Changes of the solar meridional velocity profile during cycle 23 explained by flows toward the activity belts

R. H. Cameron and M. Schüssler

Max-Planck-Institut für Sonnensystemforschung, 37191 Katlenburg-Lindau, Germany; cameron@mps.mpg.de

Received 2010 June 11; accepted 2010 July 15; published 2010 August 16

Abstract

The solar meridional flow is an important ingredient in Babcock–Leighton type models of the solar dynamo. Global variations of this flow have been suggested to explain the variations in the amplitudes and lengths of the activity cycles. Recently, cycle-related variations in the amplitude of the $P_2^1$ term in the Legendre decomposition of the observed meridional flow have been reported. The result is often interpreted in terms of an overall variation in the flow amplitude during the activity cycle. Using a semi-empirical model based upon the observed distribution of magnetic flux on the solar surface, we show that the reported variations of the $P_2^1$ term can be explained by the observed localized inflows into the active region belts. No variation of the overall meridional flow amplitude is required.

Key words: Sun: photosphere – Sun: surface magnetism

Online-only material: color figures

1. Introduction

The solar meridional flow is a large-scale plasma motion which transports material from the equator toward the poles near the surface. Temporal variations of this flow have been reported in terms of a reduced flow velocity during solar maxima (e.g., Komm et al. 1993; Chou & Dai 2001; Basu & Antia 2003) as local inflows toward the activity belts (Haber et al. 2002; Zhao & Kosovichev 2004; Gizon 2004; Gizon & Rempel 2008; Švanda et al. 2008; González Hernández et al. 2010). Recently, Hathaway & Rightmire (2010) studied the time dependence of the meridional flow by considering magnetic features in SOHO/MDI magnetograms since 1996 as tracers of the flow field near the solar surface. The large-scale motion of the magnetic elements is a combination of the real large-scale bulk plasma motions advecting the magnetic features and a diffusion-type motion caused by the action of the random granular and supergranular flows on large-scale gradients in the distribution of the number density of magnetic field elements (see Wang et al. 2009). Rather than disentangling the two effects, Hathaway & Rightmire (2010) considered the magnetic field elements to be simple tracers of the large-scale flow field near the solar surface.

The projection of the resulting flow profiles on the Legendre polynomial $P_2^1$ revealed a significant time variation of the corresponding coefficient, with lower values during the activity maximum of cycle 23 and higher values during the preceding and following activity minima. Basu & Antia (2010) used SOHO/MDI velocity maps for the same period and studied the evolution of the meridional flow by helioseismic methods, thereby also obtaining information about its variation with depth. The decomposition of the near-surface flows in Legendre polynomials yielded a variation of the $P_2^1$ coefficient in qualitative agreement with the result of Hathaway & Rightmire (2010). However, Basu & Antia (2010) also found that the variation of the meridional flow is connected with a flow pattern that migrates equatorward in parallel with the activity belts as outlined by the butterfly diagram of sunspots. This flow pattern probably reflects the latitudinal inflows toward the activity belts (e.g., Gizon & Rempel 2008; Švanda et al. 2008; González Hernández et al. 2010). This raises the question whether the variation of the $P_2^1$ coefficient could (partly or fully) be understood as the superposition of the local inflows onto an undisturbed large-scale meridional circulation.

The distinction between a general reduction of the flow speed (which should then also affect the return flow in the deep convection zone) and a superposed activity-dependent local flow near the surface is important both in terms of its effects and in terms of its cause(s). Overall meridional flow variations could possibly play a role in modulating the amplitude and length of the activity cycles. In particular, the cycle period of an advection-dominated Babcock–Leighton type dynamo is sensitive to the strength of the meridional flow (Dikpati & Charbonneau 1999), because the flow essentially acts like a “conveyor belt” in transporting the field (Dikpati & Gilman 2006). A localized near-surface inflow, on the other hand, does not influence the overall speed of the conveyor belt and thus the cycle period. A localized inflow does, however, affect the amplitude of the solar polar field and the axial dipole moment (Jiang et al. 2010), which should then affect the return flow in the deep convective zone. A localized near-surface inflow, on the other hand, does not influence the overall speed of the conveyor belt and thus the cycle period. A localized inflow does, however, affect the amplitude of the polar field and the axial dipole moment (Jiang et al. 2010), with possible attendant effects on the amplitude of the following activity cycle. In terms of the cause of the time variations, theoretical models have been suggested to explain either type of time dependence of the meridional flow (for a recent review, see Brun & Rempel 2009).

The purpose of this paper is to consider whether the variations of the $P_2^1$ coefficient reported by Hathaway & Rightmire (2010) and Basu & Antia (2010) provide conclusive evidence for a solar-cycle modulation of the overall meridional flow. We find that a semi-empirical model of the local near-surface inflows toward the activity belts results in a time-dependent $P_2^1$ signal in the Legendre decomposition that largely explains the observational results, without requiring a change in the overall meridional flow amplitude.

2. Modeling the inflow into the active region belts of cycle 23

We consider a model of the latitudinal inflows that connects their activity-related variation with the measured magnetic field at the solar surface during cycle 23. To this end, we assume that the spatial and temporal variations of the inflows are directly related to the surface magnetic field distribution. This is consistent with the theoretical model of flows toward active regions being driven by the cooling associated with the
The excess brightness of magnetic features in plage and enhanced network regions (Spruit 2003; Gizon & Rempel 2008). The strength of the inflow toward each magnetic feature is taken to be proportional to the local unsigned vertical magnetic field, $|B|$. The flow at any point is the superposition of the effect of all magnetic features. The individual inflows are radially symmetric, so that the strength of the resulting superposed large-scale flow is proportional to the horizontal gradient of $|B|$. Since we are only interested in the axisymmetric component of the meridional flow perturbation, we take the speed of the latitudinal inflow, $v(\lambda, t)$, to be proportional to the latitudinal derivative of the longitudinally averaged magnetic field, $\langle|B|\rangle_\phi(\lambda, t)$; the net meridional flow perturbation at any location reflects the difference between the effects of the inflows driven by the magnetic features lying to the north as against those lying to the south. The resulting expression reads

$$v(\lambda, t) = c_0 \left\{ d \langle|B|\rangle_\phi(\lambda, t) / d\lambda \right\}. \quad (1)$$

The constant of proportionality, $c_0$, is calibrated through matching the resulting flow amplitudes with those of the observed inflows toward the activity belts. The azimuthal average of the radial (vertical) field, determined from SOHO/MDI synoptic maps1 is shown in Figure 1. The data have been remapped from a grid equally spaced in sine latitude to one which is equally spaced in latitude (with a spacing of 0.165).

We removed small-scale fluctuations from the latitudinal derivatives by smoothing with a Gaussian filter with a half-width at half-maximum of 20°, indicated by the curly brackets in Equation (1). The time-latitude diagram of the resulting meridional flow perturbation is shown in Figure 2. The flow poleward of ±60° was set to zero to avoid the problems near the poles evident in Figure 1, which result from the poor determination of the magnetic field near the poles and the effect of the varying solar $B$ angle.

The constant of proportionality in Equation (1) was calibrated as $c_0 = 9.2$ m s$^{-1}$ G$^{-1}$ deg by requiring that the amplitude of the inflow should be comparable to that reported by Gizon et al. (2010). The results given there have, by construction, zero cycle-averaged flow at all latitudes. For the comparison, we therefore first subtracted from our model flow the time average as a function of latitude. We also took a five-year running temporal mean since the observationally inferred flows are smooth on timescales of years (again by construction). These two effects reduce the amplitude of the flow perturbation to values between $-5.4$ m s$^{-1}$ and $+4$ m s$^{-1}$, comparable to those reported by Gizon et al. (2010).

The modeled bulk inflow is into regions of higher unsigned flux densities, and hence it drives the magnetic flux elements in the direction of the gradient of the unsigned magnetic flux. The sense of the flow is thus opposite to that of the diffusive transport (via a random walk) of flux elements away from regions where the number density of such elements is high. The nature of the model inflow and diffusive transport implies the need to properly disentangle the two when using magnetic elements as tracers of the flow as was pointed out by Wang et al. (2009).

3. ANALYSIS

To compare the model with the results of Hathaway & Rightmire (2010) and Basu & Antia (2010), we decompose the modeled flow in Legendre polynomials. There are two main effects which cause the inflows toward the activity belts to contribute to the $P_2^1$ coefficient. The first is that the calculation of the coefficient more heavily weights the flow in the range 20° to 50° than near the equator. As illustrated in Figure 3,

---

1 From http://soi.stanford.edu/magnetic/index6.html.
the weighting thus favors the latitude range where the inflow corresponds to a motion toward the equator. As a consequence, the $P_2^1$ coefficient is reduced with respect to the value for the undisturbed meridional flow. The second effect is due to the fact that the inflows extend over latitudinal scales of $\sim 20^\circ$; when the activity belts approach the equator, there is overlapping and partial cancellation of the oppositely directed flow perturbations on both sides of the equator.

The time variation of the coefficient $c_2$ of the $P_2^1$ term in the Legendre decomposition is shown in Figure 4, along with the corresponding results of Hathaway & Rightmire (2010) and Basu & Antia (2010). In all cases, we subtracted the (different) mean values of the coefficient. It can be seen that the model inflows reproduce the variation of the $P_2^1$ coefficient over the solar cycle 23 as reported by Hathaway & Rightmire (2010), including the amplitude of the variation. Fluctuations on short timescales are not reproduced. The cycle variation found by Basu & Antia (2010) for a depth of 1.4 Mm is qualitatively similar, but the amplitude is about a factor two higher—reproducing this would require that our calibration factor, $c_0$, be correspondingly higher.

The observational results differ with regard to a possible difference of the meridional flow speed during the two activity minima included in the time series. While Hathaway & Rightmire (2010) find a somewhat higher speed during the recent minimum in comparison to the previous one, Basu & Antia (2010) do not detect a significant difference. In our model, the flow perturbation is related to the surface activity, so that we expect an almost undisturbed flow during solar minima and thus no significant differences between the minima.

4. CONCLUSION

The time variation of the $P_2^1$ coefficient in the Legendre polynomial expansion of the meridional flow observed by Hathaway & Rightmire (2010) and Basu & Antia (2010) is qualitatively reproduced by a model describing inflows into the activity belts. The model is based upon the instantaneous latitudinal distribution of the unsigned magnetic flux at the solar surface. Our results explain the fact that the meridional velocity, determined by the coefficient of $P_2^1$ in the Legendre expansion, is smaller during activity maxima—without the need to invoke a change of the overall meridional flow speed.

We have modeled the flow for cycle 23 using the observed magnetic fields, which is consistent with the idea that the inflow is driven by thermal changes due to the enhanced radiative cooling associated with the plage magnetic fields (Spruit 2003). Both our simple model and the underlying theory indicate that the inflows should depend on the strength of the activity cycle, so that the amplitude of the inflows in previous cycles could, in principle, be inferred. As recently shown by Jiang et al. (2010), such inflows affect the Sun’s polar fields, with potential implications for dynamo models.

SOHO is a project of international collaboration between ESA and NASA. We thank Laurent Gizon for informative discussions.

REFERENCES

Basu, S., & Antia, H. M. 2003, ApJ, 585, 553
Basu, S., & Antia, H. M. 2010, ApJ, 717, 488
Brun, A. S., & Rempel, M. 2009, Space Sci. Rev., 144, 151
Chou, D., & Dai, D. 2001, ApJ, 559, L175
Dikpati, M., & Charbonneau, P. 1999, ApJ, 518, 508
Dikpati, M., & Gilman, P. A. 2006, ApJ, 649, 498
Gizon, L. 2004, Sol. Phys., 224, 217
Gizon, L., Birch, A. C., & Spruit, H. C. 2010, arXiv:1001.0930
Gizon, L., & Rempel, M. 2008, Sol. Phys., 251, 241
González Hernández, I., Howe, R., Komm, R., & Hill, F. 2010, ApJ, 713, L16
Haber, D. A., Hindman, B. W., Toomre, J., Bogart, R. S., Larsen, R. M., & Hill, F. 2002, ApJ, 570, 855
Hathaway, D. H., & Rightmire, L. 2010, Science, 327, 1350
Jiang, J., Işık, E., Cameron, R., Schmitt, D., & Schüssler, M. 2010, ApJ, 717, 597
Komm, R. W., Howard, R. F., & Harvey, J. W. 1993, Sol. Phys., 147, 207
Spruit, H. C. 2003, Sol. Phys., 213, 1
Švanda, M., Kosovichev, A. G., & Zhao, J. 2008, ApJ, 680, L161
Wang, Y., Robbrecht, E., & Sheeley, N. R. 2009, ApJ, 707, 1372
Zhao, J., & Kosovichev, A. G. 2004, ApJ, 603, 776