A PROPOSED PARADIGM FOR SOLAR CYCLE DYNAMICS MEDIATED VIA TURBULENT PUMPING OF MAGNETIC FLUX IN BABCOCK–LEIGHTON-TYPE SOLAR DYNAMOS

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ABSTRACT

At present, the Babcock–Leighton flux transport solar dynamo models appear to be the most promising models for explaining diverse observational aspects of the sunspot cycle. The success of these flux transport dynamo models is largely dependent upon a single-cell meridional circulation with a deep equatorward component at the base of the Sun’s convection zone. However, recent observations suggest that the meridional flow may in fact be very shallow (confined to the top 10% of the Sun) and more complex than previously thought. Taken together, these observations raise serious concerns on the validity of the flux transport paradigm. By accounting for the turbulent pumping of magnetic flux, as evidenced in magnetohydrodynamic simulations of solar convection, we demonstrate that flux transport dynamo models can generate solar-like magnetic cycles even if the meridional flow is shallow. Solar-like periodic reversals are recovered even when meridional circulation is altogether absent. However, in this case, the solar surface magnetic field dynamics does not extend all the way to the polar regions. Very importantly, our results demonstrate that the Parker–Yoshimura sign rule for dynamo wave propagation can be circumvented in Babcock–Leighton dynamo models by the latitudinal component of turbulent pumping, which can generate equatorward propagating sunspot belts in the absence of a deep, equatorward meridional flow. We also show that variations in turbulent pumping coefficients can modulate the solar cycle amplitude and periodicity. Our results suggest the viability of an alternate magnetic flux transport paradigm—mediated via turbulent pumping—for sustaining solar-stellar dynamo action.

Key words: dynamo – magnetohydrodynamics (MHD) – Sun: magnetic fields

1. INTRODUCTION

The cycle of sunspots involves the generation and recycling of the Sun’s toroidal and poloidal magnetic field components. The magnetohydrodynamic (MHD) dynamo mechanism that achieves this is sustained by the energy of solar internal plasma motions such as differential rotation, turbulent convection and meridional circulation. The toroidal field is generated through the stretching of the poloidal component by differential rotation (Parker 1955) and is believed to be stored and amplified at the overshoot layer (Moreno-Insertis et al. 1992) beneath the base of the solar convection zone (SCZ). Strong toroidal flux tubes are unstable to magnetic buoyancy and erupt through the surface producing sunspots, which are strongly magnetized and have a systematic tilt (Hale 1908; Hale et al. 1919). The poloidal field is believed to be regenerated through a combination of helical turbulent convection (traditionally known as the mean-field α-effect; Parker 1955) in the main body of the SCZ and the redistribution of the magnetic field of tilted bipolar sunspot pairs (the Babcock–Leighton process; Babcock 1961; Leighton 1969).

Despite early pioneering attempts to self-consistently model the interactions of turbulent plasma flows and magnetic fields in the context of the solar cycle (Gilman 1983; Glatzmaier 1985), such full MHD simulations are still not successful in yielding solutions that can match solar cycle observations. This task is indeed difficult, for the range of density and pressure scale heights, scale of turbulence and high Reynolds number that characterize the SCZ are difficult to capture even in the most powerful supercomputers. An alternative approach to modeling the solar cycle is based on solving the magnetic induction equation in the SCZ with observed plasma flows as inputs and with additional physics gleaned from simulations of convection and flux tube dynamics. These so-called flux transport dynamo models have shown great promise in recent years in addressing a wide variety of solar cycle problems (Ossendrijver 2003; Charbonneau 2010).

In particular, solar dynamo models based on the Babcock–Leighton mechanism for poloidal field generation have been more successful in explaining diverse observational features of the solar cycle (Dikpati & Charbonneau 1999; Nandy & Choudhuri 2002; Chatterjee et al. 2004; Choudhuri et al. 2004; Guerrero & de Gouveia Dal Pino 2007; Muñoz-Jaramillo et al. 2009; Nandy et al. 2011; Choudhuri & Karak 2012; Hazra et al. 2014; Passos et al. 2014). Recent observations also strongly favor the Babcock–Leighton mechanism as a major source for poloidal field generation (Dasi-Espuig et al. 2010; Muñoz-Jaramillo et al. 2013). In this scenario, the poloidal field generation is essentially confined to near-surface layers. For the dynamo to function efficiently, the toroidal field that presumably resides deep in the interior has to reach the near-surface layers for the Babcock–Leighton poloidal source to be effective. This is achieved by the buoyant transport of magnetic flux from the Sun’s interior to its surface (through sunspot eruptions). Subsequent to this, the poloidal field so generated at near-surface layers must be transported back to the solar interior, where differential rotation can generate the toroidal field. The deep meridional flow assumed in such models (See Figure 1, left hemisphere) plays a significant role in this flux transport process and is thought to govern the period of the sunspot cycle (Charbonneau & Dikpati 2000; Hathaway et al. 2003; Yeates et al. 2008; Hazra et al. 2014). Moreover, a fundamentally crucial role attributed to the deep equatorward meridional flow is that it allows the Parker–Yoshimura sign rule (Parker 1955; Yoshimura 1975) to be
Figure 1. The outer 45% of the Sun depicting the internal rotation profile in color. Faster rotation is denoted in deep red and slower rotation in blue. The equator of the Sun rotates faster than the polar regions and there is a strong shear layer in the rotation near the base of the convection zone (denoted by the dotted line). Streamlines of a deep meridional flow (solid black curves) reaching below the base of the solar convection zone (dashed line) is shown on the left hemisphere, while streamlines of a shallow meridional flow confined to the top 10% of the Sun is shown on the right hemisphere (arrows indicate direction of flow). Recent observations indicate that the meridional flow is much shallower and more complex than traditionally assumed, calling into question a fundamental premise of flux transport dynamo models of the solar cycle.

overcome, which would otherwise result in poleward propagating dynamo waves in contradiction to observations that the sunspot belt migrates equatorwards with the progress of the cycle (Choudhuri et al. 1995; Hazra et al. 2014; Belucz et al. 2015; Passos et al. 2015).

While the poleward meridional flow at the solar surface is well observed (Hathaway & Rightmire 2010, 2011), the internal meridional flow profile has remained largely unconstrained. A recent study utilizing solar supergranules (Hathaway 2012) suggests that the meridional flow is confined to within the top 10% of the Sun (Figure 1, right hemisphere), which is much shallower than previously thought. Independent studies utilizing helioseismic inversions are also indicative that the equatorward meridional counterflow may be located at shallow depths (Mitra-Kraev & Thompson 2007; Zhao et al. 2013). The latter also infer the flow to be multi-cellular and more complex. These studies motivate exploring alternative paradigms for flux transport dynamics in Babcock–Leighton-type models of the solar cycle, which are crucially dependent on meridional circulation linking the two segregated dynamo source regions in the SCZ. This leads us to consider the role of turbulent pumping.

Magnetocconvection simulations supported by theoretical considerations have established that turbulent pumping preferentially transports magnetic fields vertically downwards (Brandenburg et al. 1996; Dorch & Nordlund 2001; Tobias et al. 2001; Ossendrijver et al. 2002; Käpylä et al. 2006; Pipin & Seehafer 2009; Racine et al. 2011; Rogachevskii et al. 2011; Augustson et al. 2015; Simard et al. 2016; Warnecke et al. 2016) and they are likely mediated via strong downward convective plumes, which are particularly effective on weak magnetic fields (such as the poloidal component). In strong rotation regimes, there is also a significant latitudinal component of turbulent pumping. In particular, two studies, one utilizing mean-field dynamo simulations (Brandenburg et al. 1992) and the other utilizing turbulent three-dimensional magnetocconvection simulations (Ossendrijver et al. 2002), recognized the possibility that turbulent pumping may contribute to the equatorward propagation of the toroidal field belt. We note that most Babcock–Leighton kinematic flux transport solar dynamo models do not include the process of turbulent pumping of magnetic flux. The few studies that exist on the impact of turbulent pumping in the context of flux transport dynamo models show it to be dynamically important in flux transport dynamics, the maintenance of solar-like parity and solar cycle memory (Guerrero & de Gouveia Dal Pino 2008; Karak & Nandy 2012; Jiang et al. 2013). In their model with turbulent pumping, (Guerrero & de Gouveia Dal Pino 2008) used a spatially distributed α-coefficient in the near-surface layers to model the Babcock–Leighton poloidal source and a meridional circulation whose equatorward component penetrated up to 0.8R⊙, i.e., more than half the depth of the SCZ. Therefore, from this modeling, it is not possible to segregate the contributions of turbulent pumping and meridional flow (the peak latitudinal component of the former coincides with the equatorward component of the latter) to the toroidal field migration.

Here, utilizing a newly developed state-of-the-art flux transport dynamo model where a double-ring algorithm is utilized to model the Babcock–Leighton process, we explore the impact of turbulent pumping in flux transport dynamo models with nonexistent, or shallow meridional circulation. Our results indicate the possibility of an alternative flux transport paradigm for the solar cycle in which turbulent pumping of magnetic flux resolves the problems posed by a shallow (or inconsequential) meridional flow.

2. MODEL

Our flux transport solar dynamo model solves for the coupled, evolution equation for the axisymmetric toroidal and poloidal components of the solar magnetic fields:

\[
\frac{\partial A}{\partial t} + \frac{1}{s} [v_p \cdot \nabla (sA)] = \eta \left( \nabla^2 - \frac{1}{s^2} \right) A + S_{BL},
\]

\[
\frac{\partial B}{\partial t} + \frac{s}{v_p} \left[ \nabla \cdot \left( \frac{B}{s} \right) \right] + (\nabla \cdot v_p) B = \eta \left( \nabla^2 - \frac{1}{s^2} \right) B + s [\left( \nabla \times (A \hat{e}_\theta) \right) \cdot \nabla \Omega] + \frac{1}{s} \left( \frac{\partial (sB)}{\partial r} \right) \frac{\partial \eta}{\partial r},
\]

where, B is the toroidal component of magnetic field and A is the vector potential for the poloidal component of magnetic field. \(v_p\) is the meridional flow, \(\Omega\) is the differential rotation, \(\eta\) is the turbulent magnetic diffusivity and \(s = r \sin(\theta)\). For the differential rotation and diffusivity profile, we use an analytic fit to the observed solar differential rotation (the near-surface shear layer is not included) and a two-step turbulent diffusivity profile (which ensures a smooth transition to low levels of diffusivity beneath the base of the convection zone) (For a detailed profile, see Hazra & Nandy 2013). We use the same meridional flow profile as defined in Hazra & Nandy (2013).

Our flow profile has a penetration depth of 0.65R⊙ to represent the deep meridional flow situation, and 0.90 R⊙ to represent the shallow meridional flow situation. We set the peak speed of the meridional flow to be 15 ms\(^{-1}\) (near mid-latitudes). The second term on the RHS of the toroidal field evolution equation acts as the source term for the toroidal field (rotational shear), while in the poloidal field evolution equation, the source term, \(S_{BL}\), is due to the Babcock–Leighton mechanism. Here, we use a
double-ring algorithm for buoyant sunspot eruptions that best captures the Babcock–Leighton mechanism for poloidal field generation (Durán 1997; Nandy & Choudhuri 2001; Muñoz-Jaramillo et al. 2010; Hazra & Nandy 2013) and which has been tested thoroughly in other contexts. Specifics about our double-ring algorithm can be found in Hazra & Nandy (2013) and Hazra (2016).

3. RESULTS

To bring out the significance of the recent observations, we first consider a single-cell, shallow meridional flow, confined only to the top 10% of the convection zone (Figure 1, right hemisphere). In the first scenario, we seek to answer the following question: Can solar-like cycles be sustained through magnetic field dynamics completely confined to the top 10% of the Sun?

In these simulations initialized with antisymmetric toroidal field condition (with initial $B \sim 100$ kG), we first allow magnetic flux tubes to buoyantly erupt from 0.90 $R_\odot$ (i.e., the depth to which the shallow flow is confined) when they exceed a buoyancy threshold of $10^4$ G. In this case, we find that the simulated fields fall and remain below this threshold (at all latitudes at 0.90 $R_\odot$) with no buoyant eruptions, thus implying that a Babcock–Leighton-type solar dynamo cannot operate. Dikpati et al. (2002) considered the contribution of the near-surface shear layer in their simulations (which we have not) and concluded that this near-surface layer contributes only about 1 kG to the total toroidal field production and hence is insufficient to drive a large-scale dynamo. Guerrero & de Gouveia Dal Pino (2008) also utilized a near-surface shear layer with radial pumping and found solar-like solutions only under special circumstances. However, given that for this particular case they utilized a local $\alpha$-effect for the latter simulations (with a spatially distributed $\alpha$-effect in the near-surface layer), it is not evident that these simulations are relatable to the Babcock–Leighton solar dynamo concept. The upper layers of the SCZ are highly turbulent and the storage and amplification of strong magnetic flux tubes may not be possible in these layers (Parker 1975; Moreno-Insertis 1983) and, therefore, this result is not unexpected. While Brandenburg (2005) has conjectured that the near-surface shear layer may be able to power a large-scale dynamo, this remains to be convincingly demonstrated in the context of a Babcock–Leighton dynamo.

In the second scenario with a shallow meridional flow, we allow magnetic flux tubes to buoyantly erupt from 0.71 $R_\odot$, i.e., from the base of the convection zone. In this case, we get periodic solutions, but analysis of the butterfly diagrams (taken both at the base of SCZ and near solar surface) shows that the toroidal field belts have almost symmetrical poleward and equatorward branches with no significant equatorward migration (see Figure 2). Moreover, as already noted by Guerrero & de Gouveia Dal Pino (2008), the solutions with shallow meridional flow always display quadrupolar parity in contradiction with solar cycle observations. Clearly, a shallow flow poses a serious problem for solar cycle models.

We now introduce both radial and latitudinal turbulent pumping in our dynamo model to explore whether a Babcock–Leighton flux transport dynamo can operate with meridional flow, which is much shallower than previously assumed. We also extend this study to the scenario where meridional flow is altogether absent.

The turbulent pumping profile is determined from independent MHD simulations of solar magnetoconvection (Ossendrijver et al. 2002; Käpylä et al. 2006). Profiles for radial and latitudinal turbulent pumping ($\gamma_r$ and $\gamma_\theta$) are:

$$\gamma_r = -\gamma_{\theta r} \left[ 1 + \text{erf} \left( \frac{r - 0.715R_\odot}{0.015R_\odot} \right) \right] \times \left[ 1 - \text{erf} \left( \frac{r - 0.97R_\odot}{0.1R_\odot} \right) \right] \times \left[ \exp \left( \frac{r - 0.715R_\odot}{0.25R_\odot} \right)^2 \cos \theta + 1 \right]$$

$$\gamma_\theta = \gamma_{\theta r} \left[ 1 + \text{erf} \left( \frac{r - 0.8R_\odot}{0.55R_\odot} \right) \right] \left[ 1 - \text{erf} \left( \frac{r - 0.98R_\odot}{0.025R_\odot} \right) \right] \times \cos \theta \sin^3 \theta.$$  

The value of $\gamma_{\theta r}$ and $\gamma_{\theta r}$ determines the amplitude of $\gamma_r$ and $\gamma_\theta$, respectively. Figure 3 (top and bottom plot) shows that radial pumping speed (dashed lines) is negative throughout the
convection zone corresponding to downward advective transport and vanishes below 0.7$R_\odot$. The radial pumping speed is maximum near the poles and decreases toward the equator. Figure 3 (top and bottom plot) shows that the latitudinal pumping speed (solid lines) is positive (negative) in the convection zone in the northern (southern) hemisphere and vanishes below the overshoot layer. This corresponds to equatorward latitudinal pumping throughout the convection zone.

Dynamo simulations with turbulent pumping generate solar-like magnetic cycles (Figures 4 and 5). Now the toroidal field belt migrates equatorward, the solution exhibits solar-like parity and the correct phase relationship between the toroidal and poloidal components of the magnetic field (see Figure 5). Evidently, the coupling between the poloidal source at the near-surface layers with the deeper layers of the convection zone where the toroidal field is stored and amplified, the equatorward migration of the sunspot-forming toroidal field belt and correct solar-like parity is due to the important role played by turbulent pumping. We note that if the speed of the latitudinal pumping is in the order of 1.0 ms$^{-1}$ the solutions are always of dipolar parity, irrespective of whether one initializes the model with dipolar or quadrupolar parity. Interestingly, the latitudinal migration rate of the sunspot belt as observed is of the same order.

The above result raises the question whether flux transport solar dynamo models based on the Babcock–Leighton mechanism that include turbulent pumping can operate without any meridional plasma flow. To test this, we remove meridional circulation completely from our model and perform simulations with turbulent pumping included. We find that this model generates solar-like sunspot cycles with periodic reversals (see Figure 6), which are qualitatively similar to the earlier solution with both pumping and shallow meridional flow. However, we find that the surface magnetic field dynamics related to polar field reversal is limited to within 60° latitudes in both the hemispheres. At higher latitudes (near the poles), the field is very weak and almost non-varying over solar cycle timescales.

This is expected if the surface magnetic field dynamics is governed primarily by diffusion. Based on this result, we argue that this scenario of nonexistent meridional circulation is not supported by current observations of surface dynamics, which seem to suggest that the fields do migrate all the way to the poles.

Two important characteristics associated with the solar magnetic cycle are its amplitude and periodicity. While the periodicity of the cycle predominantly depends on the recycling time between the toroidal and poloidal field, its amplitude depends on a variety of factors including dynamo source strengths and relative efficacy of transport timescales with respect to the turbulent diffusion timescale. We explore the dependency of the solar cycle period and amplitude to variations in the transport coefficients to explore the subtleties of the interplay between diverse flux transport processes. Figure 7 shows the dependency of cycle amplitude and periodicity on different velocity components like turbulent pumping and (shallow) meridional flow. A parametric analysis of this dependency yields the following relationships for cycle period ($T$) and cycle amplitude (Amp):

\[
T \approx 9.7 \gamma_r^{-0.25} \gamma_\theta^{-0.26} v^{-0.068},
\]

\[
Amp \approx 11.76 \gamma_r^{1.07} \gamma_\theta^{-0.27} v^{-0.16},
\]

which is gleaned from simulations within the following ranges: 0.25 ms$^{-1} \leq \gamma_r \leq 1.25$ ms$^{-1}$, 0.25 ms$^{-1} \leq \gamma_\theta \leq 1.25$ ms$^{-1}$.
and $v \lesssim 2\text{ ms}^{-1}$; $\gamma_r$ and $\gamma_q$ are radial and latitudinal turbulent pumping speeds, and $v$ is the shallow meridional flow speed.

This analysis shows that cycle period and amplitude are both governed by diverse transport coefficients such as meridional flow speed, and radial and latitudinal components of turbulent pumping. As radial turbulent pumping carries the flux directly to the base of the convection zone where toroidal field is amplified, an increase in the radial turbulent pumping speed leads to a decrease in the cycle period. Increasing latitudinal pumping also has a similar effect on period, which is similar to what is achieved by increasing meridional flow speed, namely a faster transport through the shear layer and thus shorter cycle periods. The cycle amplitude decreases on increasing the latitudinal pumping or meridional flow speed and this is due to the fact that less time is available for toroidal field induction when it is swept at a faster rate through the rotational shear layers. In surface flux transport models, a similar effect is found, but due to a different reason—wherein a faster meridional flow reduces the polar field strength, because it takes flux of both polarities and deposits this at the poles (in effect carrying less net flux to the poles). In these simulations with a shallow meridional flow and the double-ring algorithm, a similar mechanism could also be contributing to an overall reduction of the field strength. What is interesting to note, though, is the positive dependence of cycle amplitude on the radial pumping speed. We believe that a faster radial pumping moves the poloidal field down to the generating layers of the toroidal field in the deeper parts of the convection zone faster, thus allowing for less turbulent decay in the poloidal field strength; this eventually results in a stronger poloidal field in the SCZ which generates a stronger toroidal component.

Figure 5. Dynamo simulations considering both shallow meridional flow and turbulent pumping, but initialized with symmetric initial condition (quadrupolar state). The top panel shows the phase relationship between toroidal and poloidal field, while the bottom panel shows the butterfly diagram taken at the base of the convection zone ($R_{\odot} = 0.71R_{\odot}$).

Figure 6. Results of solar dynamo simulations with turbulent pumping and without any meridional circulation. The convention is the same as in Figure 2. The simulations show that solar-like sunspot cycles can be generated even without any meridional plasma flow in the solar interior.
We note that the derived exponents for the cycle period above differ from those determined by Guerrero & de Gouveia Dal Pino (2008). The cycle period in our simulations is more strongly dependent on the latitudinal speed of turbulent pumping and less so on meridional circulation, whereas in Guerrero & de Gouveia Dal Pino (2008) it is the exact reverse. In our model, the meridional flow is very shallow and limited to only the top 10% of the SCZ, whereas in the model setup of Guerrero & de Gouveia Dal Pino (2008), the meridional flow penetrates down to about 0.8 $R_\odot$; this we believe makes their dynamo cycle periods more sensitive to meridional flow compared to latitudinal pumping. Generally, we find solar-like solutions in a modest turbulent pumping speed range in the order of 1 ms$^{-1}$. This parameter study shows that our result is robust to reasonable variations in turbulent pumping coefficients and also points to how the latter may determine solar cycle strength and periodicity.

As there is some uncertainty regarding the exact details of turbulent pumping profiles, we have tested an alternative turbulent pumping profile based on Warnecke et al. (2016). Recent magnetoconvection simulations performed by Warnecke et al. (2016) suggest that radial pumping is downward throughout the convection zone below 45° and upward above 45°, while latitudinal pumping is poleward at the surface and equatorward at the base of the convection zone. Our generated turbulent pumping profiles in the northern hemisphere (defined within $0 \leq \theta \leq \pi/2$) based on the suggestions of Warnecke et al. (2016) are:

\[
\begin{align*}
\gamma_r &= -\gamma_0 \left[ 1 + \text{erf} \left( \frac{r - 0.715R_\odot}{0.05R_\odot} \right) \right] \\
& \times \left[ 1 - \text{erf} \left( \frac{r - 0.98R_\odot}{0.05R_\odot} \right) \right] \times \sin(4\theta), 
\end{align*}
\]

(7)

\[
\begin{align*}
\gamma_\theta &= \gamma_0 \sin \left[ \frac{2\pi(r - R_p)}{R_\odot - R_p} \right] \cos \theta \sin^4 \theta \quad r \geq R_p, \\
&= 0 \quad r < R_p.
\end{align*}
\]

(8)

where $R_p = 0.76R_\odot$, i.e., the penetration depth of the latitudinal pumping. The amplitudes of $\gamma_r$ and $\gamma_\theta$ are determined by the value of $\gamma_0$, and $\gamma_0$, respectively. Turbulent pumping profiles in the southern hemisphere are generated by replacing colatitude $\theta$ by $(\pi - \theta).$ Figure 8 (the top and middle panels) show that our generated turbulent pumping profiles capture the basic essence of the suggestions made by Warnecke et al. (2016). Our simulations (with shallow meridional flow) and the more complex turbulent pumping profile gleaned from Warnecke et al. (2016) reproduce broad features of the solar cycle and are qualitatively similar to those detailed earlier.

Figure 7. Dependence of amplitude and periodicity of simulated solar cycles on turbulent pumping (radial and latitudinal) and (shallow) meridional flow speeds. Pearson and Spearman correlation coefficients are 0.99 and 1, respectively, for the top left plot and $-0.99$ and $-1$, respectively, for all other plots.
4. DISCUSSIONS

In summary, we have demonstrated that flux transport dynamo models of the solar cycle based on the Babcock–Leighton mechanism for poloidal field generation does not require a deep equatorward meridional plasma flow to function effectively. In fact, our results indicate that when turbulent pumping of magnetic flux is taken into consideration, dynamo models can generate solar-like magnetic cycles even without any meridional circulation, although the surface magnetic field dynamics does not reach all the way to the polar regions in this case. Our conclusions are robust across a modest range of plausible parameter space for turbulent pumping coefficients and also indicate some tolerance for diverse pumping profiles.

These findings have significant implications for our understanding of the solar cycle. First of all, the serious challenges that were apparently posed by observations of a shallow (and perhaps complex, multi-cellular) meridional flow on the very premise of flux transport dynamo models stands resolved. Turbulent pumping essentially takes over the role of meridional circulation by transporting magnetic fields from the near-surface solar layers to the deep interior, ensuring that efficient recycling of toroidal and poloidal field components across the SCZ is not compromised. While these findings augur well for dynamo models of the solar cycle, they also imply that we need to revisit many aspects of our current understanding if indeed meridional circulation is not as effective as previously thought. For example, our simulations indicate that variations in turbulent pumping speeds can be an effective means for the modulation of solar cycle periodicity and amplitude.

It has been argued earlier that the interplay between competing flux transport processes determines the dynamical memory of the solar cycle governing solar cycle predictability.

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**Figure 8.** Results of solar dynamo simulations (with shallow meridional flow) utilizing an alternate and more complex turbulent pumping profile based on Warnecke et al. (2016). First two plots show the radial and latitudinal variation of turbulent pumping generated by analytic approximations to the Warnecke et al. (2016) results. The butterfly diagram (bottom plot) taken at the base of the convection zone (0.71R_Sun) in our dynamo simulations indicates that solar-like solutions are reproduced with this alternative profile.
(Yeates et al. 2008). If turbulent pumping is the dominant flux transport process, as seems plausible, based on the simulations presented herein, the cycle memory would be short and this is indeed supported by independent studies (Karak & Nandy 2012) and solar cycle observations (Muñoz-Jaramillo et al. 2013). It is noteworthy that on the other hand, if meridional circulation were to be the dominant flux transport process, the solar cycle memory would be relatively longer and last over several cycles. This is not borne out by the observations.

Previous results in the context of the maintenance of solar-like dipolar parity have relied on a strong turbulent diffusion to couple the northern and southern hemispheres of the Sun (Chatterjee et al. 2004), or a dynamo $\alpha$-effect, which is co-spatial with the deep equatorward counterflow in the meridional circulation assumed in most flux transport dynamo models (Dikpati & Gilman 2001). However, our results indicate that turbulent pumping is equally capable of coupling the northern and southern solar hemispheres and aiding in the maintenance of solar-like dipolar parity. This is in keeping with earlier, independent simulations based on a somewhat different dynamo model (Guerrero & de Gouveia Dal Pino 2008).

Most importantly, our results point out an alternative to circumventing the Parker–Yoshimura sign rule constraint (Parker 1955; Yoshimura 1975) in Babcock–Leighton-type solar dynamos that would otherwise imply poleward propagating sunspot belts in conflict with the observations. Brandenburg et al. (1992) and Ossendrijver et al. (2002) had already pointed toward this possibility in the context of mean-field dynamo models. While a deep meridional counterflow is currently thought to circumvent this constraint and force the toroidal field belt equatorward, our results convincingly demonstrate that the latitudinal component of turbulent pumping provides a viable alternative to overcoming the Parker–Yoshimura sign rule in Babcock–Leighton models of the solar cycle (even in the absence of meridional circulation).

We note, however, that our theoretical results should not be taken as support for the existence of a shallow meridional flow, but rather we point out that the turbulent pumping of magnetic flux effectively replaces the important roles that are currently thought to be mediated via a deep meridional circulation within the Sun’s interior. Since the dynamical memory and thus predictability of the solar cycle depends on the dominant mode of magnetic flux transport in the Sun’s interior, this would also imply that physics-based prediction models of long-term space weather need to adequately include the physics of turbulent pumping of magnetic fields.

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