Solar-cycle variation of the meridional flow

Laurent Gizon[1] and Matthias Rempel[2]

(1) Max-Planck-Institut für Sonnensystemforschung, 37191 Katlenburg-Lindau, Germany
(2) High Altitude Observatory, NCAR, Boulder, CO 80307, USA

Abstract

We present independent observations of the solar-cycle variation of flows near the solar surface and at a depth of about 60 Mm, in the latitude range $\pm 45°$. The time-varying components of the meridional flow at these two depths have opposite sign, while the time-varying components of the zonal flow are in phase. We investigate a theoretical model based on a flux-transport dynamo combined with a geostrophic flow caused by increased radiative loss in the active region belt. The model and the data are in qualitative agreement, although the amplitude of the solar-cycle variation of the meridional flow at 60 Mm appears to be underestimated by the model.

1. OBSERVATIONS

Near-surface layers:

We used series of MDI full-disk Doppler images covering the period 1996-2002 and f-mode time-distance helioseismology (Duvall & Gizon, 2000) to obtain every 12 hour a $120° \times 120°$ map of the horizontal divergence of the flow field 1 Mm below the photosphere. The flow $\boldsymbol{v} = (v_x, v_y)$ is obtained by measuring the advection of the supergranulation pattern, where x is prograde and y is northward (Gizon, Duvall & Schou, 2003).

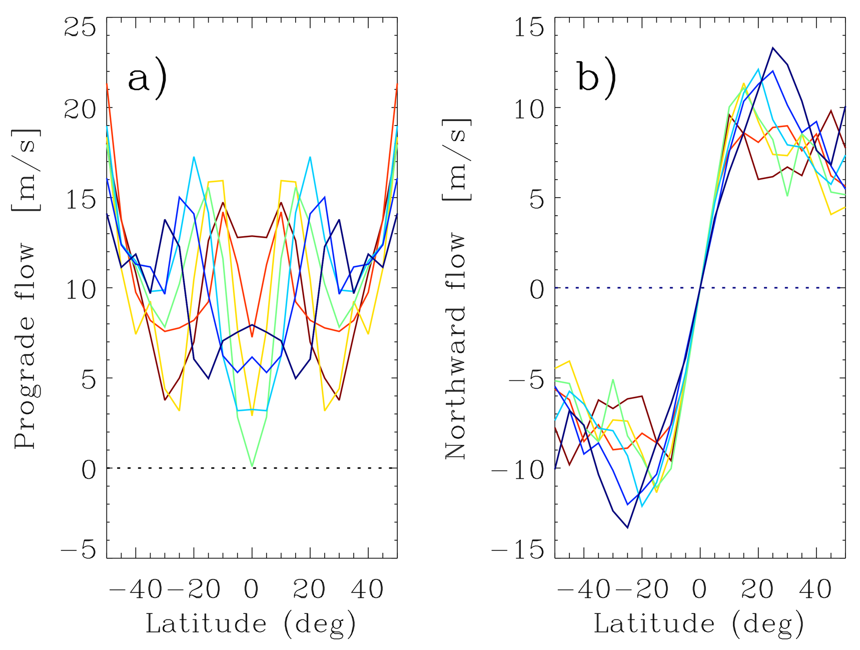

Figure 1: *(a) Rotational velocity, v_x, and (b) meridional flow, v_y, near the solar surface as a function of latitude, λ. Each MDI dynamics run is plotted with a different color from blue in 1996 to red in 2002. The rotational velocity is given with respect to the rotational velocity of the small magnetic features (Komm, Howard & Harvey, 1993).*

Deeper inside the Sun:

In order to probe deeper layers into the solar convection zone, we used acoustic waves and time-distance helioseismology. Travel times were measured by cross-corrrelation of the Doppler oscillation signal recorded during the MDI structure program according to the procedure described by Giles (1999). Using a mean travel distance of $17°$ enables us to probe layers about 60 Mm below the surface. The full details of this analysis can be found in Beck, Gizon & Duvall (2002). In order to convert travel time shifts into flows in units of $\mathrm{m\,s^{-1}}$, we use a simple calibration based on the observation by Howe et al. (2006) (global-mode helioseismology) that the amplitude of the time-varying component of the zonal flow is nearly independent of depth. We choose the near-surface zonal flow measurements of the previous paragraph as a reference.

2. SOLAR-CYCLE VARIATIONS

In order to quantify the solar-cycle dependence of the flows, we extract the eleven-year periodic component from the data. At each latitude λ and for each depth, we fit a function of the form

$$\tilde{v}_i(\lambda, t) = \overline{v}_i(\lambda) + v_i'(\lambda) \cos\left[\frac{2\pi t}{11\,\mathrm{yr}} + \phi_i(\lambda)\right]$$

to the observed velocity $v_i(\lambda, t)$, where the index i refers to either the x or the y component of the flow.

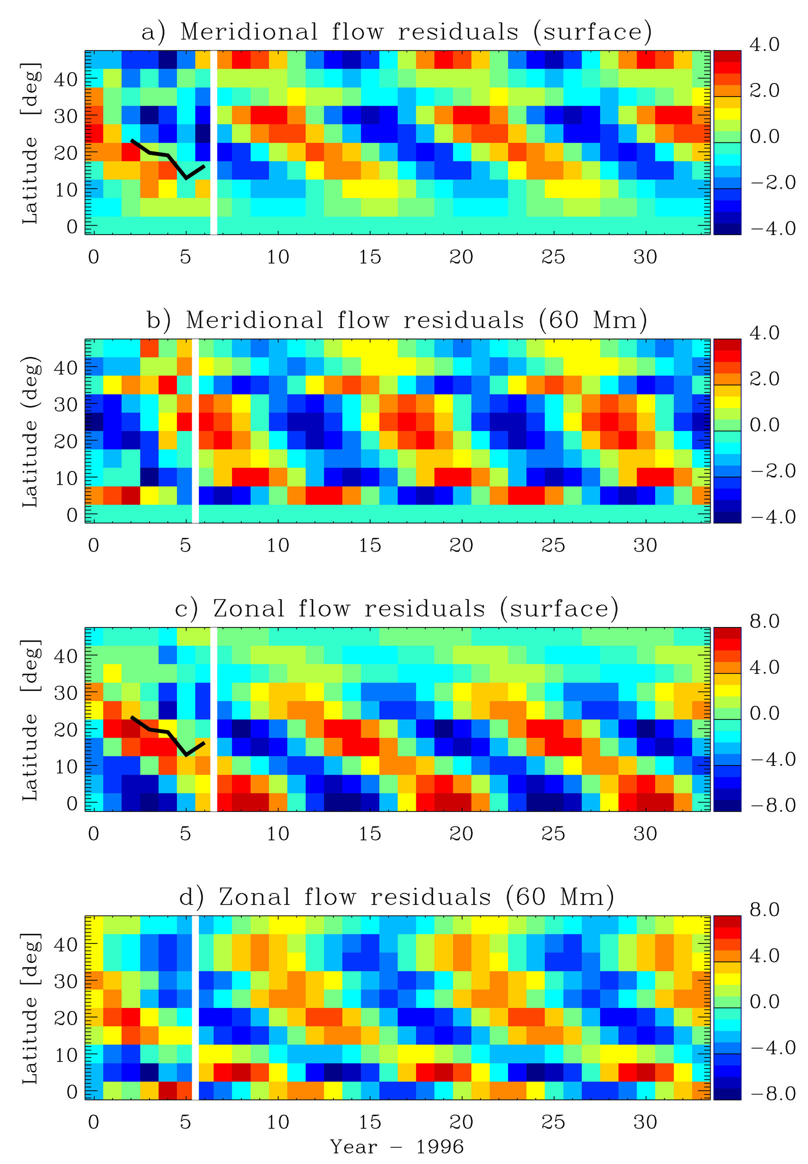

Figure 2: *Eleven-year periodic component of the meridional and zonal flows. The color bar is in units of $\mathrm{m\,s^{-1}}$. A positive value indicates a poleward (resp. prograde) meridional (resp. zonal) residual flow. The observations, $v_i - \overline{v}_i$, cover the first six years, while the purely sinusoidal component, $\tilde{v}_i - \overline{v}_i$, is extrapolated in time (beyond the vertical white line). The black curves indicate the mean latitude of magnetic activity.*

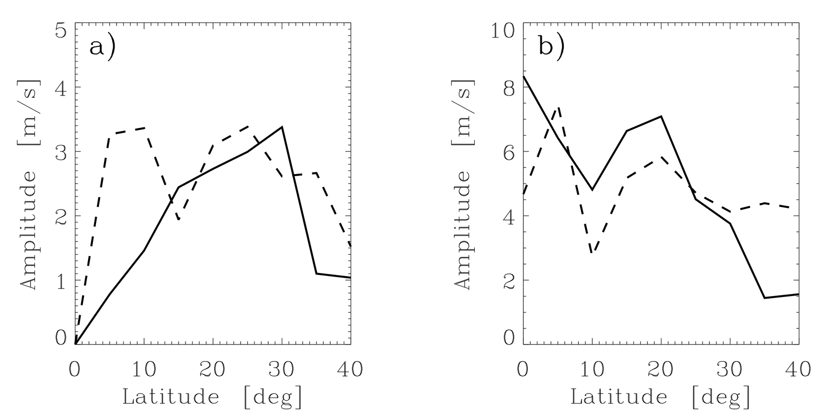

Figure 3: *Amplitude, v_i', of the eleven-year periodic component of the meridional (a) and zonal (b) flows. The near-surface values (solid lines) are absolute measurements. The calibration of the observations at 60 Mm depth (dashed lines) follows the assumption that the amplitude of the zonal torsional oscillation (panel b) is independent of depth over the latitude range $|\lambda| < 45°$.*

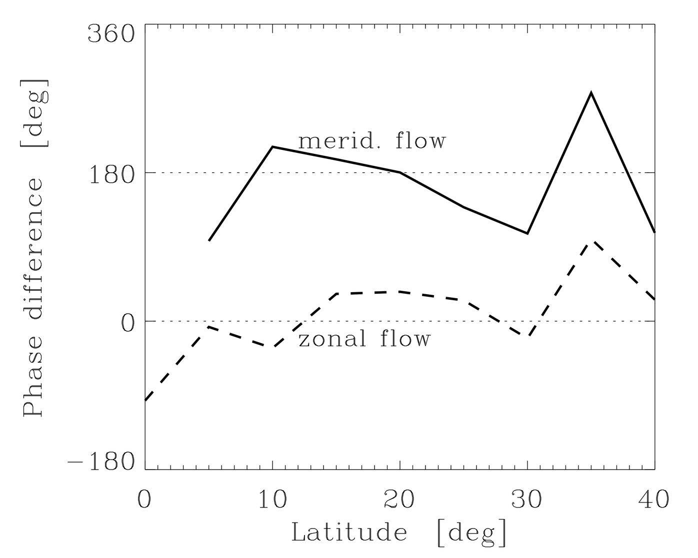

Figure 4: *Phase difference, $\Delta\phi = \phi(\mathrm{deep}) - \phi(\mathrm{surface})$, between the eleven-year periodic components of the flows measured at a depth of 60 Mm and near the surface. The solid line is for the meridional flow and the dashed line is for the zonal flow.*

3. THEORETICAL MODEL

The model results presented here are based on a non-kinematic flux-transport dynamo model developed recently by Rempel. This model combines the differential rotation and meridional flow model of Rempel (2005) with a flux transport dynamo similar to the models of Dikpati & Charbonneau (1999) and Dikpati & Gilman (2001). The differential rotation model utilizes a meanfield Reynolds-stress approach that parametrizes the turbulent angular momentum transport (Λ-effect Kitchatinov & Rüdiger, 1993) leading to the observed equatorial acceleration. A meridional circulation, as required for a flux-transport dynamo, follows self-consistently through the Coriolis force resulting from the differential rotation.

The computed differential rotation and meridional flow are used to advance the magnetic field in the flux-transport dynamo model, while the magnetic field is allowed to feed back through the meanfield Lorentz-force $\langle \boldsymbol{J} \rangle \times \langle \boldsymbol{B} \rangle$.

Parameterizing the idea proposed by Spruit (2003) that the low latitude torsional oscillation is a geostrophic flow caused by increased radiative loss in the active region belt (due to small scale magnetic flux) leads in our model to a surface oscillations pattern in good agreement with observations. In order to force a torsional oscillation with around 1 nHz amplitude a temperature variation of around 0.2 K is required. As a side effect the cooling produces close to the surface (in our model at $r = 0.985\,R_\odot$) an inflow into the active region belt of around $2.3\,\mathrm{m\,s^{-1}}$.

Figure 5 summarizes the results of the model. Figure 5a shows the temperature fluctuation (color shades) caused by increased surface cooling in the active region belt. The contour lines indicate the magnetic butterfly diagram computed from the toroidal field at the base of the convection zone in the model. At the equatorward side of the active region belt (indicated by the butterfly diagram) the rotation rate is increased, which is consistent with the increased poleward meridional flow transporting material toward the axis of rotation. On the poleward side of the active region belt the rotation rate is lower, while the meridional flow perturbation is equatorward. At a depth of around 50 Mm (Fig. 5d) the meridional flow perturbation is almost anti-correlated to the surface flow (active region belt outflow), indicating that the surface cooling drives a flow system that closes in the upper third of the convection zone. The flow amplitude at a depth of 50 Mm is around one order of magnitude lower compared to the surface flow due to the significant increase in density.

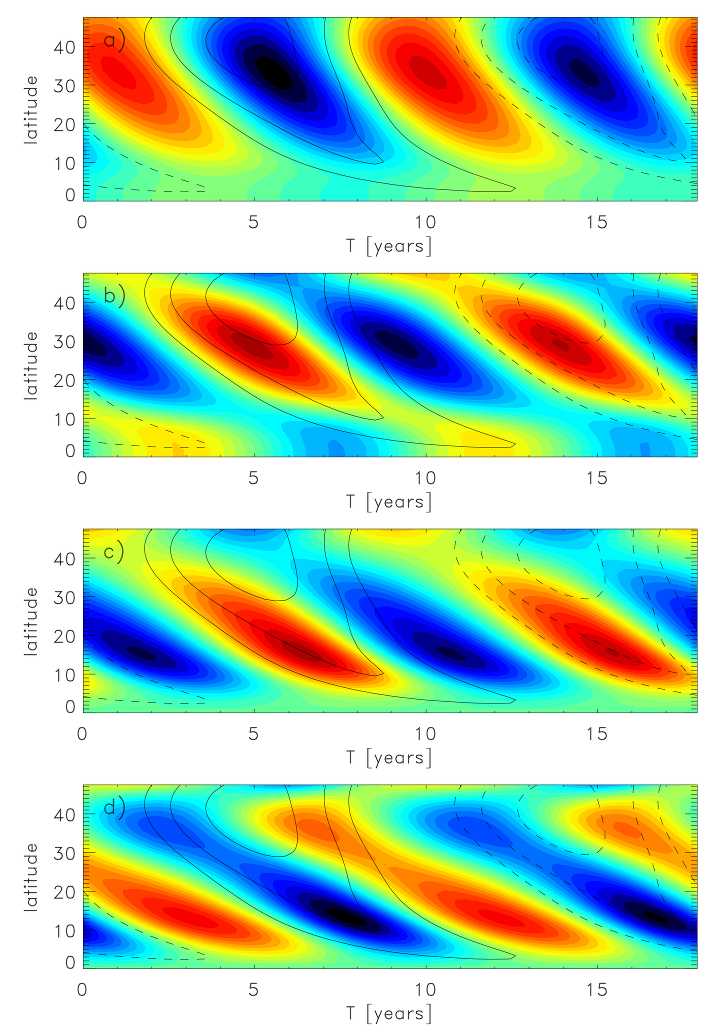

Figure 5: *Model results. a) Surface temperature variation (blue: cold, red: hot, amplitude: 0.2 K). b) Torsional oscillations (blue slower, red faster rotation; amplitude: 1.35 nHz). c) Meridional flow variation at $r = 0.985\,R_\odot$ (blue: equatorward, red poleward motion; amplitude: $2.3\,\mathrm{m\,s^{-1}}$. d) Meridional flow variation at $r = 0.93\,R_\odot$ (blue: equatorward, red poleward motion; amplitude: $0.22\,\mathrm{m\,s^{-1}}$. The variation of the meridional flow pattern at $r = 0.985\,R_\odot$ is almost in anti-correlation to the flow at $r = 0.93\,R_\odot$ (~ 50 Mm depth). In all four panels the contour lines indicate the butterfly diagram computed from the toroidal field at the base of the convection zone.*

4. CONCLUSION

The model reproduces the observations qualitatively, in particular the phase of the solar-cycle variations of the flows. Near the surface, the model is in remarkable agreement with the data: the torsional oscillation amplitude and the time-varying component of the meridional flow are predicted with the correct amplitude. Deeper in the interior, however, the model underestimates the amplitude of the time variations by an order of magnitude. Overall, it is fair to say that the model is encouraging.

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