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Review Paper

HELIOSEISMOLOGY OF TIME-VARYING FLOWS THROUGH THE SOLAR CYCLE

LAURENT GIZON
W.W. Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA 94305, USA
(e-mail: lgizon@solar.stanford.edu)

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Abstract. Flows in the upper convection zone are measured by helioseismology on a wide variety of scales. These include differential rotation and meridional circulation, local flows around complexes of magnetic activity and sunspots, and convective flows. The temporal evolution of flows through cycle 23 reveals connections between mass motions in the solar interior and the large-scale characteristics of the magnetic cycle. Here I summarize the latest observations and their implications. Observations from local helioseismology suggest that subsurface flows around active regions introduce a solar-cycle variation in the meridional circulation.

1. Introduction

With the advent of helioseismology from space and ground-based networks, our knowledge of the solar interior has considerably progressed. Methods of helioseismological analysis are usually split into two classes: global and local. Global helioseismology is based on the interpretation of the eigenfrequencies of the resonant modes of oscillations (e.g. Christensen-Dalsgaard, 2002). It has been used extensively over the last twenty years, in particular to learn about large-scale rotation as a function of depth and unsigned latitude (Schou *et al.*, 1998). The angular velocity inside the Sun was found to be larger at the equator than the poles throughout the convection zone, while the radiative interior rotates nearly uniformly (Figure 1). The layer of radial shear at the bottom of the convection zone, known as the tachocline, is commonly believed to be the seat of the solar dynamo (e.g. Gilman, 2000).

With global helioseismology, however, it is not possible to detect longitudinal variations or flows in meridional planes. New methods of local helioseismology are being developed to make three-dimensional images of the Sun's interior. These methods aim at interpreting the full wave field observed at the surface, not just the eigenmode frequencies. The most promising techniques of local helioseismology include time–distance helioseismology (Duvall *et al.*, 1993), acoustic holography (Lindsey and Braun, 2000), direct modeling (Woodard, 2002), and ring-diagram analysis (Hill, 1988). Time–distance helioseismology is perhaps the most intuitive. The basic idea is to measure the travel times of solar waves between any two locations on the solar surface. A travel-time anomaly contains the seismic signature

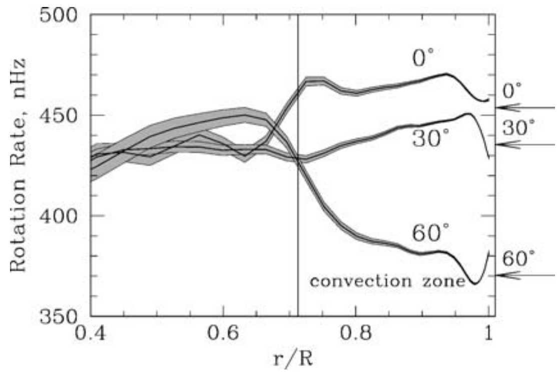

Figure 1. Solar angular velocity as a function of radius, at three different latitudes. There are sharp radial gradients at the bottom of the convection zone (*vertical line*) and in the upper 5% of the convection zone. Differential rotation is mostly independent of radius in the bulk of the convection zone. Arrows refer to surface Doppler measurements. From Kosovichev *et al.* (1997).

of buried inhomogeneities within the proximity of the ray path that connects two surface locations. For instance, a flow will break the symmetry in travel time for waves propagating in opposite directions. Ring-diagram analysis is another powerful tool to infer the speed and direction of horizontal flows below the solar surface by observing the Doppler shifts of ambient acoustic waves from power spectra of solar oscillations computed over patches of the solar surface (typically $15 \times 15°$). Thus ring analysis is a generalization of global helioseismology applied to local areas on the Sun (as opposed to the whole visible surface).

In Section 2 we consider the variations of solar rotation and meridional circulation as a function of time and latitude. The focus is on temporal variations that are slow compared to the typical lifetime of active regions. By computing longitudinal averages of rotation and meridional circulation over a few solar rotation periods it is possible to filter out small-scale flows and to reach a sensitivity of the order of 1 m s^{-1} near the surface.

In Section 3 we study the connections between local flows and regions of enhanced magnetic activity. Spatial maps of horizontal flows in the near-surface layers can be obtained with local helioseismology. These maps reveal ordered flows around large complexes of activity, which affect the longitudinal averages of rotation and meridional circulation.

2. Solar-Cycle Variations of Large-Scale Flows

2.1. Torsional Oscillations

Howard and LaBonte (1980) discovered small (± 10 m s^{-1}) latitudinal variations in the surface Doppler rotation profile that propagate toward the equator with the

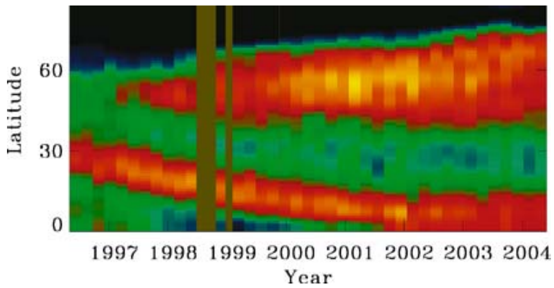

Figure 2. Zonal velocity at a depth of about 50 Mm as a function of latitude and time (one measurement per 72-day period) derived from MDI f-mode frequency splittings. *Red (blue) shades* indicate faster (slower) rotational velocity than average, with values in the range ± 9 m s^{-1}. Results by J. Schou according to the method described by Schou (1999).

sunspot latitude variation. These variations, known as torsional oscillations, provided the first evidence for a connection between mass motions and the large-scale characteristics of the magnetic cycle: the differential rotation shear is enhanced at active latitudes. Torsional oscillations have since been confirmed by global helioseismology (Kosovichev and Schou, 1997; Schou, 1999; see Figure 2). Inversions of global-mode frequency splittings have shown that torsional oscillations persist at depth over a large fraction of the convection zone (Howe *et al.*, 2000), especially at high latitudes where they extend down to the bottom of the convection zone (Vorontsov *et al.*, 2002). At low latitudes, the data support the idea that the torsional oscillation pattern originates inside the convection zone and propagates both upward and equatorward (Vorontsov *et al.*, 2002; Basu and Antia, 2003). Above 45° latitude, bands of faster and slower rotation appear to move toward the poles (Antia and Basu, 2001; Schou, 2003) suggesting a connection with the poleward migration of high-latitude magnetic activity seen at the surface (e.g. Callebaut and Makarov, 1992). Both time–distance (Giles, Duvall, and Scherrer, 1998; Beck, Gizon, and Duvall, 2002; Zhao and Kosovichev, 2004) and ring-diagram (Basu and Antia, 2000; Haber *et al.*, 2000, Haber *et al.*, 2002) analyses have confirmed the global-mode measurements of torsional oscillations. In addition, local techniques have revealed measurable differences in the rotation profile between the northern and southern hemispheres (e.g. Basu, Antia, and Tripathy, 1999). As will be discussed in Section 3, local techniques can also provide information about the longitudinal structure of the zonal flows.

Schüssler (1981) and Yoshimura (1981) suggested that the torsional oscillations may be driven by the Lorentz force due to a migrating dynamo wave. Recent numerical calculations by Covas *et al.* (2000) seem to be consistent with this hypothesis; their calculations also reproduce the poleward propagating torsional oscillations at high latitudes. Other explanations attribute the torsional oscillations to the feedback of the smaller-scale magnetic fields on the angular momentum transport mechanisms responsible for differential rotation, e.g. changes in the Reynolds/Maxwell stresses (Küker, Ruediger, and Pipin, 1996; Kitchatinov *et al.*, 1999) or the local suppression of turbulent viscosity by active regions (Petrovay and Forgács-Dajka, 2002). An alternative explanation by Spruit (2003) suggests that zonal flows may be driven by temperature perturbations near the surface due to the magnetic field: local flows around regions of enhanced magnetic activity act through the Coriolis force to balance horizontal pressure gradients. The model of Spruit (2003) naturally predicts a solar-cycle variation in the meridional flows. The reader is refered to the review paper of Shibahashi (2004) for other possible explanations.

2.2. Tachocline oscillations

Howe *et al.* (2000) discovered temporal changes in the rotational velocity near the bottom of the convection zone. The variations are quasi-periodic with a period of approximately 1.3 yr and a peak amplitude at $0.72R_\odot$. As shown in Figure 3, the angular velocity variations at $0.72R_\odot$ and $0.63R_\odot$ are anticorrelated. Notice that the signal seemed much weaker near the second half of 2001 but it has come back since. These results are somewhat controversial since they have not been confirmed by others (e.g. Basu and Antia, 2001; Vorontsov *et al.*, 2002). However, Knaack, Stenflo, and Berdyugina (2004) have detected transient 1.3-yr oscillations in the unsigned photospheric magnetic flux during cycles 21–23, which may be related to the large-scale magnetic surges towards the poles. The 1.3-yr periodicity is also seen in observations of the interplanetary magnetic field and geomagnetic activity (Lockwood, 2001).

Gough (2000) suggested that a 500 G radial magnetic field across the tachocline may lead to exchange of angular momentum with the right time scale, while Covas

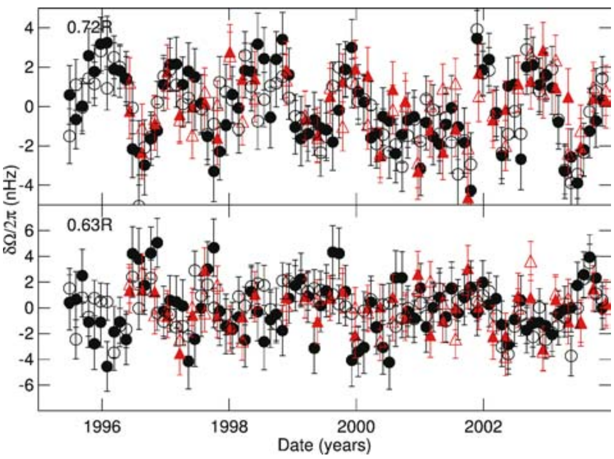

Figure 3. Variations in inferred equatorial angular velocity at $0.72R_\odot$ and $0.63R_\odot$ for GONG (*circles*) and MDI (*triangles*) data with filled (*open*) symbols representing RLS (OLA) inversion results. Results by R. Howe according to the method described by Howe *et al.* (2000).

et al. (2001) suggested a highly non-linear mechanism that does not require different physical time scales for torsional and tachocline oscillations.

2.3. Meridional flows

Surface Doppler measurements have shown the existence of a meridional flow from the equator to the poles with an amplitude of about 20 m s^{-1} (e.g. Hathaway, 1996). Meridional circulation is an important ingredient of solar dynamo models where magnetic flux is transported by a deep equatorward flow (flux-transport dynamo models). In such models, the solar-cycle period is largely determined by the amplitude of the meridional flow near the base of the convection zone (Dikpati and Charbonneau, 1999). Hathaway *et al.* (2003) claimed that the butterfly diagram is evidence for flux-transport dynamo models, and estimated a 1.2 m s^{-1} flow at the bottom of the convection zone from the drift of sunspots toward the equator. However, Schüssler and Schmitt (2004) argue that the butterfly diagram is equally well reproduced by a conventional dynamo model with migrating dynamo waves without transport of magnetic flux by a flow. The depth of penetration of the meridional flow is another parameter in some dynamo models (e.g. Nandy and Choudhuri, 2002). Knowing meridional circulation is also important to understand its feedback on differential rotation (Rekowski and Rüdiger, 1998; Gilman, 2000).

The meridional flow is hard to measure reliably since its amplitude is so much smaller than the solar rotation. Meridional circulation was first detected at depth by Giles *et al.* (1997) with time–distance helioseismology. The inversions, constrained by mass conservation, show that the data are consistent with a meridional circulation which is 20 m s^{-1} poleward at the solar surface and about 3 m s^{-1} equatorward at the base of the convection zone, with a turnover point near $0.8R_\odot$ (Giles, 2000; Figure 4). Other estimates of the meridional circulation have been obtained in the

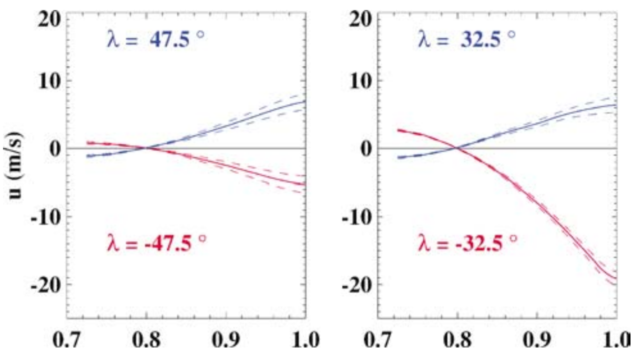

Figure 4. Meridional circulation in 1996–98 inferred from p-mode travel times at various latitudes as a function of scaled radius, $r/R_\odot$. The *blue (red)* curves are for the northern (southern) latitudes. The turnover point is roughly at $r = 0.8R_\odot$. The asymmetry between the two hemispheres is probably caused by an error in the orientation of the MDI camera. From Giles (2000).

near-surface layers with time–distance helioseismology (e.g. Chou and Dai, 2001; Duvall and Gizon, 2000; Zhao and Kosovichev, 2004) and ring-diagram analysis (e.g. Basu, Antia, and Tripathy, 1999; Gonzalez Hernández *et al.*, 1999; Haber *et al.*, 2000). Haber *et al.* (2002) found a submerged equatorward flow in the north during the years 1998–2001, which is not seen in other analyses.

Meridional circulation (averaged in longitude over several rotation periods) is observed to change from year to year through the solar cycle. To study the time-varying component of meridional circulation, we consider the residuals obtained after subtraction of a temporal average at each latitude. Meridional flow residuals have an amplitude which is less than ± 10 m s^{-1}. Like torsional oscillations, the north–south flow residuals drift equatorward with active latitudes. Unlike torsional oscillations, the residuals of meridional circulation change sign across the uppermost 70 Mm. Near the surface, the time-varying residuals converge toward active latitudes (Gizon, 2003; Basu and Antia, 2003; Zhao and Kosovichev, 2004, Figure 5), while at greater depths meridional flow residuals diverge from the dominant latitude of activity (Chou and Dai, 2001; Beck, Gizon, and Duvall, 2002, Figure 6). Notice that the time-varying component of meridional circulation has also been measured near the surface from the advection of supergranulation (Gizon and Duvall, 2004), in agreement with local helioseismology results.

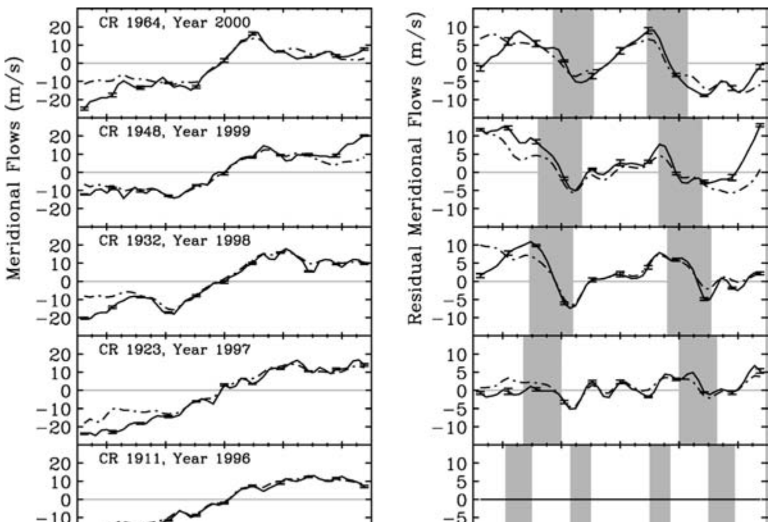

Figure 5. *Left panels*: Meridional flow measured by time–distance helioseismology at depths 4 Mm (*solid lines*) and 7 Mm (*dash-dotted lines*) as a function of latitude for different Carrington rotations. *Right panels*: Northward residual flows, computed by removing the CR1911 flow at each Carrington rotation. The grey regions show the latitudes of activity. The residuals are consistent with a converging flow toward the mean latitude of activity. From Zhao and Kosovichev (2004).

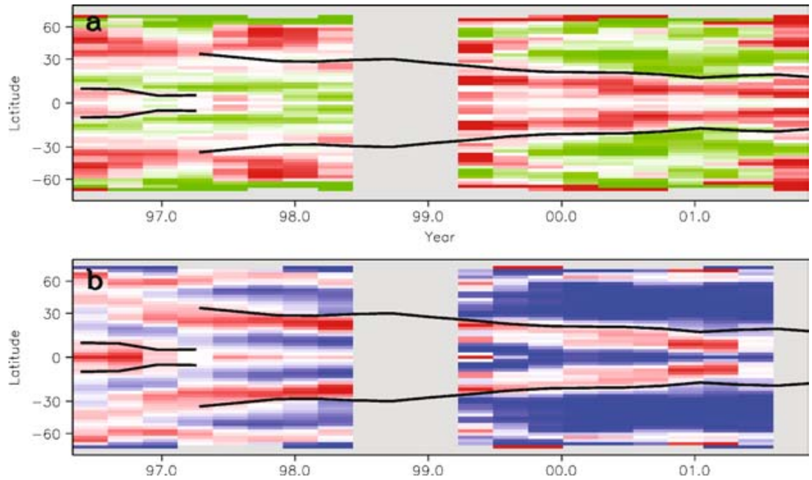

Figure 6. (a) Meridional circulation residuals as a function of time and latitude, measured by time–distance helioseismology at a depth of about 50 Mm. The residuals are obtained by removing a time average. The *green (red)* shades correspond to excess poleward (equatorward) velocities, with values in the range ± 10 m s^{-1}. The *thick black line* is the mean latitude of activity. The residuals are consistent with a flow diverging from the mean latitude of activity. (b) Zonal flow residuals (torsional oscillations) as a function of time and latitude. The *red (blue)* shades correspond to flows that are faster (slower) than average. Notice the good agreement with Figure 2. From Beck, Gizon, and Duvall (2002).

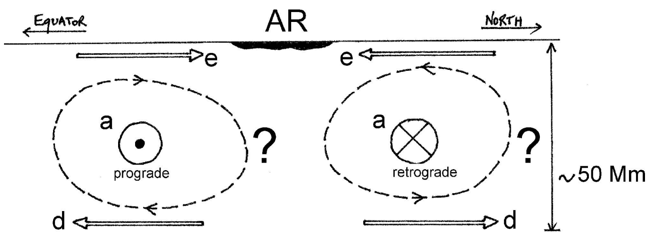

Figure 7. Sketch of the time-varying components of the large-scale flows, averaged in longitude over several rotation periods. Shown is a meridional plane in the northern hemisphere; the prograde direction is coming out of the page. Zonal flows (a) introduce a ± 10 m s^{-1} shear around the mean latitude of activity (AR). Residual meridional flows (<10 m s^{-1}) converge toward active latitudes near the surface (e) and diverge deeper inside the Sun (d). The whole pattern of flows drifts equatorward through the solar cycle. The *dashed* streamlines may be misleading because meridional flow residuals are highly structured in longitude.

These observations, summarized in Figure 7, lead Zhao and Kosovichev (2004) to postulate the existence of extra meridional ciculation rolls on each side of the mean latitude of activity, superimposed on the mean global-scale poleward flows. However, it is suggested below that the changes in the longitudinal averages of meridional flows can be attributed for a large part to flows that are localized both in longitude and latitude around active regions.

3. Ordered Flows near Complexes of Magnetic Activity

3.1. THREE-DIMENSIONAL MAPS OF HORIZONTAL FLOWS

Using local helioseismology, synoptic maps of local horizontal flows can be constructed by averaging the data in time in a frame of reference that co-rotates with the Sun. Weak 50 m s^{-1} surface flows that converge toward active regions were detected by Gizon, Duvall, and Larsen (2001) with time–distance helioseismology (Figure 8). These flows, which exist as far as 30° from the centers of active regions, are also seen in ring diagram analyses with a coarser resolution (Haber *et al.*, 2001). We note that Hindman *et al.* (2004) have shown that the two methods give remarkably similar results near the surface. Recently, both time–distance (Zhao and Kosovichev, 2004) and ring-diagram (Haber *et al.*, 2004) analyses have provided maps of horizontal flows as function of depth, down to about 15 Mm below the surface. Depth inversions indicate that, below 10 Mm, horizontal flows often diverge from active-region centers with velocities on the order of 50 m s^{-1}. Figure 9 shows the flows measured by Haber *et al.* (2004) around a particular active region. Motions appear to be organized in the form of a toroidal cell with a surface inflow and a deeper outflow. The picture is not so simple on time scales that are shorter than a week since flows do evolve from day to day.

The observed flows around active regions could be caused by the magnetic field. Indeed, the model of Spruit (2003) mentioned earlier predicts a surface inflow toward regions of enhanced magnetic field. An alternative explanation by Yoshimura (1971) suggests that the longitudinal ordering of solar magnetic fields could be due to the existence of large convective patterns that favor the formation of active regions at particular sites on the solar surface. We note that far away from active

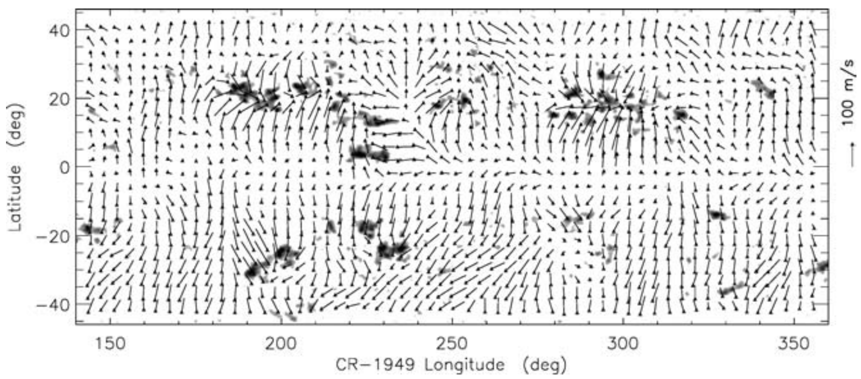

Figure 8. Map of near-surface horizontal flows obtained for Carington rotation 1949 using f-mode time–distance helioseismology. A smooth rotation profile has been subtracted. The *dark shades* are shorter travel-time anomalies that correspond to regions of enhanced magnetic activity. Local flows converge toward around complexes of activity with an amplitude of 50 m s^{-1}. Notice also the poleward meridional flow. From Gizon, Duvall, and Larsen (2001).

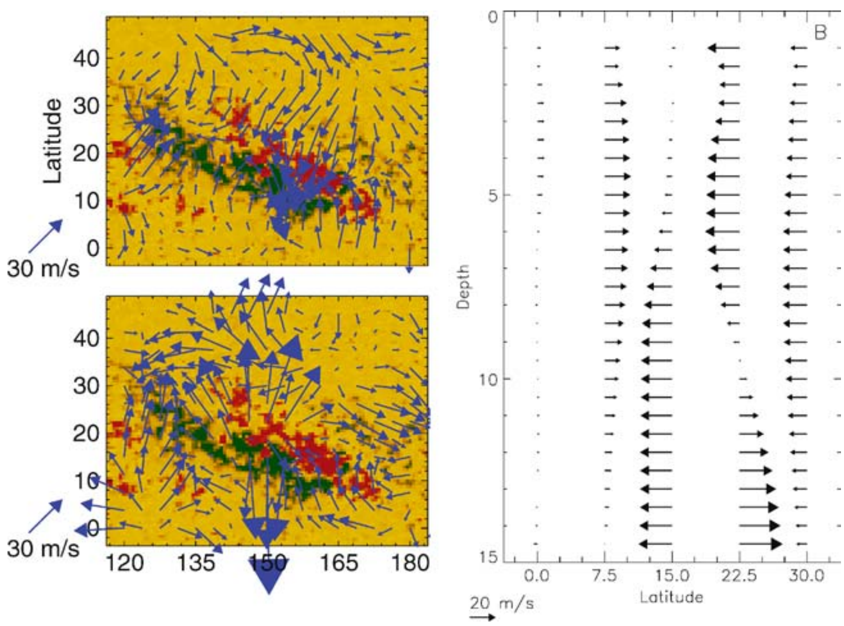

Figure 9. *Left panels*: OLA inversion of horizontal flows around active region NOAA 9433 on 23 April 2001 obtained using ring-diagram analysis. The depths shown are 7 Mm (*upper panel*) and 14 Mm (*lower panel*). *Right panel*: Horizontal flows around NOAA 9433 as a function of depth and latitude, averaged over the longitude range [142.5°, 157.5°] and the time period 23–27 April 2001. The transition between inflow and outflow occurs near 10 Mm depth. From Haber *et al.* (2004).

regions, complex flows like meanders, jets, and vortices are seen in the synoptic maps (Figure 8); Toomre (2002) suggested that they may be related to the largest scales of deep convection.

3.2. Active-region flows and longitudinal averages

An important question is to know whether the local flows that surround active regions contribute significantly to the solar-cycle variations of the longitudinal averages of rotation and meridional circulation in the upper layers of the convection zone (discussed in Sections 2.1 and 2.3). In other words, are the time-varying components of rotation and meridional circulation global phenomena or are they modulated in longitude by the presence of active regions?

In order to help answer this question, we consider synoptic maps of surface flows obtained in 1999 for Carrington rotations 1948 and 1949. By excluding the local areas of active-region flows in the computation of the longitudinal averages of rotation and meridional circulation, we obtain "quiet-Sun" estimates that can be compared to the flows averaged over all longitudes (Figure 10). It is obvious that the torsional oscillation (rotational shear at active latitudes) is present in between

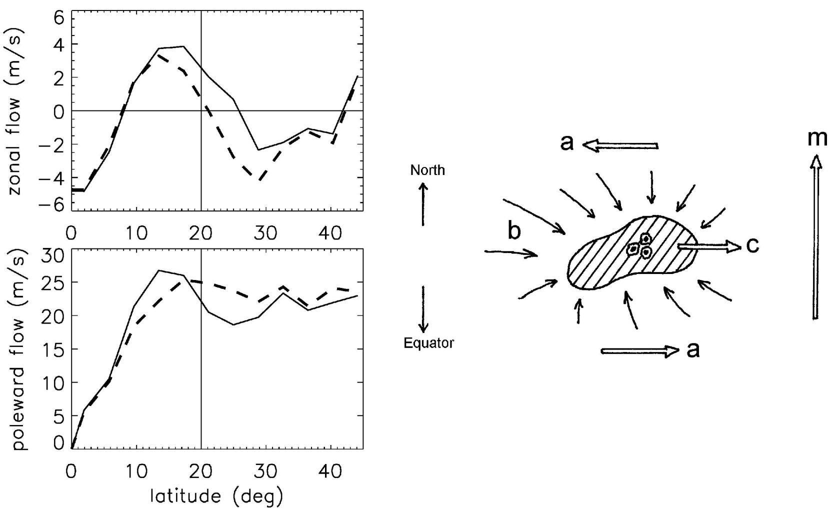

Figure 10. Left panels: Longitudinal averages of surface horizontal flows obtained with f-mode time–distance helioseismology (Carrington rotations 1948 and 1949 in 1999). The *vertical lines* indicate the mean latitude of activity. The *solid curves* show zonal flows and meridional circulation averaged over all longitudes and both hemispheres. The zonal flows are obtained after subtraction of a smooth three-term fit to the rotation profile. The *dashed curves* are averages that exclude local areas around active regions. *Right panel*: Sketch of surface flows around active regions: (a) ± 10 m s^{-1} zonal shear flow, (b) 50 m s^{-1} inflow, (c) active region super-rotation, and (m) 20 m s^{-1} background meridional circulation.

active longitudes. Indeed, it is known from surface observations and global helioseismology that the torsional oscillation pattern exists during cycle minimum. Thus the time-varying zonal flows appear to be mostly independent of longitude as they slowly drift in latitude through the solar cycle. Yet, active regions do rotate a little faster than their surroundings, thus affecting the mean rotation rate at active latitudes (Zhao, Kosovichev, and Duvall, 2004). The influence of local active-region flows on longitudinal averages of north-south flows is more serious. Indeed, the 50 m s^{-1} organized flows that surround active regions introduce a kink at active latitudes in the average meridional circulation profile, on the order of ± 5 m s^{-1}. Thus the solar-cycle variations of the meridional circulation (Section 2.3) would appear to be caused by active regions: convergence toward active latitudes near the surface and, presumably, divergence below 10 Mm.

4. Conclusion

Helioseismology has revealed temporal changes in the dynamics of the solar interior that may shed light on the mechanism of the magnetic dynamo. In particular, observations of the torsional and tachocline oscillations may help constrain dynamo models. Solar-cycle variations in the meridional flows have also been detected in the upper convection zone with local helioseismology; these variations may be due to localized effects of active regions. Local helioseismology provides a three-dimensional view of the solar interior, which is important to understand large-scale flows, magnetic structures, and their interactions in the solar interior.

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