Recent Insights into the Physics of the Sun and Heliosphere: Highlights from SOHO and Other Space Missions
IAU Symposium, Vol. 203, 2001
P. Brekke, B. Fleck, and J. B. Gurman eds.

Spatially-resolved Analysis of the Upper Convection Zone

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Abstract. Ring-diagram analysis of MDI data has revealed systematic patterns in global flow patterns in the early phase of the cycle. We report on variations and trends seen in the flows in subsequent years.

Localized plane-wave ("ring-diagram") analysis of high-degree modes permits us to determine spatial and temporal variations of the structure and dynamics of the upper convection zone, to a depth of about 0.025 $R_\odot$ ($\sim$15 Mm). The spatial resolution achieved for localized flows with full-disc data is at least 15° (180 Mm), and the temporal resolution is of order 1 day. The data for this analysis are the full-disc SOI-MDI Dopplegrams from SoHO. Suitably continuous observations cover at least two full rotations in each year since 1996.

The calibrated Dopplergrams are detrended by subtracting the per-pixel mean for each time interval being analyzed. Each analysis covers a period of 1664 minutes (27^h44^m). Samples for analysis are selected at exact intervals of 15°in longitude of the sub-observer point, so the sampling interval is fixed in the Carrington frame. The images are mapped with Postel's projection about a grid of points rotating at rates appropriate to their central latitude. The local maps have diameters of 32°. The centres are spaced at 15°intervals in latitude and longitude. We thus construct a mosaic of 189 overlapping three-dimensional data cubes of Doppler residuals versus time and surface location for each analyzed interval; there are 24 such intervals over the course of a Carrington rotation. These yield the power spectra to which the ridges can be fit.

The spectra are fit to multi-parametric models using two different procedures; one, described by Haber *et al.* (1998) is rapid and efficient for extracting mode advection parameters u_x and u_y from which the the vertical profile of

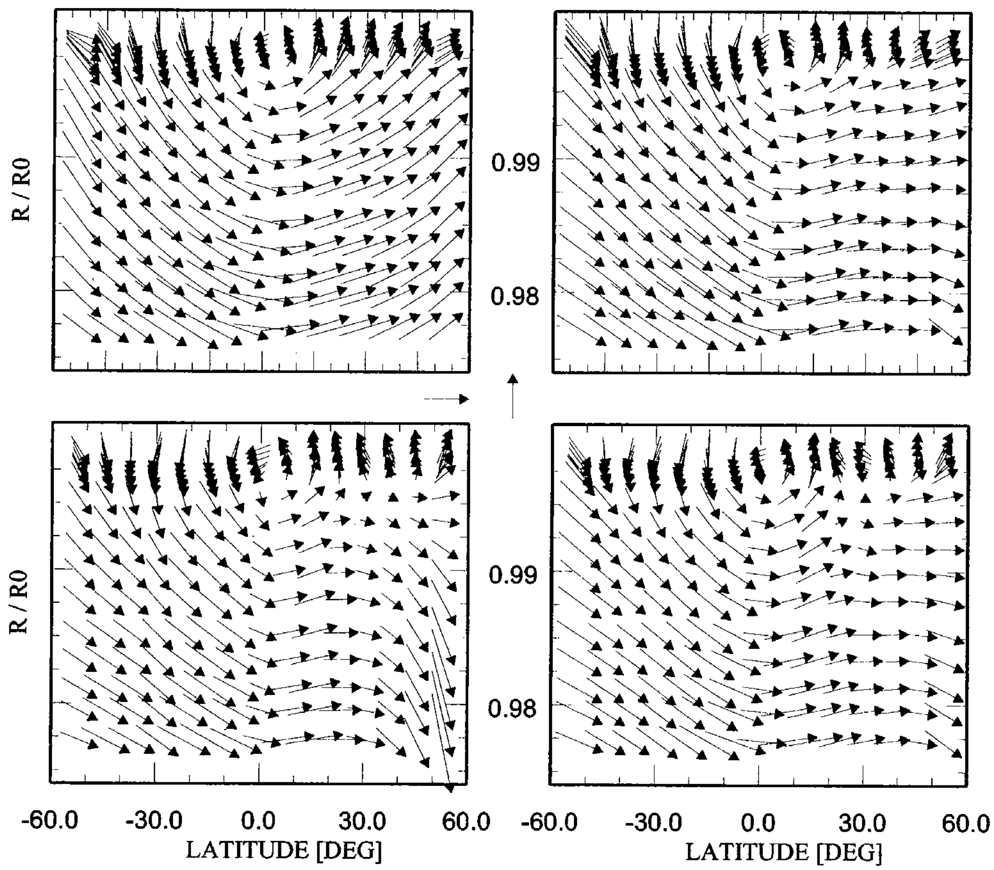

Figure 1. Transverse flow vectors as functions of latitude and depth averaged over all longitudes for full rotations during: a) June 1997; b) January 1998; c) April 1999; d) June 2000. Note that the directions of the flow vectors are unrelated to the directions of the axes. Latitude increases northward to the right, but an arrow to the right represents a westward zonal velocity, and an upward arrow represents a northward flow. Scale arrows representing 25 m/s flows west and north are shown.

transverse flows is inferred by inversion. The other, described by Basu *et al.* (1998) is a more traditional one providing a larger number of parameters in the ridge fits. The velocity parameters from the former set of fits were inverted with a regularized least-squares (RLS) procedure, the latter using optimally localized averaging (OLA). The inversions yield estimates of the average radial profiles of transverse velocities below each of the tracked elements making up a mosaic.

We have followed separate procedures for determining the mean zonal profiles of the near-surface velocity flows. In one, the ridge fits and RLS inversions are performed for each point in the mosaic for each daily tracking interval; the resulting flow maps are then averaged together for the points from several different mosaics corresponding to the same viewing angle The results shown here are based on rotational averages of all points at the same latitude, regardless of viewing angle. In the other process, we average together spectra from corresponding points on the daily mosaics, again at the same viewing angle, and then perform the mode fits and the OLA inversions to the averaged spectra. Typically we have averaged together spectra or fits from the central meridian points at each of 15 latitude centers in the range $\pm 52^\circ.5$ on both 8 and 24 consecutive mosaics, corresponding to one-third of and a full Carrington rotation.

The 8-day averages on central meridian are of course inherently noisier than the 24-day averages of all points. On the other hand, there are both symmetric and anti-symmetric systematic effects in the power spectra dependent on disc location, presumably related to variations in both the effective focal length and plate scale over the field of view and the astigmatism. When spectra from the same 8 or 9 days of points on the central meridian only are analyzed using both of the two procedures for averaging, fitting, and inversion, however, the agreement is generally excellent.

Sample velocity field profiles from the RLS inversions of the ring fits for power spectra averaged over a full rotation during each of the last four years are shown in Figure 1. The profiles in 1996, previously reported, are very similar to those in 1997.

The radial dependence of the anomalous zonal flow (with respect to the fixed differential rotation) through the outer 15 Mm has remained essentially uniform at each latitude for the last five years. The torsional oscillation amplitude is thus independent of depth and varies with the surface amplitude. The amplitude at all depths has increased regularly, however, and the latitudes of peak zonal flows have moved equatorward, in agreement with both the surface measurements and global-mode inversions. There is a hint that the asymmetric component of the zonal flow has reversed, with relatively faster flow in the northern hemisphere at cycle minimum and in the southern at maximum.

The dominant two-cell symmetric meridional circulation seen at all depths in 1996 and 1997 has given way since 1998 to a somewhat more complex pattern, with a more extended and intense cell in the southern hemisphere, and a much weaker cell in the northern hemisphere, possibly breaking up into a small poleward cell confined to mid- to low-latitudes and a counter-cell appearing at high latitudes. In the years near minimum, the mean meridional flow may have increased slightly with depth through the zone of interest. The appearance of a more complex flow in recent years in the northern hemisphere has been accompanied by greater variations in the radial profile, with substantial poleward flows at depths > 10 Mm at certain latitudes, and more pronounced reverse flows at depth at higher latitudes. While the neutral line between the two hemispheric cells has remained near the equator at the surface, it has migrated to as much as 20°north latitude below 10 Mm in the last two years.

References

Basu, S., Antia, H. M., & Tripathy, S. C. 1998, in ESA SP-418, Structure and Dynamics of the Interior of the Sun and Sun-like Stars, ed. S. Korzennik & A. Wilson (Dordrecht: ESA), 705

Haber, D. A., Hindman, B. W., Toomre, J., Bogart, R. S., Schou, J., & Hill, F. 1998, in ESA SP-418, Structure and Dynamics of the Interior of the Sun and Sun-like Stars, ed. S. Korzennik & A. Wilson (Dordrecht: ESA), 791