1. INTRODUCTION

Meridional circulation has become an important player in the flux-transport solar-dynamo models (Miesch 2005, and references therein). Until the development of local helioseismology methods, the observation of meridional circulation was limited to the surface layers by tracing magnetic elements (Komm et al. 1993; Snodgrass & Dailey 1996; Nesme-Ribes et al. 1997) or by using surface Doppler velocities (Hathaway 1996). Giles et al. (1997) showed the first meridional circulation inferences under the solar surface by applying a particular local helioseismology technique, time distance. Although the full picture of the meridional circulation throughout the convection zone remains elusive, and recent studies suggest that very long series of data are required to infer the flows deep down (Braun & Birch 2008), local helioseismology has been able to give detailed information on these flows in the subsurface layers. In particular, the variation with the solar cycle has been the focus of several studies (Haber et al. 2002; Basu & Antia 2003; González Hernández et al. 2006; Zaatri et al. 2006; González Hernández et al. 2008), which have shown that the overall amplitude of the meridional circulation is anticorrelated with the magnetic activity. This trend has been confirmed by tracing weak magnetic elements on the solar surface (Hathaway & Rightmire 2010).

Chou & Dai (2001) presented the first evidence of an additional subsurface component of the meridional circulation that varied with the solar cycle located around the center of the sunspot distribution. Applying the time-distance technique to observations from the Taiwan Oscillation Network (TON), they identified a residual of the meridional flow that correlated with the location of the surface activity for the declining phase of solar cycle 22 and the increasing phase of solar cycle 23. Beck et al. (2002) confirmed the discovery using Michelson Doppler Imager (MDI) data from 1996 to 2001 and suggested that this extra component could be a new component of the solar dynamo. In both cases, the authors conclude that this new component could be related to the well-known phenomena of material moving inward/outward from active regions, although they noticed that the inferences suggested a larger than expected depth range. Gizon (2003) tested the possibility of the extra circulation being related to the inflows around large active regions recorded by local helioseismology analysis (Zhao et al. 2001; Haber et al. 2004; Komm et al. 2004; Braun et al. 2004). He analyzed two Carrington rotations eliminating the contribution from areas with surface magnetic activity and found that the extra component decreased.

The continuous operations of the Global Oscillation Network Group (GONG) throughout the full solar cycle 23 have given us the unprecedented opportunity to study the subsurface meridional circulation without interruption. Using these data, González Hernández et al. (2008) revealed that even after aggressively masking surface magnetic activity over a 5.5 year period (2001–2006), the extra component of the meridional circulation remained present, although attenuated, under the solar surface. Here, we extend this analysis to the prolonged solar minimum and find that the formation of the bumps at medium latitudes precedes the onset of the activity, confirming the nature of this phenomenon as independent of the surface manifestation of active regions.

2. DATA ANALYSIS

We extend the study described by González Hernández et al. (2008) to years 2007, 2008, and 2009 to include the recent prolonged solar minimum. In summary, we apply standard ring-diagram analysis (Hill 1988), a local helioseismology technique, to GONG high-resolution Dopplergrams to infer the meridional flow from the solar surface to a depth of approximately 16 Mm.

The ring-diagram method uses medium/high-degree waves propagating in localized areas of the Sun to obtain an averaged horizontal velocity vector for that particular region. The input data used for the analysis are high-resolution Dopplergrams. In this typical analysis, a particular area of the Sun (16° square, apodized to 15° diameter) is tracked and remapped, and the analysis of the corresponding tridimensional power spectrum of solar oscillations renders an average horizontal velocity vector for the area at different depths (Corbard et al. 2003). By analyzing a mosaic of these patches, it is possible to infer a three-dimensional velocity map in the depth range where the waves propagate. Typical ring-diagram analysis uses 1664 minute series of data with a resolution of about 1.5 Mm pixel−1.
Figure 1. Yearly averages of the meridional flow obtained by ring-diagram analysis of continuous GONG data at four different depths. The variation with the solar cycle clearly observed at the superficial layers is less pronounced at deeper layers. The extra circulation (bumps) is also clearly visible in the shallow layers.

at the center of the disk. We obtain horizontal velocity maps from disk center to approximately 52°5 in each direction with patches centered every 7°5 (Haber et al. 2002). To study the meridional circulation, we isolate the \( v_y \) component of the calculated flows and use patches centered at no more than 22°5 heliocentric longitude to minimize projection effects.

Figure 1 presents the yearly averaged meridional flows calculated for the period of 2001 August–2009 April. The results show the well-known variation of the overall amplitude of the meridional circulation with the solar cycle: smaller amplitudes in 2001–2002 (maximum activity) and larger amplitudes in 2008–2009 (minimum activity). The variation with the solar cycle is less pronounced at deeper depths, but it is still visible at high latitudes. Gizon & Rempel (2008) present a model to account for independent observations of the meridional flow at the surface and at a depth of 60 Mm. In such a model, the meridional flow at these two depths is anticorrelated. Although our analysis only returns information on the upper 15 Mm, the depth dependence of the results is such that it would be consistent with their findings, with a reversal in the time varying component at depths below our accessible range.

Differences between the northern and the southern hemisphere can be seen in the top panel. It is important to note that local helioseismology inferred flows at high latitudes have been shown to be affected by the periodic variation of the solar \( B_0 \)-angle (González Hernández et al. 2006; Zaatri et al. 2006; Beckers 2007). Although we do not yet have a full understanding of the effect, it is suspected to be related to the foreshortening in the data associated with the variation in the solar \( B_0 \)-angle (the inclination of the solar rotation axis toward Earth). This periodic variation is clearly visible in the top panel of Figure 2. This systematic effect definitely affects our results; however, it should be consistent throughout the solar cycle and hence it cannot be responsible for the observed amplitude variation. An asymmetry between the northern and the southern hemispheres is present in the results, in particular, the fact that at the shallow layers the flows deviate from zero at the equator. The neutral line seems to be displaced toward the south during this period, which coincides with a more active period of the southern hemisphere (see Figure 3).

The bottom panel of Figure 2 shows a symmetrical plot of the flows, by averaging both the northern and the southern hemispheres. This reduces the systematic effect of the \( B_0 \)-angle, without correcting it. The amplitude variation of the meridional flow, anticorrelated with the solar cycle, is more clearly visible here.
Figure 2. Temporal variation of the fitted polynomial to the meridional circulation observations at a depth of 5.8 Mm. A symmetrical plot averaging both hemispheres is shown in the bottom panel. Positive velocities are taken toward each respective pole.

The extra circulation, in the form of bumps, superimposed on the smooth pattern of the meridional circulation, can also be seen in Figure 1 to a depth of \( \sim 11 \) Mm. For the earlier years, the bumps are centered in latitudes close to \( \sim 30^\circ \), toward the end of 2006, they have almost disappeared, only to appear again at \( > 40^\circ \) at the beginning of 2007.

3. A MERIDIONAL COMPONENT OF THE TORSIONAL OSCILLATION?

The residuals from a low-order polynomial fitting to the inferred meridional circulation at a depth of 5.8 Mm are shown in Figure 3. The top panel is a proxy to the corresponding surface activity, calculated using a longitudinal average of MDI synoptic magnetograms over the studied period. The central panel presents the residuals averaged over 60 days, using a bilinear interpolation (IDL, REBIN function) for imaging the results. The bottom panel shows a symmetric version, averaging both the northern and southern hemispheres. Positive velocities in both cases are taken toward the poles. The variation of this extra component of the meridional flows with the solar cycle resembles, to some extent, the behavior of the so-called solar torsional oscillation of the zonal flows during this extended solar minimum (Howe et al. 2009). It appears at medium latitudes (\( \sim 40^\circ - 50^\circ \)) around 2007 and seems to be moving toward lower latitudes with time. Is this a meridional component of the torsional oscillation?

The appearance of the bumps at high latitudes before the magnetic activity surfaces happens at a similar time as the onset of the torsional oscillation, with the center between faster and slower bands in 2007 located around 40° latitude. However, the amplitude of these residuals seems consistently smaller than those from the torsional oscillation, although marginally. Also, unlike the torsional oscillation, the extra component of the meridional circulation does not seem to converge toward the equator at the end of the solar cycle. The bumps are also less clear below a certain depth and seem to disappear in the range attained with our analysis, although this may be an artifact of the smoothing in the inversion technique. The results from global helioseismology analysis show that the torsional oscillation of the zonal flows remains present throughout the convection zone (Vorontsov et al. 2002; Howe et al. 2005); ring-diagram analysis shows little variation of the zonal flow amplitude in the outer 15 Mm. The center of mass of the perturbance seems to be stable above 20° latitude. Even with our limited spatial resolution, if the bumps were located directly under the surface activity, the northern and southern residual branches would be much closer to the equator toward the end of the cycle.

Figure 4 represents an illustration of the meridional flow (top panel, left) with superimposed bumps, which are inwards flows toward the center of activity (top panel, right). We move the bumps with time following the latitude location of surface activity, keeping the amplitude of bumps constant, and then subsample the results with the same resolution that we obtain from the ring-diagram analysis. To image the results, we use the same bilinear interpolation function (IDL, REBIN). The central panel shows what happens when the activity is only present at the surface. It can be seen that the residuals continue their convergence toward the equator after 2006, when they disappear from the real observations. To check if this was an effect of the new components at high latitudes, we repeat the experiment now including extra bumps centered at 50° in 2006 and moving slowly toward the equator. Neither of these two simple experiments agree with the observations. In the real data, the lower latitude bumps are suppressed from 2006 to 2008, when surface activity is still present. However, a simple
relation is not expected because, as found in previous work (Gizon 2003; González Hernández et al. 2008), removing the areas with surface activity changes the meridional circulation. Hence, there is also an expected contribution to the flows from active regions. Also, the coupling between zonal and meridional flows through the Coriolis force is latitude dependent.

Local helioseismology inferences of meridional circulation during the previous minimum do not show clear evidence of this medium-latitude formation of extra circulation before the activity appears at the surface (Chou & Dai 2001; Beck et al. 2002). Unfortunately, the availability of high-resolution helioseismic data for local helioseismology methods dates back only to 1994, with the TON instrument, and to 1996 with MDI. This, combined with the short span between the end of solar cycle 22 and the beginning of solar cycle 23 and the long-term averages needed to infer meridional circulation, makes the isolation of the medium latitude branch difficult for that period. Thanks to this extended solar minimum we have been able to clearly observe the phenomenon before the onset of the new cycle.

4. DISCUSSION AND CONCLUSIONS

Our results confirm the solar cycle variation of the overall amplitude of the meridional circulation, minimum amplitude at maximum activity, and vice versa. The trend is clearly there
during the decline of solar cycle 23 and has continued during the current prolonged solar minimum. No clear sign of trend reversal is found in the studied period.

We also present, for the first time, a conclusive proof that the extra component of the residual circulation is necessary to understand the dynamic implication of this cycle varying component. A full, comprehensive model that includes both the zonal and the meridional components of the residual circulation is necessary to understand the dynamic implication of this cycle varying component.

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