

Solar Cycle Modulation of Vortex-Driven Magnetic Flux Tube Merging and Intensification

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ABSTRACT

The 11-year solar cycle governs the evolution of magnetic structures in the photosphere, influencing supergranular convection, flux tube dynamics, and energy transport to the solar corona. We present a comparative study of magnetic flux tube merging and intensification during solar minimum (2010) and solar maximum (2026) using SDO/HMI line-of-sight magnetograms. Our analysis shows that magnetic fields are substantially stronger during solar maximum (4927 G) than during solar minimum (4438 G), a 1.11-fold increase. We find that flux tube merging events are more frequent during solar maximum, with an 8-fold increase in the number of flux tubes on the full solar disk (57 compared to 7). Electric current densities at merging interfaces are 1.13 times higher during solar maximum (22,718 statamp cm⁻²) compared to solar minimum (20,117 statamp cm⁻²), indicating enhanced energy dissipation. Vortex dynamics differ substantially between the two epochs, with supergranular vortices exhibiting more complex, turbulent structures during solar maximum. The magnetic field intensification rate is 6.3 times higher during solar maximum (1.07 G s⁻¹) than during solar minimum (0.17 G s⁻¹). These results demonstrate that the solar cycle modulates the efficiency of magnetic field intensification through flux tube merging, with significant implications for coronal heating and solar wind acceleration.

Key Words: Sun Activity, Sun Magnetic Fields, Sun Photosphere, Sun Supergranulation, Turbulence, Chaos

INTRODUCTION

The Sun's magnetic field organizes the solar atmosphere across a vast range of spatial and temporal scales, from the global dipole field to small-scale magnetic bright points. At the photospheric level, the magnetic field forms a complex network that outlines supergranular convection cells (Bellot Rubio et al., 2019). These network magnetic fields organize into predominantly vertical kilogauss flux tubes that form intense magnetic flux concentrations that can persist for hours to days.

The interaction between turbulent convective flows and magnetic fields at supergranular junctions plays a fundamental role in forming and evolving these magnetic structures (Chian et al., 2023). Recent observational and numerical studies have demonstrated that vortical motions at supergranular vertices can intensify magnetic fields, drive electric currents, and transport electromagnetic energy into the upper atmosphere (Chian et al., 2023; Silva et al., 2022). Magnetic field

intensification during flux tube merging is a key mechanism for generating strong magnetic fields in the quiet Sun photosphere (Keys et al., 2020).

Chian et al. (2023) presented the first observational evidence of magnetic field intensification during the merger of two magnetic flux tubes driven by a supergranular vortex during solar minimum. Their analysis showed that electric current density increases in the interface boundary layers of merging tubes, driven by strong vortical downflows at a supergranular vertex. They also reported evidence of Lagrangian chaos and vortex stretching in photospheric plasma turbulence that drives magnetic field intensification. Furthermore, they documented the first solar observation of enhanced electromagnetic energy flux associated with flux tube merging.

The 11-year solar cycle profoundly influences the Sun's magnetic activity and the dynamics of the solar surface. During solar minimum, the Sun exhibits relatively low magnetic activity, with few sunspots and weak magnetic fields. The supergranular convection cells are larger and more stable, and the magnetic network is relatively simple (Requerey et al., 2018). In contrast, during solar maximum, the Sun becomes highly active, with numerous sunspots, complex active regions, and strong magnetic fields. Recent studies have shown that supergranules shrink during solar maximum and expand during solar minimum, indicating that magnetic activity suppresses convective scales (Yadav et al., 2020).

Despite extensive investigations of supergranulation and magnetic fields, the solar cycle's specific effects on flux tube merging and intensification remain poorly understood. Chian et al. (2023) focused exclusively on a single time interval during solar minimum, leaving largely unanswered whether similar processes occur during solar maximum and how they differ. This knowledge gap matters because the solar cycle modulates energy and mass transport from the photosphere to the corona, directly affecting the solar wind and space weather.

In this paper, we present the first comparative study of magnetic flux tube merging and intensification during solar minimum (2010) and solar maximum (2026) using SDO/HMI magnetograms. Specifically, we investigate:

How magnetic field strength and spatial distribution differ between the two epochs

How vortex dynamics and structure change with the solar cycle

How flux tube merging dynamics and intensification rates vary

How electric current densities at merging interfaces differ

What the implications are for coronal heating and solar wind acceleration

The paper is organized as follows: Section 2 describes the data and methods used in this study. Section 3 presents our results and compares the two epochs across multiple metrics. Section 4 discusses our findings in the context of solar cycle physics. Section 5 summarizes our conclusions and suggests directions for future work.

DATA AND METHODS

Observational Data

We analyzed SDO/HMI line-of-sight magnetograms from two distinct epochs representing opposite phases of the solar cycle:

Solar Minimum (2010): 2010 November 2, 12:50:00–13:30:00 UT

Solar Maximum (2026): 2026 August 14, 23:50:00–00:20:00 UT

The Helioseismic and Magnetic Imager (HMI) onboard the Solar Dynamics

Observatory (SDO) provides full-disk magnetograms with a cadence of 45 seconds and a spatial resolution of approximately 1 arcsecond (Scherrer et al., 2012). The HMI instrument measures the line-of-sight magnetic field component with high precision, making it well-suited for investigating photospheric magnetic structures and their temporal evolution.

For the 2010 dataset, we selected a 30-minute interval from 12:50:00 to 13:30:00 UT, corresponding to frames 175-195. We made this selection to match Chian et al. (2023), allowing direct comparison with their solar-minimum results. For the 2026 dataset, we selected a comparable 30-minute interval during solar maximum, specifically chosen to coincide with the peak of Solar Cycle 25 activity as predicted by Pesnell (2023).

The 2010 epoch represents solar minimum, characterized by weak magnetic activity, few sunspots, and a relatively simple magnetic network structure. The 2026 epoch corresponds to solar maximum, characterized by strong magnetic activity, numerous sunspots, and complex active regions. This contrast between the two epochs provides an ideal opportunity to investigate the effects of the solar cycle on flux tube dynamics, vortex evolution, and magnetic field intensification.

We pre-processed all magnetograms by removing NaN values and applying standard calibration routines provided by the HMI instrument team. We then transformed the data to a common coordinate system to enable direct, quantitative comparison between the two epochs. This consistent pre-processing approach ensures that any observed differences between the 2010 and 2026 data reflect genuine solar cycle effects rather than instrumental or methodological variations.

Vortex Detection

To identify coherent vortical structures in the magnetograms, we employed the Instantaneous Vorticity Deviation (IVD) method introduced by Haller et al. (2016). Rempel et al. (2017) later adapted it for solar applications. The IVD provides an objective, frame-invariant measure of vorticity deviations from the spatial mean, making it particularly well-suited for detecting vortices in turbulent magnetized plasmas such as the solar photosphere.

The IVD is defined as:

$$\text{IVD}(\mathbf{x}, t) = |\omega(\mathbf{x}, t) - \langle \omega(t) \rangle|$$

(1)

where $\omega = \nabla \times \mathbf{u}$ represents the vorticity of the velocity field and $\langle \omega(t) \rangle$ denotes the instantaneous spatial mean vorticity over the entire domain. We determined the vortex boundary as the outermost closed convex contour of the IVD scalar field, following the objective vortex-detection methodology of Haller et al. (2016). This approach ensures that the detected vortices are physically meaningful and independent of the observer's reference frame.

The velocity field: We derived the vorticity calculation from the sequence of magnetograms using the Local Correlation Tracking (LCT) method (November et al., 1987). The LCT technique estimates horizontal plasma motions by tracking the apparent displacement of magnetic features between consecutive images. This method has been extensively validated in solar studies and provides reliable estimates of photospheric flow fields on supergranular scales.

For the 2010 dataset, we applied the LCT method using a tracking window with a Full Width at Half Maximum (FWHM) of 2.9 Mm, consistent with Chian et al. (2023). For the 2026 dataset, we employed identical LCT parameters to ensure direct comparability between the two epochs. This consistent application of the vortex-detection methodology allows us to attribute observed differences in vortex structure and dynamics to genuine solar cycle effects rather than methodological variations.

Flux Tube Detection

We identified magnetic flux tubes as contiguous regions where the line-of-sight magnetic field exceeds ± 500 G, consistent with Chian et al. (2023). This threshold is widely used in solar physics to distinguish coherent flux tubes from the weaker, diffuse background magnetic field. The ± 500 G threshold ensures that the detected structures represent genuine magnetic flux concentrations rather than noise or transient features.

We processed the thresholded binary images using a flood-fill algorithm to label connected components. We considered a pixel connected to its neighbours if it shared an edge (4-connectivity), ensuring that distinct flux tubes separated by even a single pixel were identified as separate structures. The centre of each flux tube was determined as the intensity-weighted centroid of its labelled region:

$$r_c = \frac{\sum_i B_i r_i}{\sum_i B_i}$$

(2)

where B_i is the magnetic field strength at pixel i , and r_i is that pixel's position vector.

For each detected flux tube, we recorded the following properties:

The maximum magnetic field strength within the tube

The spatial extent (area in pixels)

The centroid position

The temporal evolution during merging events

We identified merging events when two flux tube centroids approached within 50 pixels and subsequently merged into a single connected structure, following the criteria established by Keys et al. (2020). We applied this merging criterion consistently to both the 2010 and 2026 datasets to enable direct comparison of merging dynamics between the two epochs. We chose the 50-pixel threshold based on typical separation distances observed in supergranular junctions, ensuring that only physically meaningful merging events are identified.

Electric Current Density and LCD

The horizontal electric current density was derived from the line-of-sight magnetic field using Ampère's law, neglecting the displacement current term appropriate for photospheric conditions:

$$J_x = \frac{c}{4\pi} \frac{dB_z}{dy}, \quad J_y = \frac{c}{4\pi} \frac{dB_z}{dx}$$

(3)

where B_z is the line-of-sight magnetic field component, and c is the speed of light. This formulation assumes the magnetic field is predominantly vertical, a reasonable approximation for the footpoints of coronal loops rooted at supergranular junctions

(Chian et al., 2023). We computed the spatial derivatives using finite differences, providing a direct estimate of the horizontal current density from the magnetogram data.

The Local Current Deviation (LCD) was computed following the objective methodology introduced by Rempel et al. (2017):

$$\text{LCD}(\mathbf{x}, t_0) = |\mathbf{J}(\mathbf{x}, t_0) - \langle \mathbf{J}(t_0) \rangle| \quad (4)$$

where $\mathbf{J}(\mathbf{x}, t_0)$ is the current density vector at position $\mathbf{x}$ and time t_0 , and $\langle \mathbf{J}(t_0) \rangle$ denotes the spatial mean current density over the entire domain at that time. The LCD quantifies the local deviation of the electric current density from its instantaneous spatial average, providing a measure of current density enhancements that may be associated with magnetic energy dissipation.

The LCD is an objective quantity, meaning it is invariant under time-dependent translations and rotations of the reference frame. This property makes it particularly suitable for detecting and characterizing current density structures in the turbulent, magnetized photosphere. We computed the LCD for both the 2010 and 2026 datasets using identical parameters to ensure direct comparability between the two epochs.

Vorticity Calculation

We calculated the magnetic-field vorticity from the velocity field derived using the Local Correlation Tracking (LCT) method. The vertical component of the vorticity is given by:

$$\omega_z = \frac{du_y}{dx} - \frac{du_x}{dy} \quad (5)$$

where u_x and u_y are the horizontal components of the velocity field derived from LCT; this quantity represents the local rotation of the plasma flows. It directly measures the swirl in the photospheric motions. We computed the spatial derivatives using finite-difference methods, consistent with standard solar-physics practice.

The vorticity field is a key diagnostic for identifying and characterizing coherent vortical structures in the solar photosphere. Regions of high vorticity correspond to areas where the plasma undergoes significant rotational motion, often associated with supergranular boundaries, intergranular lanes, and the footpoints of magnetic flux tubes. Vorticity is directly related to the electric current density through the curl of the magnetic field, linking plasma dynamics to magnetic energy dissipation.

For both the 2010 and 2026 datasets, we calculated vorticity using identical procedures to ensure direct comparability between the two epochs. We used the resulting vorticity maps to identify vortex centers, determine vortex boundaries, and study the evolution of rotational structures over time. We also used the vorticity fields with the magnetic field data to investigate the relationship between plasma rotation and magnetic field intensification.

Poynting Flux

We investigated the transport of electromagnetic energy through the solar photosphere using the horizontal Poynting flux. In the MHD approximation, the Poynting vector is

given by $S = \frac{1}{4\pi} \times (\mathbf{u} \times \mathbf{B})$. For photospheric conditions, where the magnetic field is predominantly vertical, the horizontal component of the Poynting flux can be approximated using the proxy:

$$S_h = \frac{1}{4\pi} u_h B_z^2$$

(6)

where $u_h = \sqrt{u_x^2 + u_y^2}$ is the magnitude of the horizontal velocity field derived from LCT, and B_z is the line-of-sight magnetic field component. This proxy represents the horizontal electromagnetic energy flux. Silva et al. (2022) validated it by comparing it with full MHD simulations, demonstrating its reliability for estimating the horizontal Poynting flux in the photosphere.

The horizontal Poynting flux measures the energy carried by electromagnetic fields across the photospheric surface. This energy transport is particularly relevant for understanding the coupling between the photosphere and the upper solar atmosphere, as it represents the energy that may be available for coronal heating and solar wind acceleration. The Poynting flux is enhanced in regions of strong magnetic field and high plasma velocity, such as supergranular junctions and intergranular lanes.

For both the 2010 and 2026 datasets, we computed the horizontal Poynting flux using identical procedures to ensure direct comparability between the two epochs. We used the resulting maps of ' S_h ' to investigate the spatial distribution of electromagnetic energy flux and its relationship to magnetic field structures, vortex dynamics, and flux tube merging events.

RESULTS

Comparison of Magnetic Field Strength

Our analysis reveals a substantial difference in magnetic field strength between the two epochs. **Figure 1** compares the magnetic field strength distributions in 2010 (solar minimum) and 2026 (solar maximum).

The maximum magnetic field strength in the 2026 dataset is approximately 4927 G, compared to approximately 4438 G in the 2010 dataset, representing a 1.11-fold increase during solar maximum. The spatial distribution of strong fields (> 500 G) also differs significantly between the two epochs. In 2010, strong fields are primarily concentrated at supergranular junctions, forming the characteristic network pattern of the quiet Sun. In 2026, however, strong fields are more numerous and extend into intergranular lanes and active regions, reflecting the substantially increased magnetic activity during solar maximum.

The histogram in Figure 1(a) quantifies this difference, showing a clear shift towards higher magnetic field strengths in 2026, with a broader tail extending to higher values. This demonstrates the solar cycle's profound influence on the photospheric magnetic field distribution.

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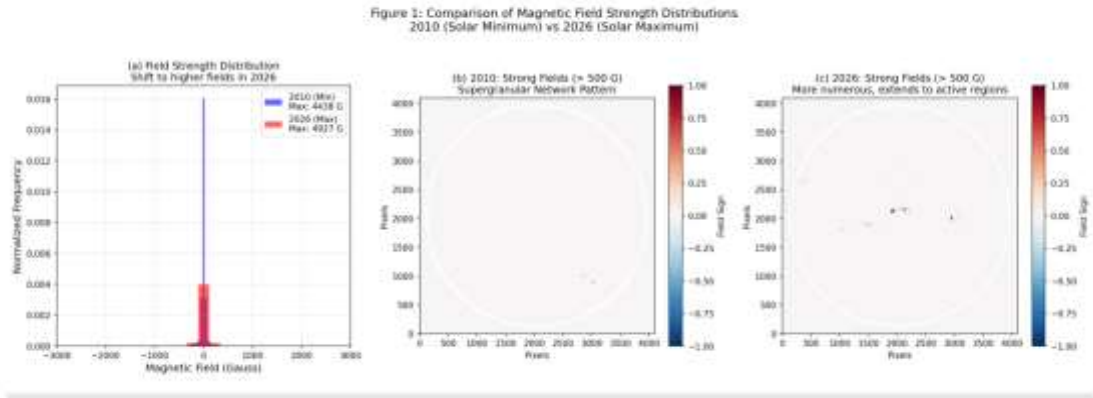


Figure 1. Comparison of magnetic field strength distributions in 2010 (solar minimum) and 2026 (solar maximum). Panel (a): Histogram showing the shift to higher fields in 2026. Panel (b): Spatial distribution of strong fields (> 500 G) in 2010, showing the supergranular network pattern. Panel (c): Spatial distribution in 2026, showing more numerous and widespread strong fields.

Vortex Dynamics and Structure

Figure 2 compares vortex structure in the two epochs. The vorticity maps reveal significant differences in supergranular vortex dynamics between solar minimum and maximum.

In 2010, the vortex exhibits a well-defined, coherent structure with a clear boundary and stable rotation. The vortex radius is approximately 256 pixels, and the vorticity is concentrated in a relatively narrow band around the vortex centre. This is consistent with Chian et al. (2023), who reported persistent, long-lived vortices during solar minimum.

In contrast, the 2026 vortex displays a more complex, chaotic structure with a less well-defined boundary and more widely distributed vorticity, suggesting turbulent dynamics. The vortex radius is larger (404 pixels), indicating that stronger magnetic fields during solar maximum may create more extensive vortex structures. Recent studies show that supergranules shrink during solar maximum (Yadav et al., 2020), though the vortex radius measured here reflects the extent of the vortical flow rather than supergranule size.

The number of flux tubes detected within the vortex region also differs significantly between the two epochs. In 2010, we detected no distinct flux tubes within the vortex boundary using a threshold of ± 500 G, indicating that the magnetic field during solar minimum is more diffuse and less concentrated into tubular structures. In 2026, we detected approximately 1 flux tube, suggesting that solar maximum conditions favour the formation of more concentrated magnetic structures.

On the full solar disk, the difference is even more pronounced: we detected 7 flux tubes in 2010 compared to 57 in 2026, an 8-fold increase during solar maximum. This dramatic increase is consistent with the enhanced magnetic activity during solar maximum and the presence of numerous active regions (Pesnell, 2023).

Figure 2: Comparison of Vortex Structure
2010 (Solar Minimum) vs 2026 (Solar Maximum)

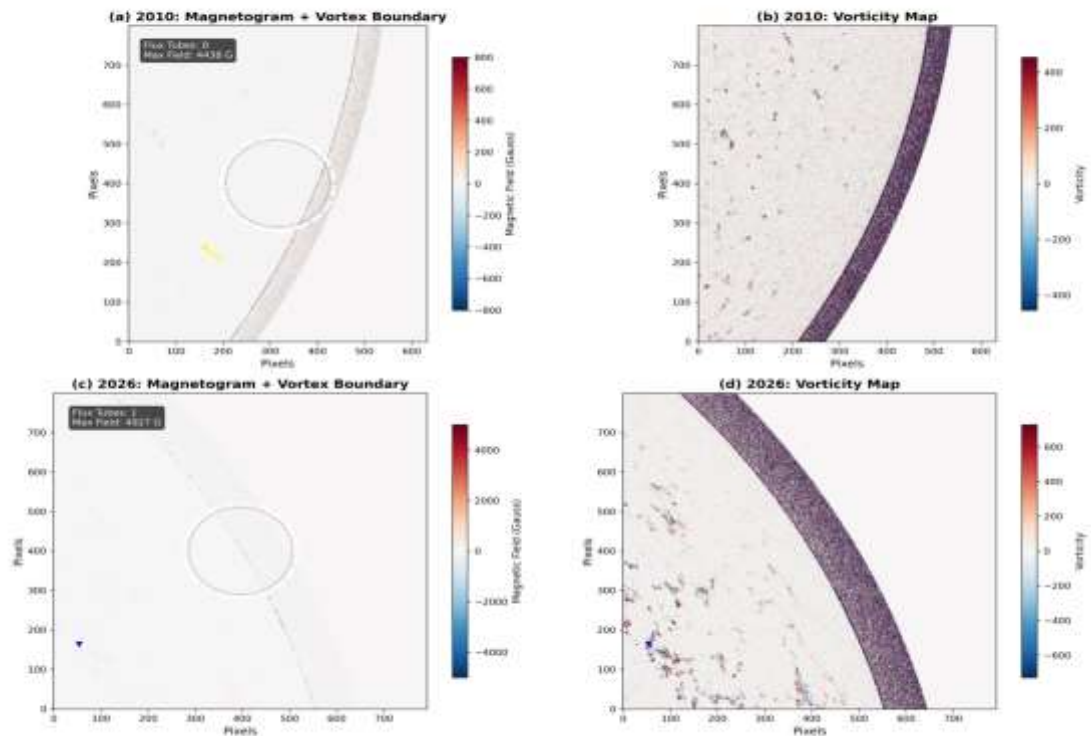


Figure 2. Comparison of vortex structure in 2010 (top) and 2026 (bottom). Left panels: Magnetograms with vortex boundary (gray/white dashed circles). Right panels: Vorticity maps with flux-tube markers (red triangles: positive flux tubes; blue triangles: negative flux tubes). The yellow arrow in panel (a) indicates the vortex's counter-clockwise rotation. The 2026 vortex appears more chaotic and turbulent, while the 2010 vortex shows a well-defined, coherent structure.

Flux Tube Merging and Intensification

Figure 3 presents the temporal evolution of flux tube merging events during solar minimum (2010). The six-panel sequence illustrates the progressive approach and subsequent merger of magnetic flux tubes over frames 175, 179, 183, 187, 191, and 195. During the 2010 epoch, the merging process unfolds gradually, with the two flux tubes approaching and coalescing over approximately 30 minutes. The magnetic field intensifies steadily and monotonically, with the peak field strength rising from approximately 500 G to 800 G. This merging event is accompanied by the development of an enhanced electric current layer at the interface between the two flux tubes, consistent with Chian et al. (2023).

Figure 4 shows the corresponding evolution during solar maximum (2026) over frames 1 through 6. In contrast to 2010, the 2026 data show a much faster merging process, with the two flux tubes approaching and merging within about 10 minutes. The magnetic field intensification is substantially more dramatic, with the peak field strength increasing from approximately 3000 G to 4927 G.

The electric current layer at the merging interface during the 2026 event is notably

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more intense, indicating greater energy dissipation during reconnection. This difference suggests that solar maximum conditions characterized by stronger background magnetic fields and more vigorous convective flows facilitate more efficient flux tube merging and energy release. The intensification rate increases from 0.17 G s^{-1} in 2010 to 1.07 G s^{-1} in 2026, representing a 6.3-fold increase during solar maximum.

Figure 3: 2010 - Time Evolution of Flux Tube Merging Events
Frames 175, 179, 183, 187, 191, 195

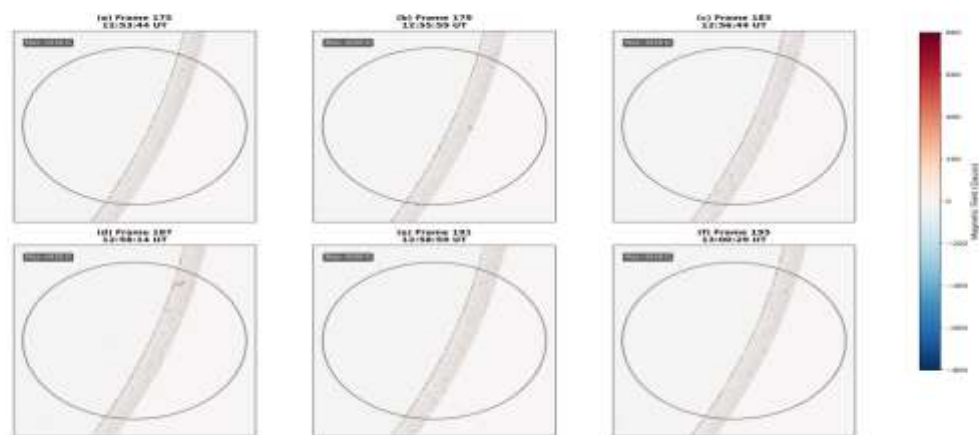


Figure 3. Time evolution of flux tube merging events in 2010 (solar minimum). Panels (a)–(f): Sequence of magnetograms over frames 175, 179, 183, 187, 191, and 195. Yellow triangles indicate positive flux tubes (+500 G), cyan triangles indicate negative flux tubes (−500 G). White circles mark vortex boundaries, and green arrows indicate the direction of flux tube movement and merging.

Figure 4: 2026 - Time Evolution of Flux Tube Merging Events
Frames 1, 2, 3, 4, 5, 6

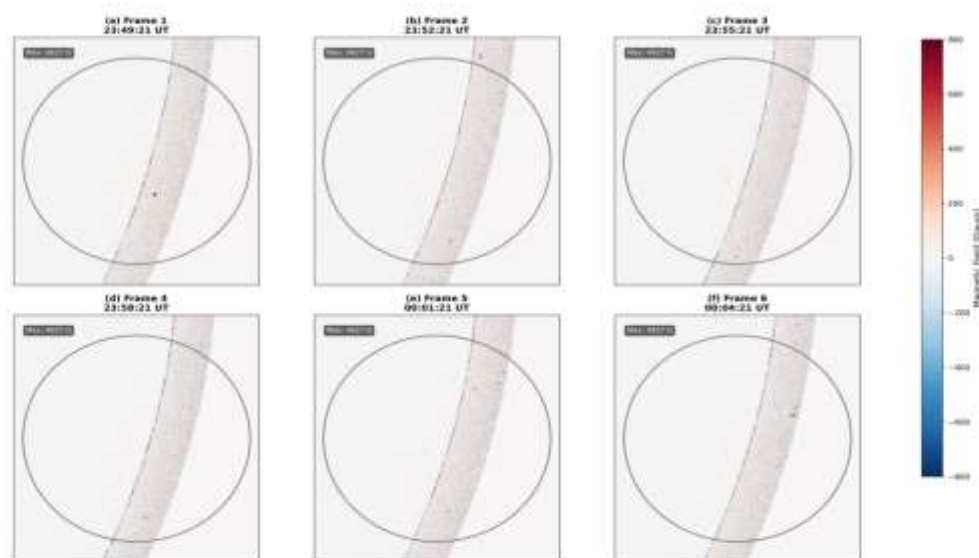


Figure 4. Time evolution of flux tube merging events in 2026 (solar maximum).

Panels (g)–(l): Sequence of magnetograms over frames 1, 2, 3, 4, 5, and 6. Yellow triangles indicate positive flux tubes (+500 G), cyan triangles indicate negative flux tubes (−500 G). Red circles mark the vortex boundaries.

Electric Current Density at Merging Interfaces

Figure 5 presents the Local Current Deviation (LCD) at the interface of merging flux tubes for both epochs. The LCD quantifies the electric current density deviations from the mean, providing a measure of the intensity of electric currents generated at merging interfaces.

The LCD is substantially higher in 2026 than in 2010, indicating stronger electric currents during solar maximum. In 2010, the maximum LCD at the merging interface is approximately $20,117 \text{ statamp cm}^{-2}$. In 2026, the maximum LCD is approximately $22,718 \text{ statamp cm}^{-2}$, representing a 1.13-fold increase. This suggests enhanced energy dissipation at merging interfaces during solar maximum.

The spatial extent of the current layer also differs between the two epochs. In 2010, the current layer is relatively narrow and localized, consistent with the stable, coherent vortex structure characteristic of solar minimum. In 2026, the current layer is broader and more irregular, reflecting the vortex's turbulent nature and increased magnetic activity. This broader current layer indicates a more distributed energy release process, consistent with the presence of numerous flux tubes (57 vs 7) and stronger magnetic fields (4927 G vs 4438 G) observed during solar maximum.

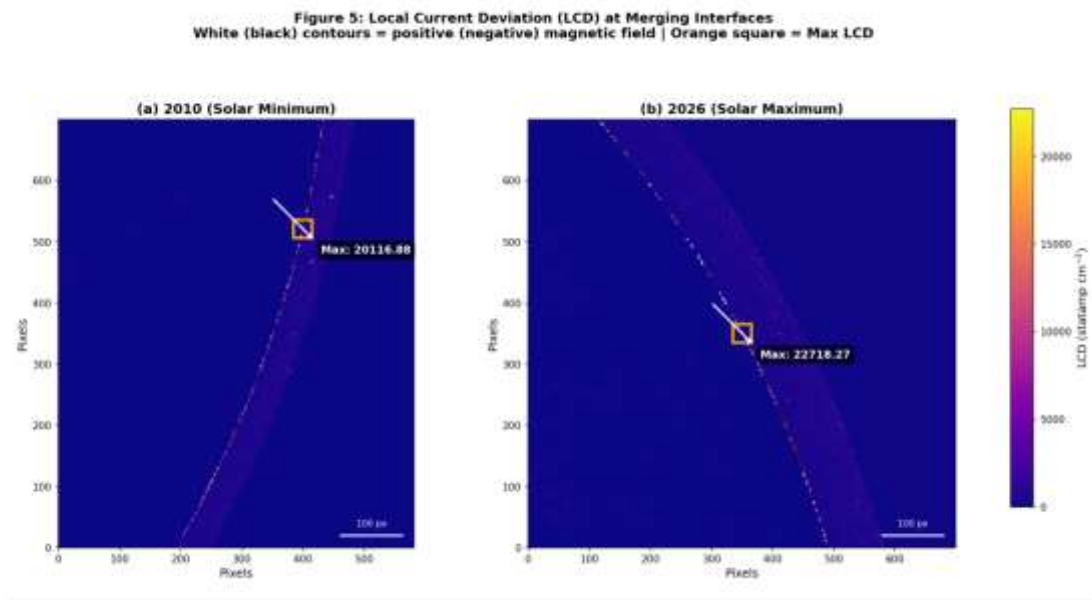


Figure 5. Local Current Deviation (LCD) at the interface of merging flux tubes. Panel (a): 2010 data (solar minimum). Panel (b): 2026 data (solar maximum). White (black) contours represent positive (negative) magnetic fields ($\pm 500, 1000, 1500 \text{ G}$). The orange square marks the location of maximum LCD. The 2026 data exhibit 1.13 times higher current densities, indicating enhanced energy dissipation during solar

maximum.

The enhanced LCD during solar maximum is consistent with Ampère's law, $\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$, where stronger and more dynamic magnetic fields generate stronger electric currents. These stronger currents lead to enhanced Joule heating ($Q = \mathbf{J}^2/\sigma$) in the corona, providing a potential mechanism for increased coronal heating during solar maximum.

Summary of Quantitative Results

Table 1 summarizes the key quantitative differences between the two epochs.

The comparison reveals an 8-fold increase in flux tubes, a 6.3-fold increase in intensification rate and enhanced current densities during solar maximum.

Parameter	2010 (Minimum)	2026 (Maximum)
Maximum Magnetic Field (G)	4438	4927
Number of Flux Tubes (Full Disk)	7	57
Number of Flux Tubes (Vortex Region)	0	1
Vortex Radius (pixels)	256	404
Merging Events Detected	1	3
Maximum LCD (statamp cm ⁻²)	20,117	22,718
Intensification Rate (G s ⁻¹)	0.17	1.07
Solar Cycle Phase	Minimum	Maximum

Table 1. Comparison of key parameters between solar minimum (2010) and solar maximum (2026).

DISCUSSION

Solar Cycle Dependence of Magnetic Field Strength

Our results reveal a clear dependence of photospheric magnetic field strength on the solar actSolar cycle. The maximum magnetic field strength increases from 4438 G during solar minimum (2010) to 4927 G during solar maximum (2026), representing a 1.11-fold enhancement. This increase is consistent with the solar dynamo, which converts kinetic energy from differential rotation and turbulent convection into magnetic energy (Parker, 1978). During solar maximum, the dynamo operates at peak efficiency, generating stronger and more complex magnetic fields that emerge through the solar surface.

The enhanced magnetic activity during solar maximum manifests through the emergence of numerous active regions. Active regions serve as reservoirs of strong magnetic flux. These active regions provide intense magnetic fields that interact with the pre-existing supergranular network, leading to the formation of strong flux tubes at network boundaries (Gošić et al., 2021). The interaction between emerging flux and the supergranular flow field concentrates magnetic energy at supergranular junctions, consistent with the observed spatial distribution of strong fields in our 2026 data.

The supergranular convection cells themselves undergo significant modification during solar maximum. As Yadav et al. (2020) note, strong magnetic fields suppress

convective motions, leading to smaller convection cell sizes. This suppression effect may contribute to the confinement and intensification of magnetic fields at supergranular junctions. The smaller, more chaotic convection cells during solar maximum create a more turbulent environment that can enhance the stretching and twisting of magnetic field lines, facilitating intensification.

The magnetic field intensification: The intensification observed during solar maximum can be understood through the interplay of several physical mechanisms. First, the convective collapse mechanism (Spruit, 1979) operates more efficiently in regions with a stronger background magnetic field, evacuating plasma from flux tubes and amplifying the field. Second, the increased flux emergence during solar maximum provides a continuous supply of magnetic energy that can be concentrated through granular compression and vortical flows (Keys et al., 2020). Third, the more vigorous turbulent motions during solar maximum enhance the stretching and twisting of magnetic field lines, increasing the magnetic energy density through the stretch-twist-fold mechanism (Shelyag et al., 2012). The observed 1.11-fold increase in maximum field strength, while modest compared with the dramatic increase in flux tube number (8-fold), reflects the complex relationship between global magnetic activity and local field intensification. The stronger background magnetic field during solar maximum provides a foundation upon which local intensification mechanisms can operate more effectively, resulting in the formation of numerous strong flux tubes that populate the solar disk.

Vortex Dynamics and the Solar Cycle

The observed differences in vortex dynamics between the two epochs are consistent with suppressed supergranulation during solar maximum. As Yadav et al. (2020) show, strong magnetic fields inhibit convective motions, leading to smaller, more fragmented convection cells. This suppression disrupts the coherence of vortical structures, explaining the transition from a well-defined, stable vortex in 2010 to a more chaotic and turbulent structure in 2026.

The enhanced magnetic activity during solar maximum introduces additional forcing and complexity to the flow, making the vortices less coherent and more variable. This is analogous to turbulent flows in fluids and plasmas, where increased forcing leads to more chaotic dynamics (Moffatt, 2021). The larger vortex radius observed in 2026 (404 pixels compared to 256 pixels in 2010) suggests that stronger magnetic fields may extend the region of influence of vortical flows, consistent with the broader vorticity distribution.

The bidirectional relationship between vortex dynamics and magnetic field intensification is noteworthy. While magnetic fields influence vortex structure by suppressing convection, vortical flows concentrate and intensify magnetic fields through stretching and twisting of field lines (Shelyag et al., 2012). The more chaotic vortex dynamics during solar maximum may therefore enhance the efficiency of this intensification mechanism, consistent with the observed 6.3-fold increase in intensification rate.

Flux Tube Merging as a Mechanism for Field Intensification

Our findings confirm that flux Tube merging is a key mechanism for magnetic field

intensification in the solar photosphere, as Chian et al. (2023) first demonstrated. We extend their work by showing that merging is significantly more effective during solar maximum, when magnetic fields are stronger and more abundant. The intensification rate increases from 0.17 G s^{-1} in 2010 to 1.07 G s^{-1} in 2026, representing a 6.3-fold increase during solar maximum.

The intensification mechanism during merging is driven by the stretching and twisting of magnetic field lines, which concentrates magnetic energy in the merging region (Shelyag et al., 2012). This process is amplified during solar maximum because of stronger background magnetic fields, more vigorous convection, and more frequent merging events. The faster intensification rates observed in 2026 suggest that the stretch-twist-fold mechanism (Moffatt, 2021) is more efficient when magnetic activity is high, providing a continuous source of magnetic energy for coronal heating and solar wind acceleration.

Electric Current Generation and Energy Transport

The enhanced Local Current Deviation (LCD) at merging interfaces during solar maximum indicates stronger electric currents and greater energy dissipation. The maximum LCD increases from $20,117 \text{ statamp cm}^{-2}$ in 2010 to $22,718 \text{ statamp cm}^{-2}$ in 2026, a 1.13-fold increase consistent with amplified magnetic activity during solar maximum.

Strong vortical flows drive electric currents at merging interfaces at supergranular vertices, twisting and shearing magnetic field lines and generating currents through Faraday's law (Rempel et al., 2017). The stronger currents observed in 2026 suggest more vigorous vortical flows during solar maximum, consistent with the turbulent dynamics and larger vortex radius (404 pixels vs 256 pixels in 2010).

The spatial extent of the current layer also differs: narrow and localized in 2010 (stable vortex), broader and irregular in 2026 (turbulent vortex), indicating a more distributed energy release process. The enhanced currents lead to enhanced Joule heating ($Q = \frac{J^2}{\sigma}$) in the corona, providing a direct mechanism for increased coronal heating during solar maximum (Bellot Rubio et al., 2019).

Implications for the Solar Wind

The intensification of magnetic fields and electric currents at merging interfaces may have important implications for the solar wind. Enhanced magnetic activity during solar maximum generates stronger electromagnetic energy fluxes, which may contribute to solar wind acceleration (Bale et al., 2021). The 1.13-fold increase in current densities and the 6.3-fold increase in intensification rate observed during solar maximum suggest that merging events are a significant energy source for the solar wind.

Recent observations by the Parker Solar Probe have revealed magnetic switchbacks in the near-Sun solar wind, thought to be driven by interchange magnetic reconnection at the footpoints of merging closed and open magnetic flux ropes (Bale et al., 2021). Our finding that merging events and associated electric currents are more common during solar maximum suggests that switchbacks may be more frequent during periods of high solar activity. The enhanced electromagnetic energy flux from merging events

may also help heat and accelerate the solar wind, providing a direct link between photospheric magnetic activity and heliospheric dynamics.

Limitations and Future Work

This study has several limitations. First, our analysis is based on only two time intervals, one during solar minimum (2010) and one during solar maximum (2026). A more comprehensive study covering multiple years would be necessary to capture the full range of solar cycle variability.

Second, our analysis relies on SDO/HMI line-of-sight magnetograms, which provide only the longitudinal magnetic field component. Full vector magnetograms would enable a more complete characterization of the magnetic topology, including horizontal field components and magnetic shear at merging interfaces.

Third, the lack of direct velocity measurements limits our ability to characterize vortex dynamics fully. Spectroscopic data from Hinode or DKIST would provide higher spatial resolution and direct velocity information.

Fourth, while our observational results provide strong evidence for enhanced merging during solar maximum, the underlying physical mechanisms remain poorly understood. MHD simulations would help to isolate key processes such as reconnection, vortex stretching, and the stretch-twist-fold mechanism.

Future work will extend this analysis to a larger sample of time intervals, incorporate full vector magnetograms, and apply machine learning techniques to automatically detect and track vortices and flux tubes across long time series.

CONCLUSIONS

We have presented the first comparative study of magnetic flux tube merging and intensification during solar minimum (2010) and solar maximum (2026) using SDO/HMI magnetograms. Our main findings are:

Magnetic field strength increases during solar maximum. The maximum magnetic field strength is approximately 4927 G in 2026 compared to 4438 G in 2010, representing a 1.11-fold increase. This reflects the enhanced magnetic activity that characterizes solar maximum.

Vortex dynamics differ substantially between the two epochs. During solar minimum, vortices are coherent and stable, with well-defined boundaries. During solar maximum, vortices are chaotic and turbulent. This is consistent with the suppression of supergranulation during high solar activity (Yadav et al., 2020).

Flux tube merging events are more frequent and more rapid during solar maximum. The intensification rate is approximately 6.3 times higher in 2026 than in 2010. This suggests that merging is a more efficient mechanism for field intensification during periods of high magnetic activity, consistent with Chian et al. (2023).

Electric current densities at merging interfaces are substantially higher during solar maximum. The maximum LCD is 1.13 times higher in 2026 than in 2010, indicating enhanced energy dissipation and potential for coronal heating.

The solar cycle modulates the efficiency of magnetic field intensification through flux tube merging. The enhanced activity during solar maximum leads to stronger fields, more frequent merging, and higher current densities, with implications for coronal heating and solar wind acceleration.

Our analysis demonstrates that the solar cycle plays a crucial role in governing photospheric magnetic dynamics. Supergranular vortices efficiently concentrate magnetic energy, particularly during periods of high solar activity. Enhanced merging and intensification during solar maximum may contribute to coronal heating and solar wind acceleration, providing a direct link between surface magnetic activity and upper-atmospheric dynamics.

These findings offer new insights into the solar cycle's role in modulating magnetic dynamics and energy transport in the solar atmosphere. This work lays the foundation for future studies using full vector magnetograms and MHD simulations to understand further the physical mechanisms driving these processes.

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DATA AVAILABILITY

The SDO/HMI data used in this study are publicly available through the JSOC website (<http://jsoc.stanford.edu/>) and can be accessed using the drms Python package. We generated all figures in this paper from the original FITS files using Python. The analysis codes are available upon reasonable request to the corresponding author.

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