SOLAR SUBSURFACE FLOWS AND VORTICITY

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ABSTRACT

We study horizontal flows in the upper solar convection zone derived from MDI Dynamics Program and high-resolution GONG data using ring-diagram analysis. Horizontal and vertical flows show clear solar-cycle variations. The zonal flows show the torsional oscillation pattern known from surface and global helioseismology measurements. The meridional flows converge near latitudes of activity and the vertical flows show downflows at these latitudes (at depths of 5 Mm or less). We also compare MDI and GONG data obtained during the MDI Dynamics Program of 2002 and 2003 and show derived vertical flows at 7 Mm. Strong downflows occur at locations of large magnetic flux at these depths. MDI and GONG data show similar results, except at high latitudes. To study the relation between the vorticity of flows and magnetic activity, we calculate an unsigned quantity from the 3-D vorticity, the so-called enstrophy. We find that vorticity appears to be enhanced near locations of active regions.

1. INTRODUCTION

We analyze MDI Dynamics Program and high-resolution GONG data covering 28 and 10 Carrington Rotations respectively with the ring-diagram technique (Haber et al., 2002) in order to study the relation between the subsurface flows and surface magnetic activity. Here, we focus on the solar-cycle variation of the horizontal flows (torsional oscillations and meridional flow) and that of the vertical flows. We also compare synoptic maps of vertical velocity derived from MDI and GONG data obtained during the Dynamics Program 2002 and 2003.

Finally, we study the vertical vorticity during epochs of high and low magnetic activity and its relation to magnetic activity. The vertical vorticity is dominated by differential rotation which leads to a nearly linear latitude dependence with positive/negative values in the northern/southern hemisphere (see Zhao & Kosovichev, 2004). At locations of magnetic activity, there appears to be excess vertical vorticity of the same sign as that introduced by differential rotation (see Komm et al., 2004, Zhao & Kosovichev, 2004).

2. DATA AND ANALYSIS

We analyze MDI Dynamics Program data covering 28 Carrington Rotations (May 1996 – Nov 2003) and GONG data covering 10 Carrington Rotations (July 2001 – Dec 2003) using the standard dense-pack ring-diagram analysis (Haber et al., 2002). For each day of 1664 minutes, the full-disk Doppler images are divided into 189 overlapping $16^{\circ} \times 16^{\circ}$ regions covering the solar disk within $\pm 60^{\circ}$ in latitude and central meridian distance. The regions have centers offset by 7.5° and are circularly apodized to a diameter of 15°. Each tracked apodized image cube is then fourier-transformed and the resulting power spectra show rings when sliced at a given frequency. The measured shifts of these rings are then inverted to determine the horizontal velocity components as a function of depth. We derive the vertical velocity component from the divergence of the measured horizontal flows assuming mass conservation (Komm et al., 2004).

3. RESULTS

Figure 1 shows the solar-cycle variation of the horizontal flows of near surface layers (0.9–4.4 Mm) derived from MDI Dynamics Program data. To highlight the variations, the average was subtracted at each latitude. The zonal flows (top) show bands of faster-than-average rotation equatorward of locations of activity and bands of slower-than-average rotation poleward of locations of activity, which is the torsional oscillation pattern well-known from surface and helioseismic measurements. The average meridional flows are poleward in each hemisphere. The residual flows are predominantely equatorward/poleward on the poleward/equatorward side of magnetic activity; they converge near locations of magnetic activity. The corresponding vertical flows, shown in Figure 2, show downflows at locations of activity at this depth range. The results from MDI and GONG data are consistent. Both data sets lead to similar vertical flows;

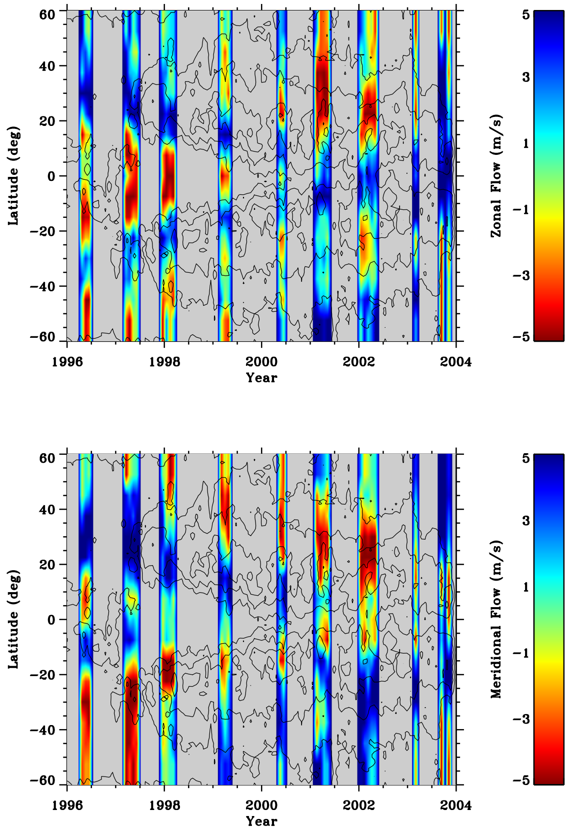

Figure 1. Zonal (top) and meridional flows (bottom) of near surface layers (0.9-4.4 Mm) derived from MDI data. The average was subtracted at each latitude. For meridional flows, positive/negative values indicate flows to the north/south.

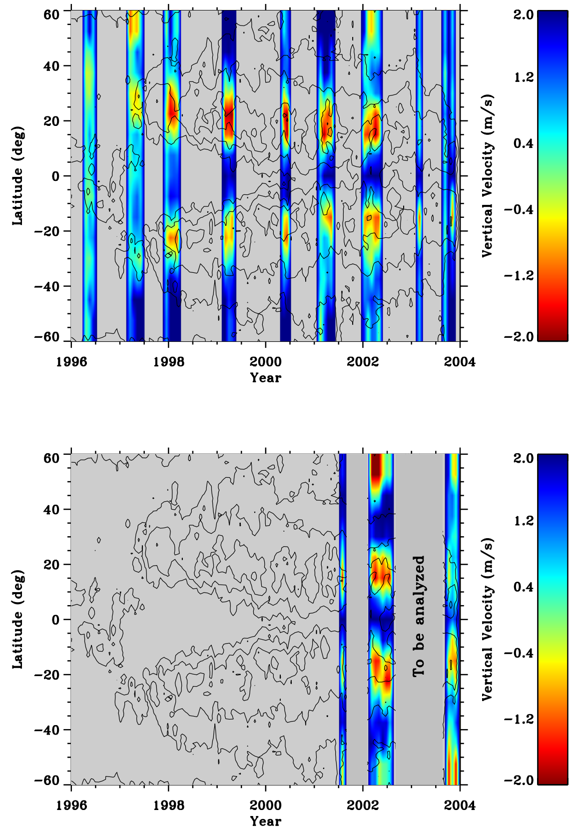

Figure 2. Same as Figure 1 for the vertical velocity derived from MDI data (top) and from GONG data (bottom). Downflows coincide with locations of magnetic activity.

differences occur mainly at high latitudes where measurement errors are larger.

To show the relation between vertical flows and magnetic activity in more detail, we show, as examples, two sets of synoptic maps of the vertical flow component at a depth of 7 Mm from the MDI Dynamics Program of 2002 and 2003. Figure 3 shows the maps of CR 1988 and CR 2009 derived from MDI and GONG data. Locations of magnetic activity are characterized by downflows of the order of 1 m/s. The unusually strong downflow in the maps of CR 2009 at 285^o longitude and -15^o latitude (3rd and bottom row) coincides with the location of active region AR 10486, which produced many flares during this epoch. As before, MDI and GONG data lead to similar results; differences occur mainly at high latitudes.

Figure 4 shows the vertical vorticity at a depth of 7 Mm during epochs of low and high magnetic activity (CR 1910 and CR 1988) derived from MDI Dynamics Program data. Positive vorticity implies a counterclockwise motion. Since the differential rotation dominates the vertical vorticity, we subtracted the contributions of the average zonal and meridional flows. The residual vertical vorticity shows large-scale patterns that lead to enhanced vorticity (of the same sign as that introduced by differential rotation) at locations of magnetic activity when averaged over each Carrington Rotation (see Komm et al., 2004, Zhao & Kosovichev, 2004). But, it is difficult to see this relation between locations of activity and vertical vorticity for individual active regions and it is nearly impossible to distinguish between high and low activity epochs.

To show this relation more clearly and to include the other two vorticity components, we calculate an unsigned quantity from the complete 3-D vorticity vector, the so-called enstrophy, defined as the variance of vorticity (Lesieur, 1987). Figure 5 shows the corresponding enstrophy maps. The difference between high and low activity epochs is now obvious; most strong active regions are also regions of enhanced enstrophy.

4. SUMMARY

We find that MDI and GONG data show similar results; differences occur mainly at high latitudes. We can derive the complete 3-D vector of velocity and vorticity in near surface layers using the ring-diagram technique. We find a solar-cycle variation of the vertical flow component which shows downflows at latitudes of magnetic activity. It is not too surprising that the 'smooth' pattern on time scales of the solar cycle is an average of 'lumpy' patterns on shorter time scales. At time scales of a single rotation, downflows occur mainly at locations of large magnetic flux. These locations are also locations of enhanced vorticity, as indicated by the variance of the 3-D vorticity (enstrophy). We will quantitatively explore these relations in the near future.

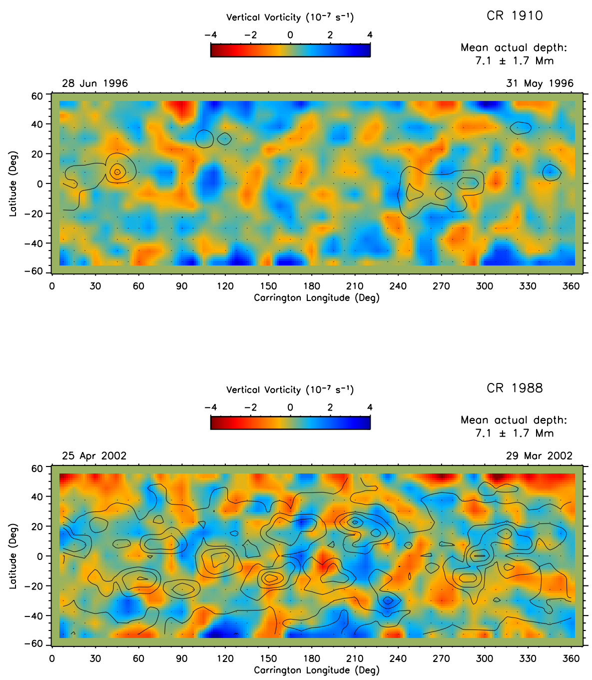

Figure 4. Vertical vorticity at a depth of 7.1 Mm during epochs of low and high magnetic activity derived from MDI data. Positive values imply a counterclockwise motion. The contour lines indicate magnetic flux (5, 20, 40, 80, and 120 Gauss) from NSO Kitt Peak magnetograms.

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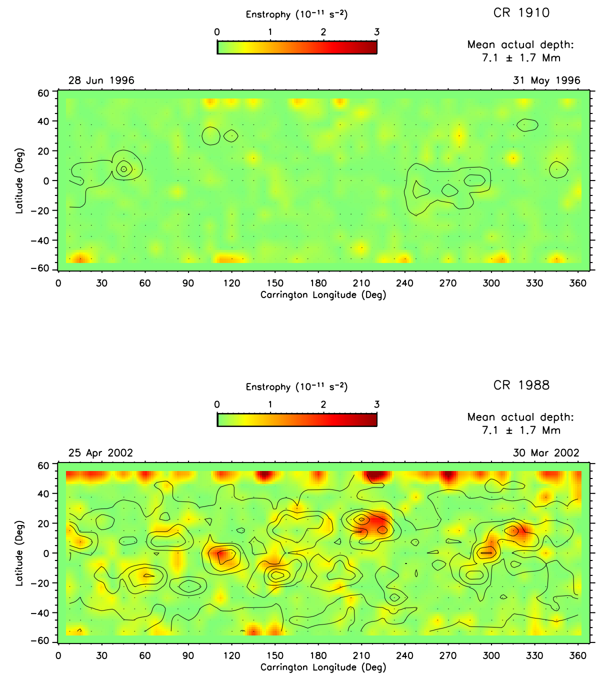

Figure 5. Same as Figure 4 for the variance of 3-D vorticity (enstrophy).

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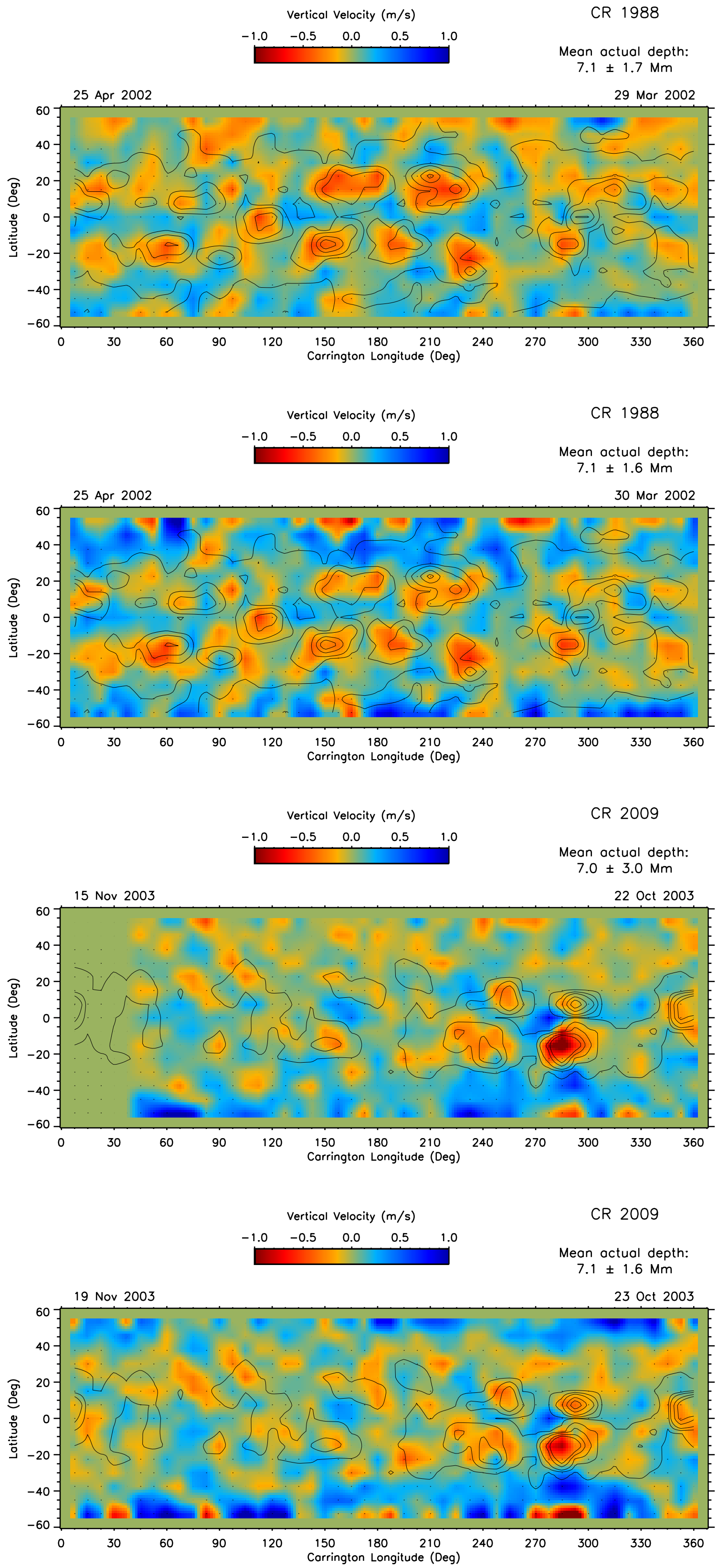

Figure 3. Vertical velocity at a depth of 7.1 Mm for CR 1988 (Top: MDI; 2nd row: GONG) and for CR 2009 (3rd row: MDI; bottom: GONG). Positive/negative values indicate upflows/downflows. The contour lines indicate magnetic flux (5, 20, 40, 80, and 120 Gauss) from NSO Kitt Peak magnetograms (CR 1988) and MDI magnetograms (CR 2009).