View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Repositório Científico da Universidade de Évora

Mon. Not. R. Astron. Soc. **422,** 1709–1713 (2012) doi:10.1111/j.1365-2966.2012.20748.x

Effects of cyclic fluctuations in meridional circulation using a low-order dynamo model

D. Passos[1,2,3]★ and I. Lopes[1,3]

[1]*Departamento de Física, Universidade de Évora, Colégio António Luis Verney, 7002-554 Évora, Portugal*
[2]*GRPS, Départment de Physique, Université de Montréal, C.P. 6128 Centre-ville, Montréal, QC H3C-3J7, Canada*
[3]*CENTRA-IST, Instituto Superior Técnico, Avenida Rovisco Pais, 1049-001 Lisboa, Portugal*

Accepted 2012 February 13. Received 2012 February 13; in original form 2012 January 2

ABSTRACT
We develop and subsequently explore the solution space of a simple flux transport dynamo model that incorporates a time-dependent large-scale meridional circulation. Based on recent observations, we prescribed an analytical form for the amplitude of this circulation and study its impact in the evolution of the magnetic field. We find that cyclic variations in the amplitude and frequency of the meridional flow affect the strength of the solar cycle. Variations in the amplitude of the fluctuations influence the shape of the solar cycle but are only relevant to the cycle's strength variations when they occur at a frequency different from or out of phase of the solar cycle's.

Key words: Sun: activity – Sun: dynamo – magnetic fields.

1 INTRODUCTION

Our civilization is increasingly becoming more and more dependent on energy distribution, communication networks and satellite operation, since these technologies provide an important backbone for our daily activities. Nevertheless, these key technological assets may face dangers that one would like to minimize. Our Sun, so important for the life on our planet, is now being pointed as a source of problems for these technologies. Solar magnetic storms can surreptitiously hit Earth and damage all the structures previously mentioned. At the origin of these storms we can find the large-scale solar magnetic field. This field is believed to be originated by a magnetohydrodynamic dynamo that converts kinetic energy from the solar plasma motions into magnetic energy (Parker 1955). Several dynamo models have been developed to explain the main observational features of the solar magnetic field (Jouve et al. 2008; Charbonneau 2010). These models can reproduce the magnetic field polarity reversals (every 11 years) and many field spatial features. Touted as being the most promising of the several existing types, flux transport dynamo models have been tentatively used for the first time as a tool for predictions of the solar cycle (Dikpati et al. 2006; Choudhuri, Chatterjee & Jiang 2007). These predictions were the first to use full dynamo models to forecast the behaviour of the solar cycle. The models solve the mean-field axisymmetric equations for the magnetic field evolution on a background structure that incorporates parametrized physical mechanisms such as solar rotation and magnetic diffusivity. The denomination 'flux transport models' comes from the fact that they incorporate the solar meridional circulation, a conveyor belt-like plasma flow that carries magnetic field from the equator to the poles near the surface and from the poles towards the equator in the base of the solar convection zone (Dikpati & Charbonneau 1999; Chatterjee, Nandy & Choudhuri 2004; Muñoz-Jaramillo, Nandy & Martens 2009). The amplitude or strength of this circulation controls the period and amplitude of the produced magnetic field (Nandy & Choudhuri 2002; Lopes & Passos 2009). With just a few exceptions (Rempel 2006; Karak & Choudhuri 2011), most of these models work on the kinematic regime, which implies that the amplitude of the meridional circulation is not affected by the electromagnetic Lorentz force feedback of the magnetic field on the flow. Observational evidence of the meridional circulation is very hard to obtain and current values for the surface poleward average velocity are centred around 10 to 20 $\mathrm{m\,s^{-1}}$. The most reliable data are available only for the last couple of decades and the recent measurements of Hathaway & Rightmire (2010) indicate that the strength of this flow might have changed by about 25 per cent from the beginning of cycle 23 to cycle 24. Experimental evidence for a variable meridional circulation was already reported by Komm, Howard & Harvey (1993). Also, a recent inversion methodology based in a simplified dynamo model and the annual sunspot time series proposed by Passos & Lopes (2008) and Passos (2012) suggests that the amplitude of the meridional circulation changes significantly from cycle to cycle and that those variations could explain (partially) the observed solar variability. This information is not usually taken into account in dynamo-based predictions but its relevance is now recognized and is starting to be addressed by some research groups (Hotta & Yokoyama 2010; Karak 2010; Nandy, Muñoz-Jaramillo & Martens 2011). It has been shown by Mininni, Gomez & Mindlin (2000), Wilmot-Smith et al. (2005) and Passos & Lopes (2008, 2011) that a truncated version of

★E-mail: dariopassos@ist.utl.pt

© 2012 The Authors
Monthly Notices of the Royal Astronomical Society © 2012 RAS

the flux transport dynamo equations set or low-order dynamo models can be used as a first-order approximation to study the temporal behaviour of the solar magnetic field. These one-dimensional (1D) truncated models allow us to calculate the evolution of the magnetic field strength by taking into account the main physical mechanisms in a simplified way in the kinematic regime, without the need to incur in heavy numerical calculations. Exploratory studies made with these models are very useful for identifying and to help focusing in the relevant aspects and physical mechanisms that should be studied in depth by 2D numerical models. In this work, we build upon the low-order dynamo presented in Passos & Lopes (2011) by taking into account a time-dependent meridional circulation's amplitude profile. After the derivation of the new low-order model equations, we parametrize the meridional circulation based on the observations of Hathaway & Rightmire (2011) and study the impact of this time dependence in this dynamical system's solution. The final section is dedicated to comments and remarks about the results.

2 THE MODEL

As previously mentioned, the model presented here is a variation of the kinematic low-order dynamo model developed in Passos & Lopes (2008, 2011). In this version, we consider that the amplitude of the meridional circulation is time dependent and the derivation of the low-order model follows this directive. We start with the equations for a flux transport mean-field axisymmetric dynamo as shown in Charbonneau (2010). These equations give us the evolution of the mean solar magnetic field, $\bar{\boldsymbol{B}} = \boldsymbol{B}_\phi + \boldsymbol{B}_\mathrm{p}$, classically decomposed into its toroidal, $\boldsymbol{B}_\phi$, and poloidal, $\boldsymbol{B}_\mathrm{p} = \nabla \times (A_\mathrm{p}\hat{e}_\phi)$, components with A_p representing a potential vector field:

$$\frac{\partial B_\phi}{\partial t} = -\bar{r}\,\boldsymbol{v}_\mathrm{p}(t)\cdot\nabla\left(\frac{B_\phi}{\bar{r}}\right) + \bar{r}\left[\nabla \times (A_\mathrm{p}\hat{e}_\phi)\right]\cdot\nabla\Omega + \eta\left(\nabla^2 - \frac{1}{\bar{r}^2}\right)B_\phi - \Gamma(B_\phi)B_\phi, \tag{1}$$

$$\frac{\partial A_\mathrm{p}}{\partial t} = -\frac{1}{\bar{r}}\,\boldsymbol{v}_\mathrm{p}(t)\cdot\nabla\left(\bar{r}\,A_\mathrm{p}\right) + \alpha B_\phi + \eta\left(\nabla^2 - \frac{1}{\bar{r}^2}\right)A_\mathrm{p}, \tag{2}$$

where we have $\bar{r} = r\sin\theta$, $\nabla\Omega$ represents the differential rotation of the Sun, $\boldsymbol{v}_\mathrm{p}$ is the flow in the meridional plane and η is the magnetic turbulent diffusivity. One of the simplifications used in this model is to assume an average magnetic diffusivity for the entire convection zone ($\partial\eta/\partial r = 0$) and plasma incompressibility. Following the suggestions found in Kitchatinov, Mazur & Jardine (2000) and Pontieri et al. (2003), we add an extra term, $\Gamma \sim \gamma B_\phi^2/8\pi\rho$, to account for magnetic flux removal by magnetic buoyancy. Here, γ is a constant related to the buoyancy regime and ρ is the plasma density. As usual, in these models the regeneration mechanism from toroidal to poloidal field, the so-called α-effect, is represented by α. In this case, for simplicity, we do not consider any non-linearity in α. In the following steps, we assume that $\boldsymbol{v}_\mathrm{p}$ depends explicitly on time and we use the dimensional approach suggested by Mininni et al. (2000) to truncate the dynamo equations by substituting $\nabla \to 1/\ell_0$, where ℓ_0 is a specific length of interaction for the magnetic fields, usually taken as $\ell_0 \sim 0.1\,\mathrm{R}_\odot$. This truncation ensures that we are bounding our solution space to magnetic phenomena that occur in the scale of ℓ_0, presumably the large-scale solar magnetic field responsible for the solar cycle. After grouping terms in B_ϕ and A_p, we get

$$\frac{\mathrm{d}B_\phi}{\mathrm{d}t} = \left[c_1 - \frac{v_\mathrm{p}(t)}{\ell_0}\right]B_\phi + c_2 A_\mathrm{p} - c_3 B_\phi^3, \tag{3}$$

$$\frac{\mathrm{d}A_\mathrm{p}}{\mathrm{d}t} = \left[c_1 - \frac{v_\mathrm{p}(t)}{\ell_0}\right]A_\mathrm{p} + \alpha B_\phi, \tag{4}$$

where we have defined the coefficients, c_n, as

$$c_1 = \eta\left(\frac{1}{\ell_0^2} - \frac{1}{\mathrm{R}_\odot^2}\right), \tag{5}$$

$$c_2 = \frac{\bar{r}\Omega}{\ell_0^2}, \tag{6}$$

$$c_3 = \frac{\gamma}{8\pi\rho}. \tag{7}$$

These coefficients now contain all the structure parameters in the model, i.e. c_1, c_2 and c_3 assume the role of magnetic diffusivity, rotation and buoyancy, respectively, in this low-order dynamo model. Next, we take the derivative of equation (3) with respect to time and drop the A_p dependence by substituting equation (4) in the terms with $\mathrm{d}A_\mathrm{p}/\mathrm{d}t$ and by noting that $c_2 A_\mathrm{p}$ can be extracted from equation (3). After this mathematical workout, we finally get

$$\frac{\mathrm{d}^2 B_\phi}{\mathrm{d}t^2} = \left[2\left(c_1 - \frac{v_\mathrm{p}(t)}{\ell_0}\right) - 3c_3 B_\phi^2\right]\frac{\mathrm{d}B_\phi}{\mathrm{d}t} - \left[\frac{1}{\ell_0}\frac{\mathrm{d}v_\mathrm{p}(t)}{\mathrm{d}t} + \left(c_1 - \frac{v_\mathrm{p}(t)}{\ell_0}\right)^2 - c_2\alpha\right]B_\phi + c_3\left(c_1 - \frac{v_\mathrm{p}(t)}{\ell_o}\right)B_\phi^3, \tag{8}$$

with $\alpha \neq 0$. The solution's space of this dynamical system is defined by the structural coefficients c_n and by the analytical form of $v_\mathrm{p}(t)$. As a note, it is important to refer that in this kind of reduced systems, the units in which some of the quantities are presented do not always coincide with the real units, rendering the direct application of known physical values troublesome. Nevertheless, studies based on the relative variation of these parameters can be done and this work follows that line of thought.

A 'static' v_p reference solution for equation (8) is calculated by assuming a constant meridional flow amplitude. The values used for the coefficients c_n in this static solution were found by fitting equation (8) to the constructed proxy for the toroidal field presented in Passos & Lopes (2008) (for further details about the methodology used, you can also see Lopes & Passos 2009). Using these c_n values, the system presents a solar-like solution with B_ϕ^2, a proxy representation of the solar cycle, showing a cyclic behaviour with a period of about 11 years (Fig. 1). In the parameter regime used in this work, $v_\mathrm{p}(t)$ behaves mathematically as a source term and c_1, the diffusivity as a sink term. The former is one order of magnitude higher than the latter. Also, in this parameter regime, magnetic flux removal by buoyancy, c_3, is the main saturation mechanism in place to avoid field growth. In the following, we bound ourselves to the study of variations in $v_\mathrm{p}(t)$ maintaining the other coefficients with the values presented in the static solution. A complete study of the full parameters space is therefore deferred to a future work but some preliminary results are presented in Section 3.

2.1 Introducing cyclic fluctuations in $v_\mathrm{p}(t)$

According to the latest measurements of the surface meridional flow amplitude spanning a full magnetic cycle from

© 2012 The Authors, MNRAS **422,** 1709–1713
Monthly Notices of the Royal Astronomical Society © 2012 RAS

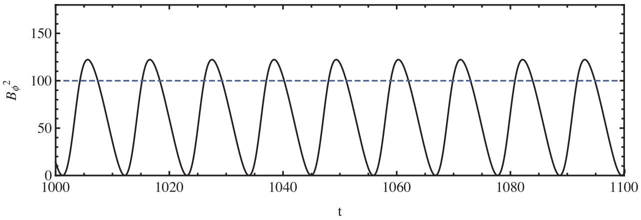

Figure 1. Static solution (obtained for constant v_p), after the system evolved for some time into stability. The solid black line represents B_ϕ^2, our chosen proxy to represent the solar cycle and the dashed blue line represents the scaled amplitude of v_p/ℓ_0 in order to plot both quantities in the same scale (in this example, the scaling used is $1000\,|v_p|$), t is displayed in years. Values used here are $c_1 = -0.01$, $c_2\alpha = -0.095$, $c_3 = 0.002$ and $v_p/\ell_0 = -0.1$.

Hathaway & Rightmire (2010), $v_p(t)$ varies in a roughly sinusoidal way, reaching a maximum amplitude near the half of the decreasing part of the solar cycle and dropping to its lower value near the sunspot maximum (see fig. 4 of Hathaway & Rightmire 2010). Based on this result, we propose an Ansatz where we take $[v_p(t)/\ell_0] \propto v_{p0} + A\sin(\omega t + \theta)$, where A is the amplitude of the meridional flow fluctuations, ω is the frequency of these fluctuations and θ is used to control the initial phase. This parametrization translates in a fluctuation of v_p around a mean value of v_{p0} (value used in the static solution). The top panel of Fig. 2 shows the solution for $\omega = 2\pi/T$, with $T = 11$ years and a fluctuation's amplitude $A = 0.025$, which corresponds to an amplitude variation of 25 per cent v_{p0} (roughly the amplitude variation between cycle minimum and maximum for solar cycle 23 presented in Hathaway & Rightmire 2010). It is important to mention that even if our meridional circulation is time dependent, the model still operates in the kinematic regime since v_p does not depend on the magnetic field.

We note that the initial phase, θ, has no impact on the solution's shape (for the range of tested parameters). One interesting result is the fact that for $\omega = 2\pi/11$, the phase difference between v_p and B_ϕ^2 is approximately the same as the observed one, i.e. maximum amplitude of v_p at the decreasing phase of the solar cycle and minimum amplitude of v_p near the cycle maximum. We used as initial conditions for solving equation (8) that $B_\phi(0) = 0.01$ and $dB_\phi/dt(0) = 0$. For these specific initial conditions, $B_\phi(t)$ enters a steady oscillation regime approximately after $t = 100$. For an oscillation amplitude of v_p of 25 per cent and an initial phase $\theta = 0$, the phase difference between $B_\phi(t)$ and v_p 'locks' around $t = 300$, while for $\theta = \pi/2$ this occurs at approximately $t = 750$. For different initial conditions, we get different times for the 'phase lock'. For higher values of v_p (either v_{p0} or A), the time to achieve the phase lock decreases. The phase lock occurs when the frequency ω associated with the v_p fluctuation is the same as (or very close to) the natural frequency of B_ϕ. In this low-order model, the period of the cycle is given primarily by $c_2\alpha$ with a small influence of $c_1 - v_p/\ell_0$ (for details cf. Passos 2012). This small dependence on v_p seems enough to ensure that after some time B_ϕ is synchronized with $v_p(t)$. Another way of explaining this is to resort to a $\{v_p, B_\phi\}$ phase space. If the solution in this phase space is a limit cycle, then the two quantities will synchronize phases after the solution evolves towards the attractor. See Fig. 3 for an illustrative example.

With this set of parameters, the system is well behaved and has a stable solution in the form of an attractor or limit cycle, best viewed in the phase space of $B(t)$ (Fig. 2, bottom panel). On the other hand, different values of the fluctuation's frequency, ω, yield some impact in the solution. For fluctuations with frequencies different from those of the solar cycle, like the one presented in the middle panel of Fig. 2, we observe a clear modulation of the field strength. This is best viewed in the corresponding phase space where we change from a stable well-defined limit cycle to a 'limit region'. A natural variability appears in the system even if the average meridional circulation amplitude remains constant (here v_{p0}). Solutions computed with different values of the fluctuation's amplitude show that it has an influence mainly in the shape of the cycle, creating higher asymmetries between its rising and falling parts. We also observe very small changes in the frequency of the cycle but there are no signs of any long-term variability (amplitude variations in the cycle's strength). With fluctuations as high as 200 per cent v_{p0},

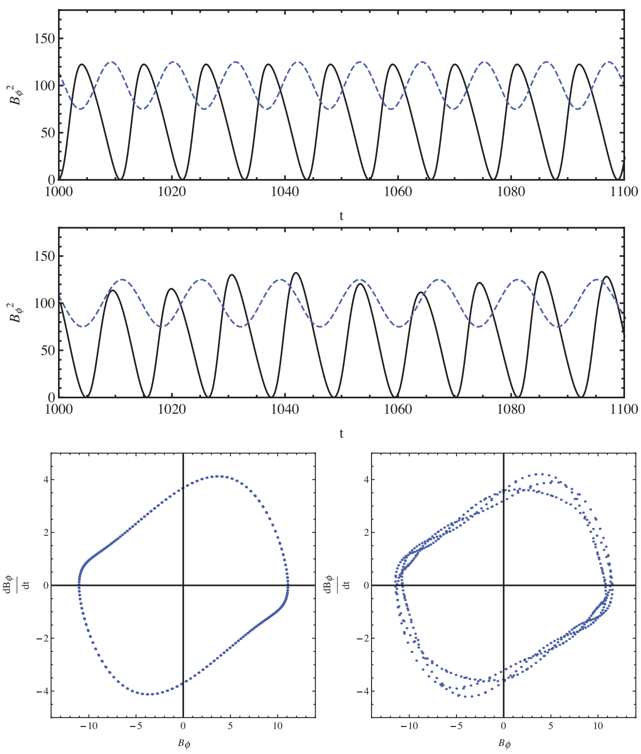

Figure 2. The line representation is the same as in Fig. 1. Top: $c_1 = -0.01$, $c_2\alpha = -0.095$, $c_3 = 0.002$, $v_{p0} = -0.1$, $A = 0.0225$, $\omega = 2\pi/11$ and $\theta = 0$. Middle: same parameters as the top panel, but with a change of the fluctuation's frequency, $\omega = 2\pi/14$. Bottom: the phase space $\{B_\phi, dB_\phi/dt\}$ for both solutions with $T = 11$ (left) and $T = 14$ (right) sampled at regular intervals.

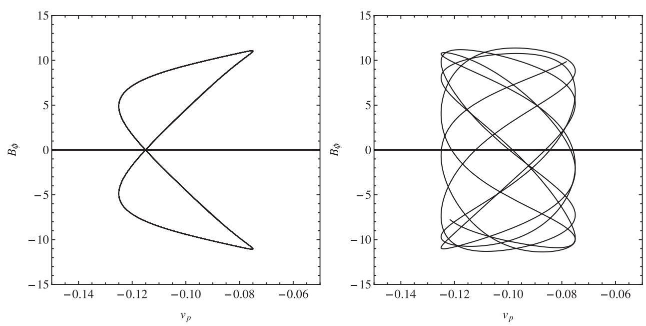

Figure 3. $\{v_p, B_\phi\}$ phase space for the solution between $t = 1000$ and 1100 using $\omega = 2\pi/11$ (left) and $\omega = 2\pi/12$ (right). The limit cycle on the left-hand panel is observed because ω and the frequency of oscillation of B_ϕ are the same.

© 2012 The Authors, MNRAS **422,** 1709–1713
Monthly Notices of the Royal Astronomical Society © 2012 RAS

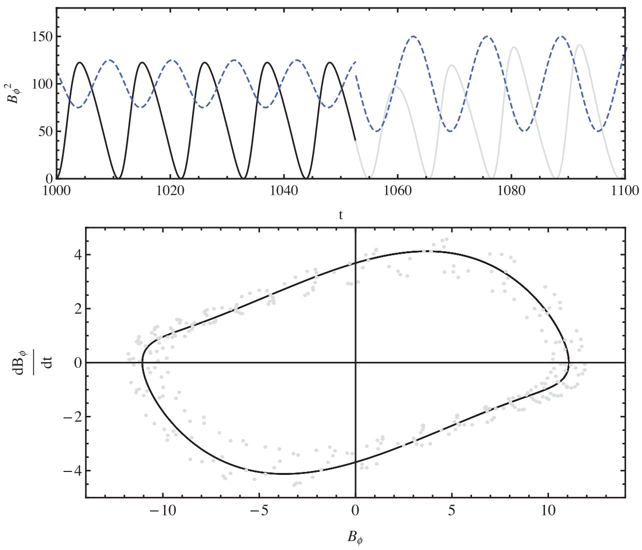

Figure 4. Solution assuming a variation in the fluctuation's amplitude A and frequency ω at a certain moment. Fixed parameters $c_1 = -0.01$, $c_2\alpha = -0.095$, $c_3 = 0.002$, $\theta = 0$ and $v_{p0} = -0.1$. In the top panel, we used $\omega = 2\pi/11$ and $A = 0.025$ (black) until $t = 1052$ and $\omega = 2\pi/13$ and $A = 0.05$ (grey) afterwards. The corresponding phase space is presented in the bottom panel. The line in black corresponds to the solution between $t = 1000$ and 1052 and the grey dots denote a sampling of the solution at regular intervals after the change.

the solution in the phase space remains a limit cycle. According to observations, the most realistic scenario is to consider small variations in the fluctuation's amplitude and perhaps in the period (of the order of a couple of years). These variations will create a variability in the strength difference between cycles N and following cycles. In this case, the observed solar cycle variability becomes dependent on changes in the fluctuations pattern of v_p. We present in Fig. 4 a test case where the amplitude of the fluctuations rises from 25 per cent v_{p0} to 50 per cent v_{p0}, and the frequency decreases from $\omega = 2\pi/11$ to $\omega = 2\pi/13$ at $t = 1055$. In this case, we find that both amplitude and frequency of the fluctuations influence the system's response. Changing the oscillation amplitude only (maintaining the frequency) results in a small variation of the limit cycle, i.e. a very smooth variability in the amplitude of the cycle appears ($\sim$0.2 per cent) and phase lock between the flow and the field is maintained. If one allows for variations in the oscillation frequency as well, a larger variability of the order of 30 per cent or larger appears (transition from limit cycle to limit region in the phase space). When the fluctuation's frequency occurs out of phase with the solar cycle, the amplitude of the fluctuations influences the strength of the future cycles in a more pronounced way.

3 CONCLUSIONS AND FINAL REMARKS

The main objective of this work is to quickly probe the impact that cyclic fluctuations in the solar meridional circulation profile have on the dynamo process operating in our Sun. To do so, we use a simplified dynamo model where meridional circulation amplitude is forced in a sinusoidal way that mimics recent observations. We found that regular cyclic fluctuations in the amplitude of the solar meridional circulation do not seem to have an impact in the overall inner works of the solar dynamo. This is specially true when the period of these fluctuations is the same as the solar cycle's. Nevertheless, if the frequency at which the meridional flow varies becomes different from the natural frequency of the solar cycle, then the cycle becomes naturally variable. In terms of phase space of the magnetic field, we go from a well-behaved solution, a limit cycle attractor, to a strange attractor (or attracting region). This might be a characteristic of this specific model because here the meridional flow term v_p acts as a source term. When this source term is not synchronized with the natural frequency of the solar cycle set by $c_2\alpha$, the variability appears. In this reduced model, the relationship between cycle period and amplitude that results from changes in the meridional flow presents a non-typical solar behaviour. Observations show that, in average, the stronger solar cycles have shorter periods (amplitude–period rule) while in this model we get stronger cycles having longer periods. This apparent shortcoming can give us some clues about other quantities that can be varying over time. More specifically, variations in the physical mechanisms that are present in $c_2\alpha$ could produce the desired effect. Variations in the α effect or in the solar rotation could occur in parallel with meridional flow changes to produce the cycle's amplitude–period rule.

According to this model, amplitude variations in the fluctuation profile of v_p have an impact on the shape of the solar cycle, increasing the asymmetries between rising and falling parts and even creating double-peaked cycles. In this case, a solar-like feature is observed, i.e. stronger cycles tend to have a steeper rising phase than weaker cycles. Large and long-term variations in the amplitude of the solar cycle only occur when the frequency and amplitude of the fluctuations change in parallel.

It is interesting to note that when our dynamo equation is forced with a sinusoidal meridional flow, the phase difference between both the flow and the field is nearly the same as the observational one. This is true as long as $c_2\alpha$ is set to reproduce the 11-yr periodicity of the solar cycle. We find that for different $c_2\alpha$ values (e.g. variations in the solar rotation or in the case of other stars rotating faster or slower than the Sun), the phase difference between the meridional flow and the magnetic field changes. As long as both frequencies (ω and the solar cycle's) are the same (or very close), the phase difference between the flow and the field seems to lock independent of the initial phase θ used. Another parameter that influences the phase difference between the field and the flow is c_1. By changing the diffusivity of the system the phase lock between the field and the flow can be modified.

It is worth mentioning that the exact moment, in respect to cycle N, at which the variation in the fluctuations regime occurs has an impact on the amplitude of the following cycles. Depending on the variation scenario chosen (amplitude, period or both of v_p), cycle $N + 1$ can be stronger or weaker than cycle N. A similar effect has also been recently reported in 2D dynamo simulations by Nandy et al. (2011). We defer the details of this and other effects to a future work, where we plan to perform a complete parameter space study of the model (including variations in c_1 and c_3).

From a physical point of view, the information that can be extracted from such a truncated model is limited. Nevertheless, we get important clues about the system's overall behaviour when forced under certain parametrizations. One of the questions that this model, in its present kinematic form, does not address is what could be the cause(s) of the observed variations in the meridional flow. A possible explanation could be that the meridional circulation, being a weak flow, can be influenced by the Lorentz feedback from the magnetic field. This feedback can be enough to modify significatively the meridional circulation. This scenario is supported by a recent analysis of the large-eddy global magnetohydrodynamic simulations of the solar convection zone produced by Ghizaru, Charbonneau & Smolarkiewicz (2010), in which Passos, Charbonneau & Beaudoin

(2012b) find evidence that the toroidal field at the base of the convection zone modulates the amplitude of the meridional circulation. If meridional circulation fluctuations are produced in this way, they should occur at the same frequency as the solar cycle. Although different variations in amplitude from cycle to cycle could occur, the phase difference between this flow and the magnetic field should remain the same. Future observation will gives us the answers.

On the other hand, if indeed the Lorentz feedback of the field into the flow is the reason (or partially responsible) for the observed amplitude fluctuations, then it is reasonable to assume that this same feedback will also influence the solar rotation, although on a smaller scale. According to the found results, variations in these two large-scale flows would be more than enough to produce a variable solar cycle. More details about this physical scenario could be presented here but those would be more speculative. Our intention here is not to create/feed speculations but to explore plausible physical scenarios and motivate future studies.

The final remark that we would like present is the fact that, since numerical dynamo models are now starting to emerge as forecasting tools for solar activity, meridional variation mechanisms should be studied/implemented in order to improve their reliability. Most probably this will require a departure from the classical kinematic approach. In terms of the future, we also believe that if we keep monitoring $v_{\rm p}(t)$ [and probably $\Omega(t)$] in the Sun then, according to the presented model, we would be able to predict the behaviour of future solar cycles since the variability associated with the large-scale flows seems to be mostly deterministic.

ACKNOWLEDGMENTS

The authors would like to acknowledge an anonymous referee for the useful comments and the financial support of Fundação para a Ciência e Tecnologia grant SFRH/BPD/68409/2010 and CENTRA-IST.

REFERENCES

Charbonneau P., 2010, Living Rev. Solar Phys., 7, 3
Chatterjee P., Nandy D., Choudhuri A. R., 2004, A&A, 427, 1019
Choudhuri A. R., Chatterjee P., Jiang J., 2007, Phys. Rev. Lett., 98, 131103
Dikpati M., Charbonneau P., 1999, ApJ, 518, 508
Dikpati M., de Toma G., Gilman P. A., 2006, Geophys. Res. Lett., 33, L05102
Ghizaru M., Charbonneau P., Smolarkiewicz P. K., 2010, ApJ, 715, 133
Hathaway D. H., Rightmire L., 2010, Sci, 327, 1350
Hathaway D. H., Rightmire L., 2011, ApJ, 729, 80
Hotta H., Yokoyama T., 2010, ApJ, 709, L308
Jouve L. et al., 2008, A&A, 483, 949
Karak B., 2010, ApJ, 724, 1021
Karak B., Choudhuri A. R., 2011, Sol. Phys., preprint (doi:10.1007/s11207-012-9928-5)
Kitchatinov L. L., Mazur M. V., Jardine M., 2000, A&A, 359, 531
Komm R. W., Howard R. F., Harvey J. W., 1993, Sol. Phys., 147, 207
Lopes I., Passos D., 2009, Sol. Phys., 257, 1
Mininni P. D., Gomez D. O., Mindlin G. B., 2000, Phys. Rev. Lett., 85, 5476
Muñoz-Jaramillo A., Nandy D., Martens P. C. H., 2009, ApJ, 698, 461
Nandy D., Choudhuri A. R., 2002, Sci, 296, 1671
Nandy D., Muñoz-Jaramillo A., Martens P. C. H., 2011, Nat, 471, 80
Parker E., 1955, ApJ, 122, 293
Passos D., 2012, ApJ, 744, 172
Passos D., Lopes I. P., 2008, ApJ, 686, 1420
Passos D., Lopes I. P., 2011, J. Atmos. Sol. Terr. Phys., 73, 191
Passos D., Charbonneau P., Beaudoin P., 2012, Sol. Phys., submitted
Pontieri A., Lepreti F., Sorriso-Valvo L., Vecchio A., Carbone V., 2003, Sol. Phys., 213, 195
Rempel M., 2006, ApJ, 647, 662
Wilmot-Smith A. L., Martens P. C. H., Nandy D., Priest E. R., Tobias S. M., 2005, MNRAS, 363, 1167

This paper has been typeset from a TEX/LATEX file prepared by the author.

© 2012 The Authors, MNRAS **422,** 1709–1713
Monthly Notices of the Royal Astronomical Society © 2012 RAS