Review

Not peer-reviewed version

Surface Inflows Toward Active Regions in Solar Dynamo Models: A Short Review

Mohammed H. Talafha *

Posted Date: 3 March 2025

doi: 10.20944/preprints202502.2340.v1

Keywords: solar dynamo; flux transport dynamo; solar cycle; magnetic field; meridional flows; surface inflows

Review

Surface Inflows Toward Active Regions in Solar Dynamo Models: A Short Review

Mohammed H. Talafha [1]

Research Institute of Sciences and Engineering, University of Sharjah, Sharjah 27272, UAE; mtalafha901@gmail.com

Abstract: Surface inflows toward solar Active Regions (ARs) are horizontal plasma movements that play a significant role in shaping solar magnetic activity and dynamo processes. This review synthesizes current knowledge on these inflows within solar dynamo frameworks—Babcock-Leighton, Flux Transport, and Mean-Field models highlighting their consistent presence across ARs and their dual impact of enhancing flux cancellation while limiting flux dispersal. Acting as a nonlinear feedback mechanism, inflows modulate polar field buildup and axial dipole amplitude, influencing solar cycle strength, with effects more pronounced in strong cycles. Observational advances, such as helioseismic data and high-resolution imaging, alongside 3D simulations, underscore their ties to meridional circulation and cycle amplitude. Yet, uncertainties remain regarding their drivers—magnetic versus thermal—and their full integration into dynamo models, particularly concerning turbulent pumping and deep flows. This study identifies trends, gaps, and future research directions, emphasizing the critical role of surface inflows in linking local AR dynamics to global solar behaviour.

Keywords: solar dynamo; flux transport dynamo; solar cycle; magnetic field; meridional flows; surface inflows

---

1. Introduction

Both large and small-scale flows govern the magnetic field and surface activity of the Sun. Differential rotation and meridian flow constitute large-scale flows [1–3]. Observations on the solar surface reveal the presence of converging flows surrounding Bipolar Magnetic Regions (BMRs) [4,5]. These inflows collectively generate average flows around the activity belt, [6,7], and their intensity is contingent on the level of flux within the solar cycle, as demonstrated by [7,8]. Additionally, it can reach a substantial fraction of the mean axisymmetric poleward meridional flow at mid-latitudes, but its spatial extent remains confined to the belts where the active regions are located. The magnetic influence on surface flows can induce variations in the transportation of magnetic flux towards the pole, consequently affecting the dynamo efficiency of decaying bipolar active regions. This variation is attributed, at least in part, to surface inflows directed towards large active regions [8–10], which leads to a reduction in the cross-equatorial cancellations of BMRs and suppresses the effectiveness of the Babcock–Leighton process. In the case of a strong solar cycle, this effect becomes more pronounced and imparts a stabilising influence on the dynamo, as demonstrated by [11,12].

Surface inflows toward active regions have been identified also using local correlation tracking of solar granules observed in continuum images. These inflows are characterized by converging flows of about 20-30 m/s, which become visible approximately one day before the emergence of an active region [13]. From one solar cycle to the next, the mean poleward meridional flow changes by about 25%. [14,15].

To modulate the surface inflows toward active regions in the Solar dynamo models, one should identify these models, which can be separated into three main categories:

1. Babcock-Leighton (BL) Dynamo Models: explains the solar cycle through the generation of the poloidal magnetic field near the solar surface and the toroidal field in the solar interior. The coupling of these fields introduces a memory effect, allowing for short-term predictions of solar

 doi:10.20944/preprints202502.2340.v1

activity [16]. The accuracy of these models can be affected by turbulent pumping, which degrades the memory of the dynamo, limiting long-term predictions. Additionally, the depth variation of equatorward flow and strong turbulent diffusivity pose challenges [17]. The recent development of the model was described in [18].

2. Flux Transport Dynamo Models: focus on the transport of magnetic flux by large-scale flows, such as differential rotation and meridional circulation. They are particularly useful for explaining the cyclic nature of solar magnetic activity [19]. The emergence and growth of the flux transport dynamo model of the sunspot cycle were described in [20]. Recent advancements include three-dimensional non-kinematic simulations, which incorporate the emergence of BMRs and their tilt angles, influenced by the Coriolis force [21].
3. Mean-Field Dynamo Models: use mean-field electrodynamics to describe the generation of magnetic fields through the α-effect (helical turbulence) and Ω-effect (differential rotation). They can reproduce irregularities in solar cycles, including grand minima [22]. Incorporating additional turbulent induction effects, such as the $\Omega \times J$ effect, can improve the agreement with observed solar cycle periods and magnetic field concentrations at low latitudes [23]. These models of flux transport dynamo and meridional circulation in the Sun and stars were reviewed by [24].

Solar active regions exhibit complex surface inflows that influence dynamo processes, yet their role remains debated. This short review aims to synthesize current knowledge on these inflows within solar dynamo models, highlight trends in observational and theoretical advances, and identify gaps where further research could refine our understanding of solar magnetic activity.

2. Background

Solar ARs are areas on the Sun with very strong magnetic fields where various solar activities, such as solar flares and coronal mass ejections (CMEs), occur [25,26]. ARs exhibit self-similar structures with fractal dimensions ranging from 1.2 to 1.7, indicating complex magnetic field configurations [27]. The magnetic field in ARs is significantly stronger than in surrounding regions, leading to the formation of giant arches of hot plasma that emit strong UV and X-ray radiation [28]. ARs often host sunspots, which are regions of intense magnetic activity and appear darker due to lower temperatures compared to their surroundings [29]. It typically exhibits opposite magnetic polarity [25]. The locations, areas, heights, and widths of ARs vary and can be analyzed to predict solar activities [30].

Observations from instruments like the Helioseismic and Magnetic Imager (HMI) and the Solar Dynamics Observatory (SDO) provide high-resolution data for monitoring ARs [31,32]. Various models, including those based on deep learning and machine learning, have been developed to predict solar flares and CMEs by analyzing the magnetic and geometric features of ARs [33]. Historical data and statistical models help in understanding the evolution and characteristics of ARs, aiding in the prediction of solar activities [34]

Surface inflows toward ARs feature converging horizontal flows with speeds of roughly 20-30 m/s, becoming noticeable about a day before the active regions appear. These inflows keep developing after the regions emerge, with their strength and reach tied to the region's total magnetic flux. Within the first six days following emergence, the inflows can extend as far as 7° from the centre of the active region, with speeds peaking at 50 m/s. The strength of inflows along the latitude grows with the region's magnetic flux, peaking between one and four days after emergence. These inflows occur consistently, regardless of the active region's latitude or flux, suggesting a predictable pattern. While they boost flux cancellation, this is balanced by reduced flux movement away from the region, as noted in [13].

The inflows act as a saturation mechanism for the global dynamo by decreasing the amplitude of the axial dipole moment [11]. This reduction is more pronounced after strong cycles, supporting the idea that inflows help in saturating the dynamo and modulating the solar cycle [35]. Inflows decrease the amplitude of the axial dipole moment by approximately 30%, relative to a no-inflows scenario. The relative amplitude of the generated axial dipole is about 9% larger after very weak cycles than

 doi:10.20944/preprints202502.2340.v1

after very strong cycles, indicating the non-linear impact of inflows on the solar dynamo [36]. Surface inflows toward ARs provide a nonlinear feedback mechanism that limits the amplitude of the solar dynamo [7]. This feedback is crucial in modulating the strength of solar cycles by affecting the build-up of polar fields and the axial dipole moment [37]. Inflows reduce the tilt angles of bipolar magnetic regions and influence the cross-equator transport of magnetic flux, which in turn affects the amplitude of the solar cycles [11]. The inflows are believed to play a role in the diffusion of the magnetic field within active regions, although the exact mechanisms and effects are still under investigation.

These inflows impede the dispersal of magnetic flux into the surrounding network, influencing the larger-scale and longer-term patterns of the surface magnetic field [38]. Simulations incorporating these inflows show that they lead to a strong correlation between the simulated axial dipole strength and the observed cycle amplitude. This supports the hypothesis that inflows are a key ingredient in determining the amplitude of solar cycles [37]. Inflows into active regions alter the global surface pattern of the meridional circulation, contributing to the observed anti-phase variation with the solar cycle [39]. [40] proposed that the near-surface meridional flow consists of a three-component flow a constant baseline flow, variations due to inflows around active regions, and solar-cycle-scale variations [40].

3. Current understanding and open questions

Meridional flows are essential in transporting magnetic flux from low to high latitudes, influencing the solar cycle's amplitude and period [10,41,42]. These flows are poleward at the surface and equatorward at deeper layers, forming a circulation pattern that is vital for the dynamo process [41–43]. Based on Helioseismic data, the meridional circulation may form multiple cells along the radius in the convection zone, which can significantly impact dynamo models [44]. Incorporating helioseismically inferred meridional flow profiles into dynamo models has shown compatibility with observed solar cycle properties, such as the butterfly diagram and the 11-year cycle period [42]. Helioseismic techniques lack the sensitivity to capture the dynamics of weak large-scale flows deep inside the convection zone. This limitation hinders our understanding of the behaviour of meridional circulation at greater depths [39]

Babcock-Leighton model, which includes surface flux transport and meridional flows, remains a robust framework for explaining solar cycles. These models have been enhanced by including observed surface inflows and their effects on magnetic field evolution [7,35,45]. Surface inflows towards active regions and sunspot zones provide a nonlinear feedback mechanism that limits the amplitude of the solar dynamo, affecting the cycle strength [7]. These inflows modulate the build-up of polar fields by reducing the tilt angles of bipolar magnetic regions and influencing the cross-equator transport of magnetic flux [7]. Observations of inflows around active regions show that these inflows extend up to 30° from the active region centroids. However, excluding active regions reduces the observed solar-cycle-scale variation in the background meridional flow, indicating that more comprehensive coverage is needed to fully understand these variations [40]

Recent studies suggest that even shallow meridional flows when combined with turbulent pumping, can sustain solar-like magnetic cycles, challenging the necessity of deep equatorward flows [45,46]. Advanced 3D dynamo models have been developed to capture the buoyant emergence of tilted bipolar sunspot pairs and cyclic large-scale field reversals [47].

High-resolution observations are necessary to detect and analyze persistent inflows and their impact on solar dynamics. However, even with advanced instruments like the SDO and Hinode, there are challenges in consistently identifying and tracking these inflows over long periods [48]. BL dynamo model needs to incorporate more accurate meridional flow profiles and account for the loss of toroidal flux through the solar surface to align better with observations [42]. The influence of magnetic torques on the global angular momentum distribution and the development of upward flows at mid-latitudes during the solar cycle maximum are not fully captured in conventional kinematic models. [39]. Turbulent pumping, which affects the transport of magnetic flux, is not fully integrated into many solar dynamo models. This mechanism is crucial for understanding the storage and latitudinal distribution of magnetic fields [46]. Non-local convection models often rely on assumptions like the quasi-normal approximation, which may not accurately represent the dynamics in the superadiabatic and quasi-adiabatic layers of the Sun [49]

Several improvements can be proposed to handle the previous aspects and give more robust results. Firstly, developing more sensitive helioseismic methods and combining them with machine learning techniques could improve the detection of internal solar flows and reduce the need for extensive temporal averaging [50]. Secondly, increasing the temporal and spatial resolution of observations, particularly around active regions, can provide better insights into the dynamics of solar surface inflows [40,48]. Thirdly, incorporating more realistic meridional flow profiles, accounting for magnetic field interactions, and integrating turbulent pumping mechanisms can enhance the accuracy of solar dynamo models [42,46].

The exact drivers of solar surface inflows and their feedback on the dynamo process remain unresolved, with ongoing debates about the relative contributions of magnetic forces versus thermal effects. Observations indicate systematic horizontal inflows near the photosphere surrounding active regions, which are likely driven by magnetic forces. These inflows impede the dispersal of magnetic flux, influencing larger-scale patterns and the evolution of the surface magnetic field [7,38]. Additionally, the solar surface exhibits convective motions forming granular patterns, with magnetic fields accumulating in intergranular lanes. These motions, driven by thermal effects, are believed to generate and maintain quiet Sun magnetic features through local dynamo action [11,35]. Numerical simulations show that inflows around regions of concentrated magnetic flux can be driven by reducing the surface temperature as a function of local magnetic flux, indicating a thermal effect [38]. BMR inflows can regulate the amplitudes and periods of magnetic cycles by reducing the buildup of the global poloidal field through local flux cancellation, acting as a nonlinear feedback mechanism that saturates the dynamo [11,35] (i.e. it limits the amplitude of the solar dynamo and determines the variation of cycle strength). This modulation is achieved by reducing the tilt angles of bipolar magnetic regions and affecting the cross-equator transport of magnetic flux [7].

The inclusion of inflows in solar cycle models leads to a strong correlation between the simulated axial dipole strength during activity minimum and the observed amplitude of the subsequent cycle, supporting the role of inflows in modulating the solar cycle [7]

Inflows stabilize cycle characteristics, reducing the scatter in individual cycle amplitudes and enhancing cross-hemispheric coupling, which decreases hemispheric cycle amplitude asymmetries and temporal lags [12]

4. Conclusion

Surface inflows toward solar active regions represent a critical yet complex component of solar dynamics, influencing the evolution of magnetic fields and the broader solar cycle. These inflows, characterized by converging horizontal flows with velocities of 20-30 m/s—peaking at 50 m/s post-emergence—consistently emerge approximately one day before AR formation and persist thereafter, with their strength and spatial extent (up to 7° from AR centres) closely tied to the region's magnetic flux. This review synthesizes observational and theoretical insights, revealing a consistent pattern: inflows are a ubiquitous feature across ARs, regardless of latitude or flux, and they play a dual role by enhancing local flux cancellation while reducing flux dispersal, thus acting as a nonlinear feedback mechanism within solar dynamo processes. In the context of dynamo models Babcock-Leighton, Flux Transport and Mean-Field models, these inflows modulate key processes such as the buildup of polar fields and the axial dipole moment, which ultimately shape cycle amplitude and stability. Notably, their impact is more pronounced in strong cycles, where they contribute to dynamo saturation, while their nonlinear influence is evident in the 9% larger dipole amplitude following weak cycles compared to strong ones. Advanced observations, including helioseismic data and high-resolution imaging from instruments like the Solar Dynamics Observatory, alongside 3D simulations, have

 doi:10.20944/preprints202502.2340.v1

bolstered our understanding by linking inflows to meridional circulation variations and magnetic flux transport. However, gaps persist: the precise drivers of inflows—whether magnetic forces or thermal effects—remain debated, and their integration into dynamo models is incomplete, particularly regarding turbulent pumping and deep meridional flow dynamics. This synthesis highlights the need for refined observational techniques, such as enhanced helioseismic sensitivity and machine learning-driven flow detection, alongside improved model realism incorporating magnetic-thermal interactions and multi-cell meridional profiles. Addressing these gaps could clarify the inflows' role in cycle modulation and enhance solar activity predictions. Ultimately, while significant progress has been made in understanding the drivers and feedback mechanisms of solar surface inflows, the exact contributions of magnetic forces versus thermal effects remain unresolved. Further observational and modelling studies are needed to clarify these mechanisms and their impact on the solar dynamo process.

Funding: This research received no external funding.

Acknowledgments: The author thanks Sharjah Academy for Astronomy, Space Sciences and Technology (SAASST) at the University of Sharjah for providing the necessary resources and infrastructure for this study

Conflicts of Interest: The author declares no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AR	Active Regions
BL	Babcock-Leighton
BMR	Bipolar Magnetic Region
CME	Coronal Mass Ejection
SDO	Solar Dynamics Observatory
HMI	Helioseismic and Magnetic Imager

References

1. Jiang, J.; Cao, J. Predicting solar surface large-scale magnetic field of Cycle 24. *Journal of Atmospheric and Solar-Terrestrial Physics* **2018**, *176*, 34–41.
2. Sanchez, S.; Fournier, A.; Pinheiro, K.J.; Aubert, J. A mean-field Babcock-Leighton solar dynamo model with long-term variability. *Anais da Academia Brasileira de Ciências* **2014**, *86*, 11–26.
3. Jiao, Q.; Jiang, J.; Wang, Z.F. Sunspot tilt angles revisited: Dependence on the solar cycle strength. *Astronomy & Astrophysics* **2021**, *653*, A27.
4. Gizon, L.; Duvall, T.; Larsen, R. Probing surface flows and magnetic activity with time-distance helioseismology. In Proceedings of the Symposium-International Astronomical Union. Cambridge University Press, 2001, Vol. 203, pp. 189–191.
5. González Hernández, I.; Kholikov, S.; Hill, F.; Howe, R.; Komm, R. Subsurface meridional circulation in the active belts. *Solar Physics* **2008**, *252*, 235–245.
6. Jiang, J.; Cameron, R.H.; Schmitt, D.; Schuessler, M. The solar magnetic field since 1700-I. Characteristics of sunspot group emergence and reconstruction of the butterfly diagram. *Astronomy & Astrophysics* **2011**, *528*, A82.
7. Cameron, R.; Schüssler, M. Are the strengths of solar cycles determined by converging flows towards the activity belts? *Astronomy & Astrophysics* **2012**, *548*, A57.
8. Jiang, J.; Işik, E.; Cameron, R.; Schmitt, D.; Schüssler, M. The effect of activity-related meridional flow modulation on the strength of the solar polar magnetic field. *ApJ* **2010**, *717*, 597.
9. Gizon, L. Helioseismology of time-varying flows through the solar cycle. *Solar Physics* **2004**, *224*, 217–228.
10. Cameron, R.; Schüssler, M. Changes of the solar meridional velocity profile during cycle 23 explained by flows toward the activity belts. *The Astrophysical Journal* **2010**, *720*, 1030.
11. Martin-Belda, D.; Cameron, R.H. Inflows towards active regions and the modulation of the solar cycle: A parameter study. *Astronomy & Astrophysics* **2017**, *597*, A21.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 3 March 2025 doi:10.20944/preprints202502.2340.v1

12. Nagy, M.; Lemerle, A.; Charbonneau, P. Impact of nonlinear surface inflows into activity belts on the solar dynamo. *Journal of Space Weather and Space Climate* **2020**, *10*, 62.
13. Gottschling, N.; Schunker, H.; Birch, A.; Löptien, B.; Gizon, L. Evolution of solar surface inflows around emerging active regions. *Astronomy & Astrophysics* **2021**, *652*, A148.
14. Komm, R.; Howard, R.; Harvey, J. Meridional flow of small photospheric magnetic features. *Solar Physics* **1993**, *147*, 207–223.
15. Hathaway, D.H.; Rightmire, L. Variations in the Sun's meridional flow over a solar cycle. *Science* **2010**, *327*, 1350–1352.
16. Nandy, D.; Karak, B.B. Forecasting the solar activity cycle: new insights. *Proceedings of the International Astronomical Union* **2012**, *8*, 439–444.
17. Jiang, J.; Wang, J.; Zhang, J.; et al. What drives the solar magnetic cycle? *Chin Sci Bull* **2016**, *61*, 2973–2985.
18. Karak, B.B. Recent Developments in the Babcock–Leighton Solar Dynamo Theory. *Proceedings of the International Astronomical Union* **2023**, *19*, 87–97. https://doi.org/10.1017/S1743921323005057.
19. Choudhuri, A.R. The origin of the solar magnetic cycle. *Pramana* **2011**, *77*, 77–96.
20. Choudhuri, A.R. The emergence and growth of the flux transport dynamo model of the sunspot cycle. *Reviews of Modern Plasma Physics* **2023**, *7*, 18.
21. Bekki, Y.; Cameron, R.H. Three-dimensional non-kinematic simulation of the post-emergence evolution of bipolar magnetic regions and the Babcock-Leighton dynamo of the Sun. *Astronomy & Astrophysics* **2023**, *670*, A101.
22. Kitchatinov, L. The solar dynamo: Inferences from observations and modeling. *Geomagnetism and Aeronomy* **2014**, *54*, 867–876.
23. Pipin, V. V..; Seehafer, N.. Stellar dynamos with $\Omega \times J$ effect. *A&A* **2009**, *493*, 819–828. https://doi.org/10.1051/0004-6361:200810766.
24. Hazra, G.; Nandy, D.; Kitchatinov, L.; Choudhuri, A.R. Mean field models of flux transport dynamo and meridional circulation in the Sun and stars. *Space Science Reviews* **2023**, *219*, 39.
25. Granados-Hernández, N.; Vargas-Domínguez, S. Analysis of magnetic polarities in active regions for the prediction of solar flares. *Revista de la Academia Colombiana de Ciencias Exactas, Físicas y Naturales* **2020**, *44*, 984–995.
26. Mason, H.; Tripathi, D. Chapter 7: Active Region Diagnostics. In *Physics of the sun and its atmosphere*; Physics of the Sun and Its Atmosphere, World Scientific, 2008; pp. 127–150.
27. Vlahos, L. Solar and Stellar Active Regions A Cosmic Laboratory for the study of Complexity. In Proceedings of the Chaos in Astronomy: Conference 2007. Springer Science & Business Media, 2009, p. 423.
28. Zaffar, A.; Abbas, S.; Ansari, M.R.K. A Study of Largest Active Region AR12192 of 24th Solar Cycle Using Fractal Dimensions and Mathematical Morphology. *Solar System Research* **2020**, *54*, 353–359.
29. Lopez, K.; Cañedo, V.; Cabezas, D.; Buleje, Y. Sunspot characteristics of active regions NOAA 2268 and NOAA 2305. In Proceedings of the Journal of Physics: Conference Series. IOP Publishing, 2018, Vol. 1143, p. 012007.
30. Zhang, T.; Hao, Q.; Chen, P. Statistical Analyses of Solar Prominences and Active Region Features in 304 Å Filtergrams Detected via Deep Learning. *The Astrophysical Journal Supplement Series* **2024**, *272*, 5.
31. Yan-mei, C.; Si-qing, L.; Li-qin, S. Automatic Recognition of Solar Active Regions Based on Real-time SDO/HMI Full-disk Magnetograms. *Chinese Astronomy and Astrophysics* **2021**, *45*, 458–469.
32. Yang, X.; Lin, G.; Deng, Y. A real-time prediction system for solar weather based on magnetic nonpotentiality (I). In Proceedings of the Software and Cyberinfrastructure for Astronomy IV. SPIE, 2016, Vol. 9913, pp. 1410–1415.
33. Guesmi, B.; Daghrir, J.; Moloney, D.; Ortega, C.U.; Furano, G.; Mandorlo, G.; Hervas-Martin, E.; Espinosa-Aranda, J.L. EoFNets: EyeonFlare Networks to predict solar flare using Temporal Convolutional Network (TCN). In Proceedings of the 2024 10th International Conference on Control, Decision and Information Technologies (CoDIT). IEEE, 2024, pp. 1120–1126.
34. Chumak, O.; Zhang, H.Q. Integrated characteristics of the radial magnetic field in solar active regions during quiet and flare-productive phases of their evolution. *Astronomy reports* **2005**, *49*, 755–766.
35. Teweldebirhan, K.; Miesch, M.; Gibson, S. Inflows Towards Bipolar Magnetic Active Regions and Their Nonlinear Impact on a Three-Dimensional Babcock–Leighton Solar Dynamo Model. *Solar Physics* **2024**, *299*, 42.
36. Cameron, R.; Jiang, J.; Schmitt, D.; Schüssler, M. Surface flux transport modeling for solar cycles 15–21: effects of cycle-dependent tilt angles of sunspot groups. *The Astrophysical Journal* **2010**, *719*, 264.

37. Cameron, R.; Jiang, J.; Schüssler, M.; Gizon, L. Physical causes of solar cycle amplitude variability. *Journal of Geophysical Research: Space Physics* **2014**, *119*, 680–688.
38. Hurlburt, N.; DeRosa, M. On the stability of active regions and sunspots. *The Astrophysical Journal* **2008**, *684*, L123.
39. Passos, D.; Miesch, M.; Guerrero, G.; Charbonneau, P. Meridional circulation dynamics in a cyclic convective dynamo. *Astronomy & Astrophysics* **2017**, *607*, A120.
40. Mahajan, S.S.; Sun, X.; Zhao, J. Removal of active region inflows reveals a weak solar cycle scale trend in the near-surface meridional flow. *The Astrophysical Journal* **2023**, *950*, 63.
41. Li, Q.; Xu, Y.; Verma, M.; Denker, C.; Zhao, J.; Wang, H. Study of Global Photospheric and Chromospheric Flows Using Local Correlation Tracking and Machine Learning Methods I: Methodology and Uncertainty Estimates. *Solar Physics* **2023**, *298*, 62.
42. Cloutier, S.; Cameron, R.; Gizon, L. A Babcock-Leighton dynamo model of the Sun incorporating toroidal flux loss and the helioseismically inferred meridional flow. *Astronomy & Astrophysics* **2023**, *680*, A42.
43. Mitra-Kraev, U.; Thompson, M.; Woodard, M. Meridional flow measurements with statistical waveform analysis. In Proceedings of the Proceedings of SOHO 18/GONG 2006/HELAS I, Beyond the spherical Sun, 2006, Vol. 624.
44. Pipin, V.; Kosovichev, A. The mean-field solar dynamo with a double cell meridional circulation pattern. *The Astrophysical Journal* **2013**, *776*, 36.
45. Hazra, S.; Nandy, D. A proposed paradigm for solar cycle dynamics mediated via turbulent pumping of magnetic flux in Babcock–Leighton-type solar dynamos. *The Astrophysical Journal* **2016**, *832*, 9.
46. Guerrero, G.; Dal Pino, E.d.G. Turbulent magnetic pumping in a Babcock-Leighton solar dynamo model. *Astronomy & Astrophysics* **2008**, *485*, 267–273.
47. Kumar, R.; Jouve, L.; Nandy, D. A 3D kinematic Babcock Leighton solar dynamo model sustained by dynamic magnetic buoyancy and flux transport processes. *Astronomy & Astrophysics* **2019**, *623*, A54.
48. Roudier, T.; Švanda, M.; Malherbe, J.; Ballot, J.; Korda, D.; Frank, Z. Photospheric downflows observed with SDO/HMI, HINODE, and an MHD simulation. *Astronomy & Astrophysics* **2021**, *647*, A178.
49. Kupka, F.; Robinson, F. On the effects of coherent structures on higher order moments in models of solar and stellar surface convection. *Monthly Notices of the Royal Astronomical Society* **2007**, *374*, 305–322.
50. Masaki, H.; Hotta, H. Detection of solar internal flows with numerical simulation and machine learning. *Publications of the Astronomical Society of Japan* **2024**, *76*, L33–L38.