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Characteristics of Solar Meridional Flows

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Abstract. We have done a ring-diagram analysis of MDI full-disc data to determine the properties of solar meridional flow in the outer 2% of the Sun over the solar cycle 23. The meridional flows show a migrating pattern with higher-velocity flows migrating toward the equator as activity increases. Additionally, we find that the migrating pattern of the meridional flow matches those of the sunspot butterfly diagram and the zonal flows in the shallow layers. A Legendre polynomial decomposition of the meridional flows shows that the latitudinal pattern of the flow was also different during the maximum as compared to that during the two minima. We also find that the dominant component of the meridional flows during solar maxima was much lower than that during the minima of solar cycles 23 and 24.

1. Introduction

Meridional flows from the equator toward the poles have been detected on the solar surface using observations of magnetic features (Komm et al. 1993) as well as direct Doppler measurements (e.g., Hathaway 1996). Splittings of the global modes of solar oscillations are not sensitive to the first order contributions of meridional flows and as a result local helioseismic techniques have been used to study these flows in the solar interior. These techniques so far only give information about the near-surface regions of the Sun. Giles et al. (1997) studied meridional flows using the time-distance technique, while Schou & Kosovichev (1997) and Basu et al. (1998) applied the ring diagram technique to study these flows. They found that the flow velocities in the outer convection zone are similar to those seen at the surface velocities. With the availability of seismic data covering the solar cycle 23, temporal variations of these flows can also be studied.

2. Data and Technique

We use MDI data to study solar meridional flows using ring-diagram analysis (Hill 1988). The technique uses 3D power spectrum (two spatial wave-numbers and the temporal frequency) of solar oscillations. The spectra that we use were obtained along the central meridian for $16^\circ \times 16^\circ$ patches in heliographic longitude and latitudes up to 52.5° in steps of 7.5° in both hemispheres. To reduce noise at each latitude we averaged over a Carrington rotation. We used 15 data sets covering a period from June 1996 to June 2009, with roughly one data set every year. These data cover the entire solar cycle 23 and a very small part of the beginning of cycle 24. The resulting 3D power spectra were fitted to the model of Basu & Antia (1999) to determine the shift in frequencies caused by the horizontal components of solar flows. The meridional flow velocities were obtained by inverting the parameter that describes the shift in frequencies due to

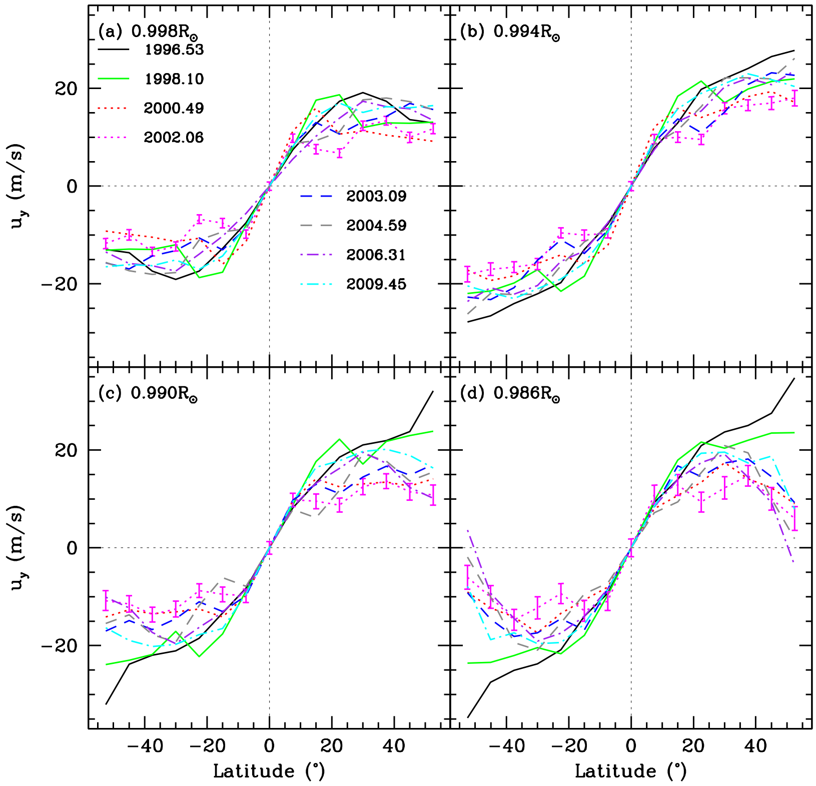

Figure 1. The north-south antisymmetric component of the solar meridional velocity shown as a function of latitude at a few different depths as marked in the panels. These results were obtained using OLA technique for inversion. The results obtained using RLS are similar.

meridional flows. We used both the Optimally Localised Averages (OLA) and the Regularised Least Squares (RLS) techniques to invert for the meridional velocity as a function of depth. The results are robust when two techniques give similar results. The inversions of the flow parameters obtained from the power spectrum of any patch gives the meridional flow velocity as a function of depth in that patch. Inversions of flow parameters of patches that cover different latitudes and times give us the latitude and time dependences of the flow. To determine the details of the latitudinal dependence of the flows at any given time, we decompose the flows in terms of the Legendre polynomials (Hathaway 1996):

$$u_y(r,\theta,t) = -\sum_i C_i(r,t) P_i^1(\cos\theta). \qquad (1)$$

Here u_y is the velocity toward the north pole, θ is the angle measured from the north pole. The even values of i correspond to the antisymmetric component of meridional velocity and those are the only ones considered in this work.

3. Results

A sample of the results obtained using the technique described in Section 2 is shown in Figure 1. It should be noted that at some epochs and depths our results show flows across the equator. It is possible that these are artifacts of position-angle errors (Giles et al. 1997) and hence we ignore these in our analysis and concentrate only on the component that is antisymmetric about the solar equator. This is the component that is shown in Figure 1. To show the temporal variations more clearly we show the results at constant depth in Figure 2. This figure shows meridional flow velocity as a function of time and latitude. To make the figure look symmetric we have reversed the sign of meridional velocity in the southern hemisphere. Thus the positive velocity in both hemispheres points toward the respective poles. The results show bands of fast and slow

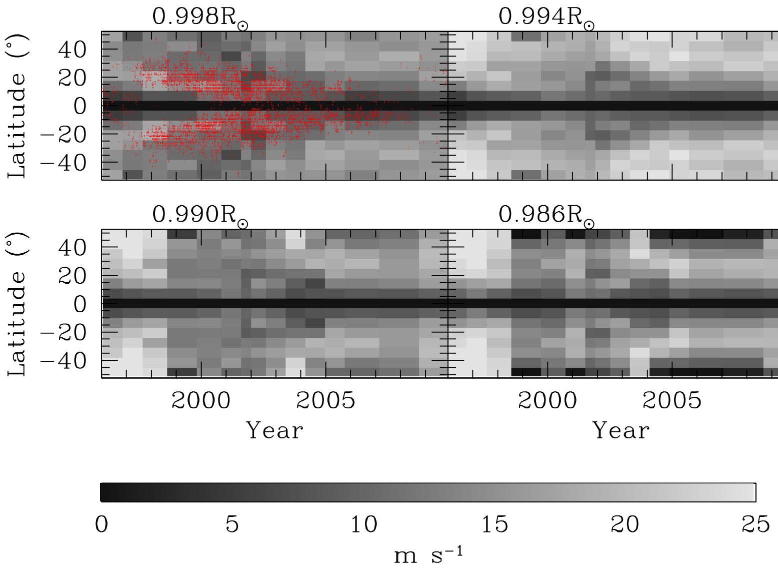

Figure 2. The speed of the north-south antisymmetric component of meridional velocity is shown as a function of latitude and time at a few different depths as marked in the panel. For comparison in one of the panel the position of each sunspot is marked in the time vs latitude plot. In each hemisphere positive velocities imply a flow toward the corresponding pole.

flows migrating toward the equator, very similar to the the zonal flow pattern. The mid-latitude meridional-flow band at a depth of 1.4 Mm coincides with the position of sunspots[1] (i.e. the butterfly diagram) as well as the zonal flow bands at this depth. However, the meridional-flow pattern shows a steeper dependence on depth than the zonal flows and thus the correspondence between the patterns of meridional and zonal flows is lost in deeper layers.

The decomposition of meridional flows in terms of Legendre polynomials shows that the latitudinal behaviour is different at different depths. The behaviour is also different at different phases of solar activity. Although the first even component $C_2(r,t)$ is the dominant component, higher-order components also contribute significantly to the flow pattern. Figure 3, shows the coefficients of various components as a function of time at two different depths. The dominant component, $C_2(r,t)$ is smallest when solar activity is at maximum and is larger during minima. This was also found by Hathaway & Rightmire (2010) from observations at the solar surface. While the $C_2(r,t)$ component shows a clear anti-correlation with solar activity indices, higher-order components show a more complicated behaviour.

Zhao & Kosovichev (2004) and Cameron & Schüssler (2010) have suggested that the temporal variations in the meridional flow can be explained by flows into the active region belts. If this is indeed the case, the higher-order components of the meridional-flow decomposition will be affected to a much larger extent than the C_2 component that the authors calculate. It is not completely clear at this time if this mechanism can explain the depth dependence of the temporal variations in the meridional flows. Furthermore, there are some differences in the meridional flows between the minima of cycles 23 and 24. These cannot be explained by flows into the active latitudes since there were very few, if any, active regions during these times.

4. Summary

Solar meridional flows close to the surface show bands of fast and slow speeds which migrate toward the equator, as noticed earlier by Beck et al. (2002) for the rising phase of cycle 23 and Gonzalez Hernandez et al. (2010) for declining phase of cycle 23. The meridional flow pattern at a depth of 1.4 Mm is very similar to the zonal flow pattern and the fast mid-latitude band coincides with sunspot positions throughout the solar cycle. A decomposition of meridional flows in terms of associated Legendre polynomials show that higher-order components make a

[1] Sunspot positions from http://solarscience.msfc.nasa.gov/greenwch.shtml

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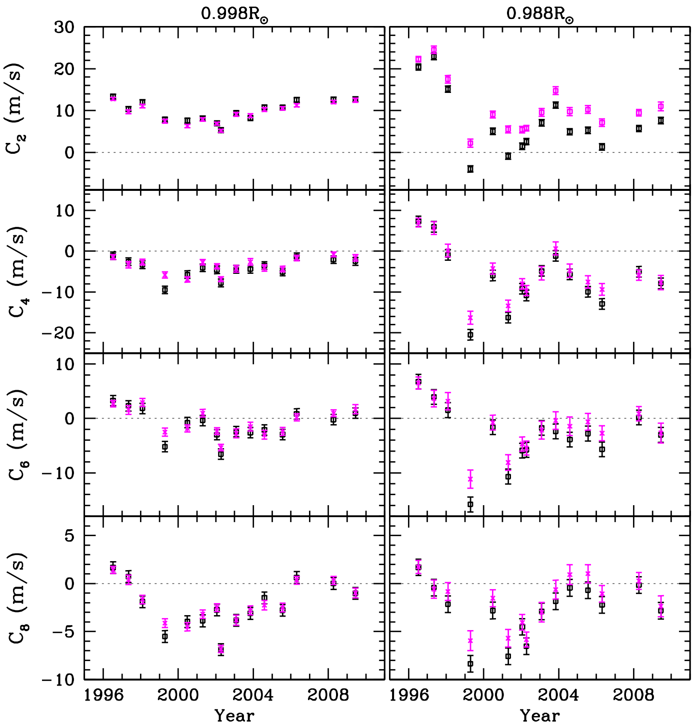

Figure 3. The components of meridional flow in terms of Legendre polynomials are shown as a function of time at two different depths.The black points are results obtained by OLA inversions, the other by RLS inversions.

significant contribution to the flows. The different Legendre components show different time dependences. The dominant component of the flow ($P_2^1(\cos\theta) = 3\cos\theta\sin\theta$) is found to be anti-correlated with global solar activity indices. This is consistent with results of Chou & Dai (2001) and Basu & Antia (2003), as well as with the surface observations of Hathaway & Rightmire (2010).

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