in the appearance and evolution of granulation. The granulation pattern is shown to be thermally driven, with radiatively cooled matter being transported downward in the network of dark lanes separating individual granules. In addition, these granulation simulations produce photospheric absorption line profiles, acoustic oscillation frequencies and excitation characteristics in close agreement with measurements of comparable quantities determined from observations of actual granulation.

### 1.2.3 Models Including Magnetic Effects

The inclusion of magnetic effects into hydrodynamic convection models adds another level of both complexity and realism. It is believed that both the large-scale and small-scale photospheric magnetic field structures are merely the surface manifestation of magnetism produced by the *solar dynamo* (Parker 1979) thought to be operating within the solar convection zone and possibly just below its base in the overshoot layer. The observed 22-year pattern of sunspot emergence during each solar activity cycle, as characterized by Hale's polarity laws, must be directly linked to a *global solar dynamo* operating within the sun. On smaller scales, filaments of magnetic flux are observed to emerge through the photosphere and are advected horizontally in response to the organized granulation and supergranulation flow patterns. Because these small-scale flux elements possess less ordered behavior than larger magnetic structures such as sunspots and appear to be unaffected by the 22-year global magnetic cycle, they may be the result of a *local solar dynamo* that is at least partially distinct from the global dynamo (e.g. Cattaneo 1999). Any dynamical picture must account for both the organized large-scale dynamo activity and the small-scale magnetic filaments.

Shear flows such as the interior differential rotation profile are extremely efficient at stretching out poloidal magnetic field into toroidal field. For sustained dynamo action to occur in the sun, however, there must exist a mechanism which regenerates poloidal field from toroidal field; otherwise, the toroidal magnetic field which results from the differential rotation of the solar interior would eventually diffuse away. One promising way such poloidal field may be created is known as the  $\alpha$ -effect, and operates via the cyclonic twisting of toroidal field by turbulent convective fluid motions, as originally suggested by Parker (1955a). The earliest models which investigated the feasibility of the  $\alpha$ -effect in producing a solar-like global magnetic cycle were of the mean-field type. Such models showed that dynamo action is indeed possible for systems containing both

shear and rotation-induced helical motions (e.g. Stix 1976), but have trouble reproducing the relative strength of magnetic features observed on the sun. This effect occurs because strong magnetic fields tend to inhibit the small-scale helical motions that may be responsible for the  $\alpha$ -effect, a process known as  $\alpha$ -*quenching*.

We now know from helioseismology that a strong region of radial shear is located at the base of the convection zone within the tachocline, and it is within this region that the strongest toroidal magnetic fields are believed to be formed. The existence of this shear layer led to the idea of *interface dynamos* (Parker 1993), a class of mean-field models which contain a layer of convection placed immediately above a stably stratified overshoot layer containing shearing flows. The flows within the shear layer produce the toroidal field, while the poloidal field necessary to complete the dynamo cycle is regenerated within the convection zone. Because the region of storage is spatially distinct from the region where the  $\alpha$ -effect occurs, the quenching problem is avoided; however, there must now exist a mechanism that transports the magnetic flux between each region. Toroidal magnetic structures naturally drift upward into the convecting layer due to their magnetic buoyancy (Parker 1955b), where some fraction is converted into poloidal field via the  $\alpha$ -effect. Transporting this poloidal field back down into the shear layer is more problematic, and is accomplished by turbulent diffusion in some of the most recent interface dynamo models (e.g. Charbonneau & MacGregor 1997). These models are successful in reproducing waves of antisymmetric dynamo activity reminiscent of the 22-year sunspot cycle, but suffer from the drawback that the resulting dynamo behavior depends strongly on the details of the  $\alpha$ -effect, which results from unresolved turbulent motions that can only be approximated in such a mean-field model.

Another mechanism which is able to regenerate poloidal field from toroidal field stems from the Coriolis force acting on large-scale concentrations of toroidal flux. Such dynamo models, called *Babcock-Leighton* or *flux-transport* dynamos, require magnetic structures within the convection zone large enough and long-lived enough to be influ-

enced by the Coriolis force. To avoid the quenching problem, the Babcock-Leighton dynamos must also rely upon a mechanism to transport the poloidal flux down into the tachocline. Recent mean-field models (e.g. Dikpati & Charbonneau 1999) show that the advection of poloidal flux by a solar-like meridional circulation may be a viable mechanism, as suggested by their ability to produce realistic dynamo activity.

One drawback of the Babcock-Leighton models, which also applies to the  $\alpha$ -effect models described above, is that the magnetism generated by most of these models does not feed back on the shearing flows in any way, and thus it is unclear how these prescribed flows are affected by the presence of a magnetic field within the domain. This problem suggests the need for dynamically consistent models which solve for both the flow velocities and the magnetic fields. Such full MHD simulations of Boussinesq fluids have been computed by Gilman & Miller (1981) and Gilman (1983), with compressibility added later by Glatzmaier (1984, 1985). For the relatively laminar parameter regimes considered, however, it was found in both the Boussinesq and compressible simulations that waves of dynamo activity tended to propagate poleward rather than toward the equator. In addition, these simulations could not reproduce the alternating polarity observed in the solar dynamo with each new sunspot emergence cycle. More turbulent simulations are just beginning to be attempted.

The highly organized patterns of sunspot and active region emergence associated with the 22-year magnetic cycle suggest that portions of the toroidal field must rise coherently through the convection zone and emerge at the surface. Simulations of thin flux tubes rising through a convectively unstable spherical shell (e.g. Moreno-Inertis 1986; D'Silva & Choudhuri 1993; Fan et al. 1993) reproduce many of the observed characteristics of bipolar active regions, including the emergence and tilt angles of sunspot pairs. These simulations, while encouraging, only consider thin flux tubes and thus neglect effects associated with the tube thickness. Such effects may be important, as three-dimensional magnetic structures within the solar convection zone may be subject

to several MHD instabilities which may cause their destruction before they ever reach the photosphere. For example, vortical motions within these flux tubes may cause their fragmentation, after which they are likely to be shredded by the surrounding vigorous convection (Schüßler 1979; Longcope et al. 1996). Structures which manage to remain coherent are subject to kink instabilities which also may enhance their dissipation (Linton et al. 1996; Fan et al. 1999). In addition, strong downflow plumes within the convection may prevent some tubes from emerging at all, as such fast downwelling fluid motions can counteract their rising and pump the magnetic flux back into the tachocline (Tobias et al. 1998).

Theoretical modeling of turbulent fluids has provided valuable insight toward our understanding of convection zone dynamics. These simulations have identified likely mechanisms for sustaining the observed solar differential rotation profile and the global dynamo, even though severe approximations and parameterizations were used in most cases. These results suggest that the differential rotation throughout the solar interior is almost certainly achieved by the influence of rotation on the turbulent motions located within the solar convection zone, while the global solar dynamo is believed to occur via the interaction of magnetic field with strong shearing motions within the tachocline and with the turbulent fluid motions of the convection zone. While much attention has been focused on the relevant processes occurring within the bulk of the convection zone and the tachocline region below, the dynamics occurring in the upper shear layer immediately below the photosphere have not been studied in as much detail. This thesis seeks to address this area.

### **1.3 SUMMARY OF RESEARCH PRESENTED IN THIS THESIS**

This thesis is devoted to a study of the upper shear layer within the solar convection zone, which forms the transition region between the deep convection zone interior and the photosphere. This layer is visible in helioseismic inversions as a region of radial

gradients in angular velocity which occupy about the outer 5% (or 35 Mm) of the sun. The upper shear layer is of great interest because the multiple modes of convection contained therein are likely to influence both the dynamics of the deeper convection zone as well as the photosphere in ways that are not yet well understood. Convection on supergranular size and time scales in particular may be weakly influenced by rotation, facilitating the transport of angular momentum. In combination with such rotational effects, the large horizontal and radial extent of supergranular flows suggest that they most likely play the largest role in the dynamics of this shearing boundary layer.

We first seek to characterize the supergranulation pattern using correlation tracking methods applied to observations of line-of-sight Doppler velocity to identify supergranular outflows on the surface. Chapter 2 is devoted to an overview of surface flow measurements, including a description of the correlation tracking technique and an assessment of the systematic and random errors associated with this technique. We then in Chapter 3 apply correlation tracking methods to one  $45^\circ$ -square region of quiet sun to generate flow maps of horizontal velocity for a duration of six days, representing the longest uninterrupted time series of solar supergranulation studied to date. Distributions of supergranular sizes and lifetimes are obtained after directly identifying individual supergranules on each image in the time series. The intricate evolution of the supergranulation pattern is evident in the numerous examples of cell emergence, disappearance, fragmentation, and merging events, as well as in the systematic advection of intercellular lanes.

This observational study is complemented in Chapters 4 and 5 by global numerical simulations of turbulent convection within thin spherical shells. Such simulations approximate the conditions present in the upper solar convection zone as solar-like stratification, rotation, and thermal forcing profiles are imposed. We find that convection subject to solar-like density gradients naturally produces convective structures on multiple scales, the smallest of which is analogous in size to solar supergranulation. We

investigate the influence of these supergranular-like convection cells on the global differential rotation and meridional circulation contained within the thin shells, including their contribution to the maintenance of shearing flows within the domain. Finally, concluding remarks and future directions associated with this research are presented in Chapter 6.