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EFFECTS OF SOLAR ACTIVE REGIONS ON MERIDIONAL FLOWS

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ABSTRACT

The aim of this Letter is to extend our previous study of the solar-cycle variations of meridional flows and to investigate their latitudinal and longitudinal structure in the subphotospheric layer, especially their variations in magnetic regions. Helioseismology observations indicate that mass flows around active regions are dominated by inflows into those regions. On average, those local flows are more important around the leading magnetic polarities of active regions than around the following polarities and depend on the evolutionary stage of particular active regions. We present a statistical study based on MDI/*SOHO* observations of 1996–2002 and show that this effect explains a significant part of the cyclic change of meridional flows in near-equatorial regions, but not at higher latitudes. A different mechanism driving solar-cycle variations of the meridional flow probably operates.

Subject headings: Sun: activity — Sun: atmospheric motions — Sun: magnetic fields

1. INTRODUCTION

Meridional flows are one of the integral properties of solar convective envelope dynamics. They are essential for the magnetic flux transport from the activity belt toward the solar poles and therefore play a significant role in the polar field reversals (e.g., Wang et al. 1989). The average meridional flow profile (MFP) derived by local helioseismology is often used as an observational input in models describing the solar dynamo and magnetic flux transportation (e.g., Dikpati & Gilman 2006). As we pointed out in our previous study (Švanda et al. 2007), it seemed that the flows around large active regions affect the mean MFP obtained as a longitudinal average of the north-south component of the flow velocity map. In this Letter we investigate this effect in more detail and show that it may explain most of the observed variations of the meridional flow speed in low-latitude regions, but not at high latitudes.

2. DATA AND ANALYSIS

Local helioseismology methods provide unique information about the subsurface dynamics of the Sun (e.g., Haber et al. 2004). In particular, time-distance helioseismology (Duvall et al. 1993) is a tool that allows us to use inversions of solar oscillation observations to infer the structure and topology of subsurface flows (Kosovichev 1996). Solar acoustic waves (*p*-modes) are believed to be excited in the upper convection zone. They travel between various points on the surface through the interior and are perturbed by mass flows along the path of propagation. The mass flow velocities in the interior are inferred from the differences of travel times from the central point to the surrounding annuli and the travel times from the surrounding annuli to the central point.

The travel-time inversions are applied to full-resolution full-disk 1 minute cadence data observed by Michelson Doppler Imager (MDI; Scherrer et al. 1995) on board the *Solar and Heliospheric Observatory* (*SOHO*). These data are available for only approximately 2 months a year uninterruptedly. From those data seven nonconsecutive synoptic flow maps covering seven solar rotations during the period of 1996–2002 were constructed (Zhao & Kosovichev 2004). The data from the declining phase of the solar cycle were not used because they contain some probably instrumental issues, and we decided not to use them for this particular study. For study of the relationship between the flows and magnetic fields, synoptic maps of the line-of-sight component of the magnetic field were constructed using the same algorithm based on MDI magnetograms.

In seven processed Carrington rotations we selected 92 magnetic active regions to investigate the influence of the flows in and around them on the total longitudinally averaged meridional flows by applying masks to isolated local flow patterns. For a proper masking, we need to determine the area of influence of the active regions. We started with a rectangular box around each selected region, in which the magnitude of the line-of-sight component of the magnetic field is above 25 G. In this box we calculated a characteristic perturbation δv, defined as the mean of the absolute differences of meridional speed with respect to the MFP calculated separately for each Carrington rotation, when the box around a particular active region was masked. Then we expanded the box around this region while calculating the deviations δv in this box. The expanded box, where δv reaches its first maximum, we considered as an area of influence of a particular active region. Other maxima are attributed to the presence of other magnetic regions, which appeared in the expanded box. The regions of influence around each magnetic area were masked in the synoptic map. The size of the region of influence was on average twice as large as the initial 25 G box.

3. RESULTS

3.1. *Variations Caused by Active Regions*

The new analysis confirmed the results of our previous study (Švanda et al. 2007). The local flows around strong active regions affect the mean meridional flow obtained as a longitudinal average of the north-south component of the synoptic flow map. On average, the large-scale inflow pattern in the activity belt prevails, which is in agreement with findings by

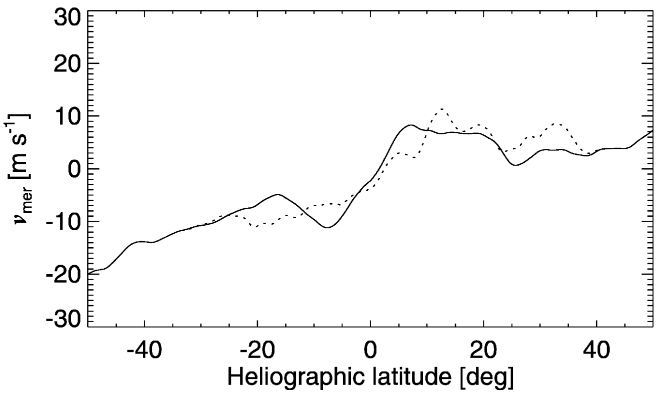

FIG. 1.—The longitudinally averaged meridional component of the time-distance helioseismology flow map at 3–4.5 Mm depth (*solid line*) and the same quantity when active regions are masked (*dotted line*) for CR 1975 (2001 April). Error bars are ∼2 m s^{-1}.

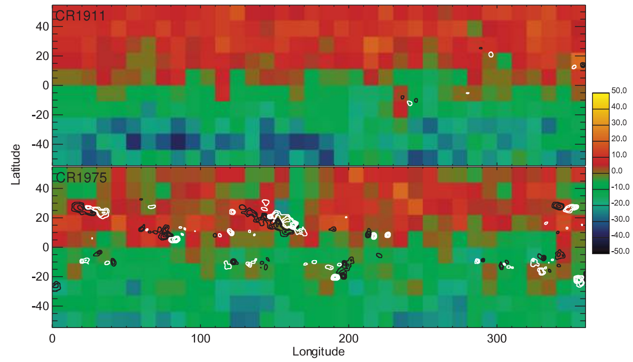

FIG. 3.—Examples of synoptic maps of the meridional (north-south) component at the depth of 3–4.5 Mm smoothed and binned by 10 heliospheric degrees. The positive meridional speed is northward. The magnetic active regions are displayed with contours: white contours show the positive polarity, and black ones show the negative polarity. These maps demonstrate a longitudinal structure of meridional flows close to minimum (CR 1911) and maximum (CR 1975) of solar activity. The errors of individual flow velocity measurements are ∼2 m s^{-1} (Zhao & Kosovichev 2004).

Basu & Antia (2003), Zhao & Kosovichev (2004), Haber et al. (2004), and Komm et al. (2006). For example, in Figure 1 one can clearly see that the MFP calculated excluding active regions (henceforth called as the reference meridional flow profile, or RMFP) varies less with latitude than when the flows associated with active regions are included. The deviations between the profiles with and without the active region flows are up to 5 m s^{-1}. On average, the positive deviations in the areas of influence prevail in the northern hemisphere (by 0.08 m s^{-1}), while the negative ones prevail in the southern hemisphere (by 0.10 m s^{-1}). This may be interpreted to mean that the inflows into active regions are stronger on their equatorial side than on their poleward one, in both hemispheres. Such small differences are not statistically significant; thus, to confirm this, a detailed study is needed. An analytical model of torsional oscillations by Spruit (2003) predicted such inflows into the activity belt with a characteristic amplitude of 6 m s^{-1}. Similar values were predicted also by the numerical model by Rempel (2006). Both models assumed a mechanism of thermal forcing for the low-latitude torsional oscillation branches. The inflow in the activity belt was a side effect of these models, but it resembles the observed inflow in active regions.

We investigated a possible dependence of the characteristic perturbation of the flows at different depths in individual active regions on the amount of magnetic flux present in their areas. As a measure of the characteristic perturbation δv_{mer}, we used a mean of the absolute differences between the measured meridional component of the flow field and the RMFP at a given latitude calculated over the region of interest.

The dependence of δv_{mer} on the total unsigned flux for all 92 active regions is shown in Figure 2. Other characteristics, such as a geometrical average of deviations over the whole active region, display a similar dependence. The perturbations become less significant with the increase of depth in the convection zone. Figure 2 indicates that the active regions containing more magnetic flux cause more significant deviations from the RMFP than those containing less flux.

Examples of synoptic maps of the meridional flow component for Carrington rotations CR 1911 (1996 July) and CR 1975 (2001 April) are shown in Figure 3. These maps contain a wide range of local motions of various scales, but their structure is far from the idealized single-cell picture. In the map of CR 1975 one can see very large and complex active regions with converging flows (inflows) prevailing in the leading parts of the active regions, while the trailing parts do not seem to differ in the topology of flows from the quiet-Sun regime. This effect was already suggested by Kosovichev & Duvall (2006). In those examples we see that converging flows extend from

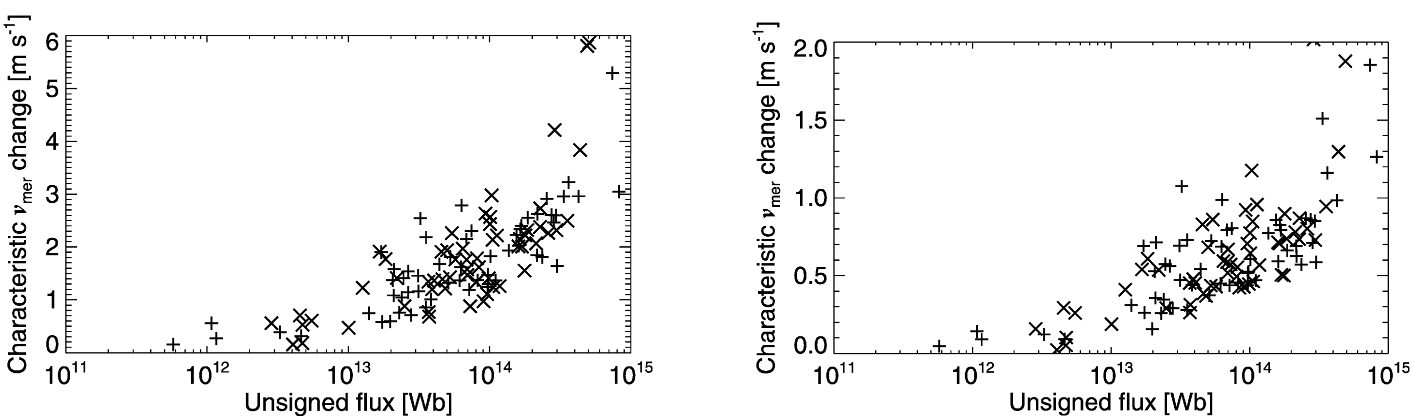

FIG. 2.—A dependence of the characteristic variations of the meridional flow on the total unsigned flux localized in active regions for the flows at depths of 0–3 Mm (*left*) and 3–4.5 Mm (*right*). The dependence in both depth intervals is very similar, but the magnitude of deviations is smaller at greater depth. The plus signs are for areas in the northern hemisphere, crosses are for the southern hemisphere ones.

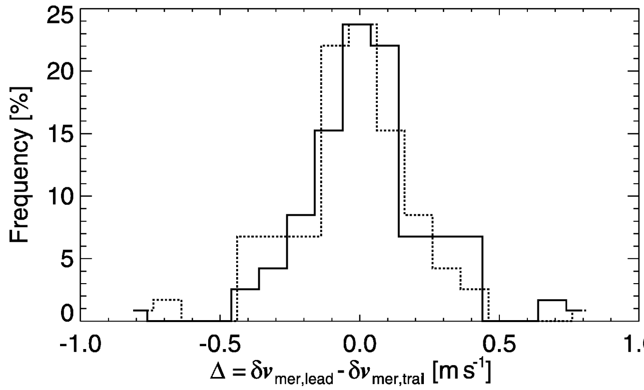

FIG. 4.—Histogram of the characteristic deviations of meridional components from the RMFP, showing the difference between the leading and trailing polarities of active regions in our sample. The histogram reflected around $\Delta = 0$ is shown as a dotted line to enhance the visibility of the asymmetry.

the active region far in the poleward direction and form a surge-shaped structure.

3.2. *Asymmetry between the Flows around Leading and Following Polarities of Active Regions*

The question is whether this asymmetry between the flow around the leading and following polarities is common for all active regions. To study this issue we divide the box around each active region in two parts, separating the regions of the leading and following polarities. As a measure of the flow deviations in leading and trailing polarities we use the difference Δ between $\delta v_{\rm mer}$ in both polarities of each active region, i.e.,

$$\Delta = \delta v_{\rm mer}(\text{leading}) - \delta v_{\rm mer}(\text{trailing}). \qquad (1)$$

We do not find a clear correlation of Δ with any characteristic of magnetic field of the active regions. However, a histogram of Δ (Fig. 4) shows that the leading and following polarities differ quite often as the positive part contains more cases than the negative one.

The distribution of Δ seems to be bimodal. The second peak (around 0.4 m s^{-1}) suggests the existence of a group of active regions, where inflows in their leading polarities are significantly stronger than in their trailing ones. Some examples of active regions, for which the flows have the behavior described above, can be seen in Figure 3. There is no typical characteristic or feature among the active regions responsible for the second peak in the distribution of Δ in our sample, except for the tilt angle, calculated from positions of the centers of mass of both polarities. The tilt angle is on average larger (38° vs. 19°) for the active regions that form the second peak in the distribution of Δ. However, those numbers are not convincing due to the small sample. Perhaps this effect can be related to the age of active regions. As pointed out, e.g., by Howard (1994) the tilt angle of bipolar sunspot groups on average may increase during their evolution.

Our visual inspection shows that most of 11 active regions making the second peak of the histogram have a trailing polarity dispersed probably by diffusion, while the leading one seems to be more compact. A quick look on NASA's SolarMonitor[1] and the Mount Wilson drawings archive showed that these

[1] See the SolarMonitor at NASA Goddard Space Flight Center's Solar Data Analysis Center (http://www.solarmonitor.org).

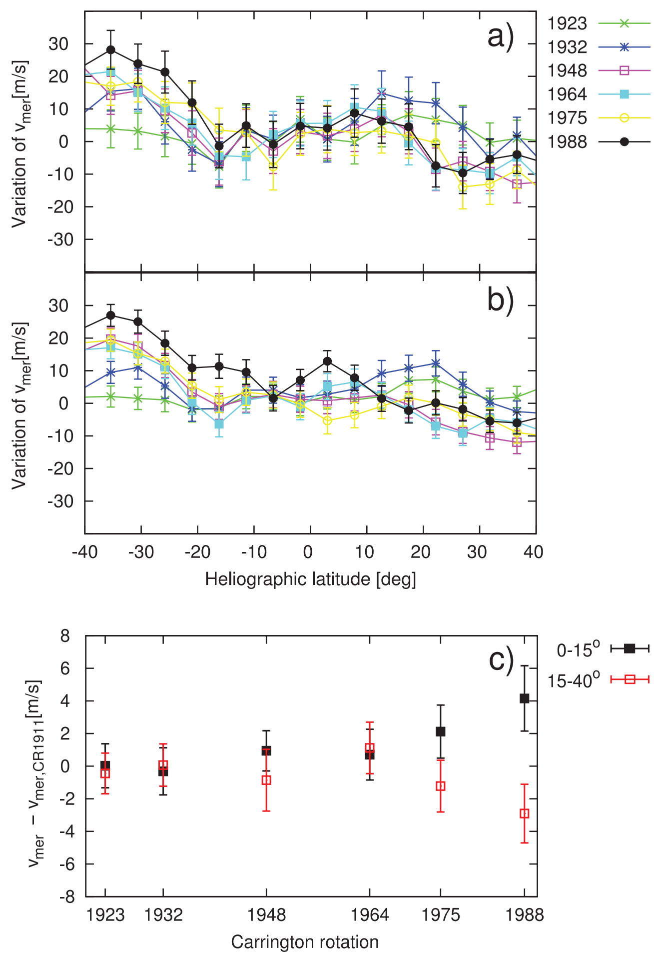

FIG. 5.—(*a*) Solar-cycle variations of the MFP averaged over depths of 0–9 Mm after the subtraction of the MFP in CR 1911. (*b*) Same as (*a*), but with active regions masked in the maps. (*c*) The difference of (*a*) and (*b*) averaged over two latitudinal belts to demonstrate the effect of the active regions on the longitudinally averaged MFP at various phases of the magnetic activity (the negative values represent equatorward flow).

active regions are old and highly evolved with complex topology. A detailed investigation of this effect requires a larger data set of helioseismic and magnetic observations of active regions.

3.3. *Latitudinal Variations of the Meridional Flows*

In Figure 5, the evolution of the RMFP averaged over depths of 0–9 Mm with solar cycle is given, from which the profile in minimum of solar activity (CR 1911) was subtracted. We basically see that the meridional flow slows down at higher latitudes with the increasing magnetic activity and that variations are larger when the magnetic regions are included in the synoptic flow maps. The differences between corresponding curves in Figures 5*a* and 5*b* are statistically significant. In Figure 5*c* the variations caused by the magnetic regions averaged over two latitudinal belts in both hemispheres are given. The opposite sign of the meridional flow in both hemispheres was taken into account. We see that the deviations from the RMFP caused by the active regions increase with activity cycle, which is consistent with the results described in previous sections.

A large amount of cycle-related variation can be explained by flows around the active regions in the near-equatorial belt.

If we quantify this effect by calculating the value $\vartheta = (v_{\rm mer} - v_{\rm mer,ref})/(v_{\rm mer} - v_{\rm mer,CR1911})$, where $v_{\rm mer}$ is the MFP including flows around the active regions, $v_{\rm mer,ref}$ is the one with active regions masked, and $v_{\rm mer,CR1911}$ is the MFP in minimum of solar activity, we may estimate the importance of the flows around the active regions on the cycle-related variations of the MFP. For the equatorial region (latitudes of 0°–15°) we find $\vartheta = (0.65 \pm 0.21)$ in the southern hemisphere and $\vartheta = (0.34 \pm 0.26)$ in the northern hemisphere, and for higher latitudes (15°–40°) we find $\vartheta = (0.20 \pm 0.15)$ for the southern hemisphere and $\vartheta = (0.37 \pm 0.29)$ for the northern hemisphere. The north-south asymmetry is statistically significant; the effect is stronger in the southern hemisphere, where the surface magnetic activity is also stronger than in the northern hemisphere. On average, the effect of the flows around the active regions is not sufficient to explain cycle-related changes of the MFP, especially at higher latitudes, where the remaining cycle-related variations may be explained by the formation of persistent high-latitude countercells providing the mass inflow on the poleward side of the activity belt. The peak speed in such a countercell could be estimated by $\sim$10 m s^{-1} in the northern hemisphere and $\sim$25 m s^{-1} in the southern hemisphere. Perhaps this may be due to the existence of a deep magnetic field, which could also depict north-south asymmetry. We think that these results represent an interesting challenge for theories and numerical simulations of the solar meridional circulation.

3.4. *Longitudinal Variations of the RMFP*

The question of whether or not the MFP without active regions is the same at different longitudes naturally arises. Unfortunately, we cannot provide a clear answer based on the available data. As we can see in Figure 3, the synoptic maps of the large-scale north-south flow components show many variations, which are not persistent for the whole synoptic map. These local disturbances of the meridional component of the flow have greater magnitude than the mean flow. The magnitude of the disturbances is decreasing with depth. One needs to keep in mind that, in general, it is impossible to distinguish between the temporal evolution of the meridional flow and its longitudinal structure in a synoptic map, which is composed of daily strips around the central meridian. However, the assumption that the persistent component of the meridional flow evolves slowly with a characteristic time of several days seems reasonable, which justifies our approach. It was described in numerical simulations (e.g., Miesch et al. 2008) that the meridional flow has a strong fluctuating component, the magnitude of which is larger than the magnitude of the mean temporally averaged meridional flow. Some fluctuations surviving for many hours are also detected in our data, and the mean poleward meridional flow appears only after averaging. Perhaps similar fluctuations happen in the real Sun as well.

4. CONCLUSIONS

From our study it becomes clear that the large-scale mass flows around active regions significantly influence the mean meridional flow. This is an important conclusion for the dynamo and solar-cycle models, which use the longitudinally averaged meridional flow from local helioseismology as a measure of the mean meridional flow. Profiles calculated simply by taking a longitudinal average do not represent the mean meridional circulation in and between activity belts. For a particular active region, the deviations caused by the circulation flows around them depend on the total magnetic flux in the area. On average, the local circulation flows are represented by inflows in the activity belt, as predicted by Spruit (2003) and observed by, e.g., Basu & Antia (2003) or Zhao & Kosovichev (2004).

Moreover, it seems that, on average, the local flows are more important in the areas of leading magnetic polarities of active regions. There is a group of active regions in our sample for which local flows are significantly more important in the leading polarities. This effect may be related to the evolution of active regions and requires a detailed study based on an extended data set describing the three-dimensional structure of flows in and around active regions in various stages of their evolution. Those deviations explain a significant part of the cyclic change of the meridional profile shape in the equatorial region, but not at higher latitudes. A different mechanism must operate to explain all cyclic variations. Using the currently available data set we find evidence that the latitudinal variations of the meridional flow at high latitudes may be related to subsurface magnetic activity, but at the present state this is inconclusive. Another interesting problem is how the asymmetry in the strength of the local inflows around leading and following polarities of active regions affects the magnetic flux transport to the polar regions and the Sun's polarity reversals. As we pointed out in Švanda et al. (2007) this phenomenon is not important for the meridional flux transport averaged over a few Carrington rotations. We expect that in detail this conclusion may be changed. This problem can be studied when more local helioseismology data will become available from the *Solar Dynamics Observatory*.

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