Hemispheric Asymmetry of Sunspot Groups during Solar Cycles 23-25

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Abstract: We investigate the hemispheric asymmetry of sunspot groups (SGs) during Solar Cycles (SC) 23–25 using daily data from the National Oceanic and Atmospheric Administration/Space Weather Prediction Center (NOAA/SWPC) for the period January 1996 to December 2024. Sunspot groups were classified according to the modified Zurich scheme into small (A, B, H), medium (C), and large (D, E, F) categories, and their temporal evolution was analyzed in terms of sunspot group counts (SGCs), sunspot areas (SSAs), and total sunspot counts (SSCs). A 13-month running average was applied to indicate long-term trends, cross-correlation analysis was used to assess hemispheric relationships and time lags, and the Asymmetry Index (AI) quantified the hemispheric asymmetry. Our main findings are as follows: i) Small sunspot groups (A, B, H) exhibit near symmetry between hemispheres with only minor fluctuations, whereas medium groups (C) reveal alternating dominance that depends on the solar cycle phase, and large groups (D, E, F) display a persistent southern dominance, most notably during SC25. ii) The double-peaked structure of the solar cycle reveals that the first peak is generally dominated by the northern hemisphere, whereas the second peak is governed by the southern hemisphere, indicating phase-dependent hemispheric shifts.

Key words: Hemispheric asymmetry, Solar cycle, Sunspot complexity, Sunspot groups

1. Introduction

The Sun, as the primary driver of space weather, exhibits a wide range of magnetic activity such as solar flares, prominences, sunspots etc., among which sunspots are the most prominent and long-studied indicators of solar activity. These darker regions on the solar photosphere represent the visible signs of concentrated magnetic flux and serve as crucial proxies for examining the dynamics of the solar dynamo. Beyond individual spots, sunspot groups (SGs) that develop and disappear together provide a more comprehensive measure of solar activity. Their morphological properties, such as size, magnetic complexity, and classification, are widely used to track the strength and evolution of solar cycles and to assess flare productivity. While sunspots are widely recognized as the longest indicators of solar activity, their role becomes even clearer when examined as active regions (ARs), where classification schemes help to reveal underlying magnetic structures and evolutionary stages.

ARs, visible as sunspots, represent magnetic structures on the solar surface that evolve with diverse sizes, shapes, lifetimes, and topologies. Their classification is commonly made using the McIntosh classification scheme (McIntosh, 1990), which includes the modified Zurich class (A-H), penumbral class, and compactness. The Zurich classes (A, B, C, D, E, F, H) reflect the scale and magnetic flux of sunspot groups, while compactness provides additional insight into their evolutionary stage and flare productivity. Larger and more compact groups (e.g., D, E, F with complex internal structure) are generally more flare-productive, highlighting the link between morphology, magnetic complexity, and solar activity (Nikbakhsh, Tanskanen, & Hackman, 2025). Although classification captures magnetic complexity and flare potential, understanding solar activity also requires examining how such groups are unevenly distributed across solar hemispheres.

An essential feature of sunspot evolution is their uneven distribution across the northern and southern solar hemispheres, referred to as hemispheric asymmetry. Hemispheric asymmetry refers to the unequal timing, frequency, or intensity of solar features such as sunspots, sunspot areas, solar flares, or magnetic complexity between two hemispheres. The hemispheric asymmetry is commonly characterized using the asymmetry index (AI; Newton & Milsom 1955; Waldmeier 1971), defined as:

$$AI=(N-S)/(N+S) \quad (1)$$

where N and S represent the parameter values (SGCs, SSAs, SSCs) for the northern and southern hemispheres, respectively. Positive values of AI correspond to northern dominance, while negative values indicate southern dominance (Li et al., 2009, Zhang et al., 2015; Wang et al., 2025).

This index has since been widely applied to various solar parameters, including sunspot numbers, areas, solar flare index, etc., (Li et al. 2009; Chowdhury et al. 2013; Roy et al. 2020). Previous analyses reported that the magnitude of asymmetry typically remains within ±0.15 for sunspot-related parameters. For instance, Li et al. (2009) found that the asymmetry index of sunspot groups during SC23 ranged from –0.14 to –0.03, indicating a slight dominance of the southern hemisphere. More recent investigations also revealed

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alternating hemispheric dominance in the modern era: Roy et al. (2020) showed that hemispheric asymmetry in the solar flare index fluctuated around zero throughout SC21–24, while Wang et al. (2025) reported that SC23 was predominantly southern-hemisphere dominated, SC24 showed a tendency toward northern dominance, and the early phase of SC25 exhibited weak asymmetry. Numerous studies have shown that this type of asymmetry is not only common but also dynamically variable throughout solar cycles (Batista et al., 2022; Zhang et al., 2022; Prasad, Roy, and Sarkar, 2024). The size and continuity of this asymmetry provide important insights into the solar dynamo mechanism, underlying meridional flows, and the interaction between sub-surface and surface magnetic structures (Ravindra and Javaraiah, 2015; Muraközy, 2022).

Previous studies have demonstrated that one hemisphere often dominates during certain phases of the solar cycle, and this dominance may persist for months or even years (Chowdhury, Choudhary, & Gosain 2013; Ravindra and Javaraiah, 2015). Such long-lasting asymmetries are not only fundamental for understanding solar dynamo processes but also hold significant consequences for space weather predictions, as they may influence the distribution and intensity of solar flares, coronal mass ejections (CMEs), and solar energetic particles (SEPs). Building on these findings, we focus on SC23–25 to quantify hemispheric asymmetry using group counts, areas, and classifications, thereby providing new insights into cycle-dependent variations.

In this study, we analyze the hemispheric asymmetry of sunspot groups during SC23–SC25 by considering their number, area, and complexity classes. We aim to quantify the extent of the asymmetry, evaluate its temporal evolution across different solar cycle phases, and discuss the possible connection with the underlying solar dynamo processes. The results will provide insights into the role of hemispheric asymmetry as a diagnostic tool for solar cycle dynamics and as a potential contributor to the variability of solar-terrestrial interactions.

2. Data and Methods

The dataset used in this study was obtained from the Space Weather Prediction Center (SWPC) daily records of sunspot activity. The dataset used in this study covers the period from January 1996 to December 2024, encompassing SC23–25. The raw data include several parameters such as the date, NOAA active region number (NOAAAR), heliographic coordinates of sunspot groups (COORD), central meridian longitude (L0), sunspot group area (SSA), Zurich classification (ZURICH), extension (EXT), sunspot number (SSN), and associated flare classification (MCLASS). From these records, we specifically utilized the sunspot group counts (SGCs), sunspot counts (SSCs), and sunspot areas (SSAs). Following the approach of Kilcik et al. (2011), sunspot groups were categorized according to the modified Zurich classification into Small Groups (A, B, H), Medium Groups (C), and Large Groups (D, E, F) in order to investigate the relationship between group size and hemispheric asymmetry.

A 13-step running average was applied to the monthly time series to smooth out short-term fluctuations and emphasize long-term solar activity trends, as this is the standard smoothing method used to define solar maxima and minima in sunspot analyses (Hathaway, 2010). The hemispheric relationship was further examined through cross-correlation analysis, which allowed us to identify the strength of the correlation between the northern and southern hemisphere data sets as well as possible time lags in their peak activities, thereby determining whether one hemisphere systematically leads or lags the other. In addition, the hemispheric asymmetry for each parameter was quantified using the AI as defined in Equation (1) to determine which hemisphere is dominant during each solar cycle.

3. Results

The hemispheric evolution of sunspot group activity across SC23–25 was examined using SGCs, SSAs, and SSCs, categorized into small (A, B, H), medium (C), and large (D, E, F) groups. The results reveal distinct patterns of hemispheric asymmetry depending on the group size and solar cycle phase.

In the top panel, Figure 1 illustrates the temporal variation of small groups in both hemispheres. An ~11-year solar cycle is clearly evident across all parameters, with the northern hemisphere generally reaching peak activity earlier than the southern hemisphere. SC23 shows the strongest amplitudes, SC24 appears weaker, and SC25 exhibits a rising trend. The asymmetry in small group activity remains modest, with AI values mostly within ±0.10 and cross-hemispheric correlations of about $r \approx 0.4–0.5$ (Tables 1 and 2).

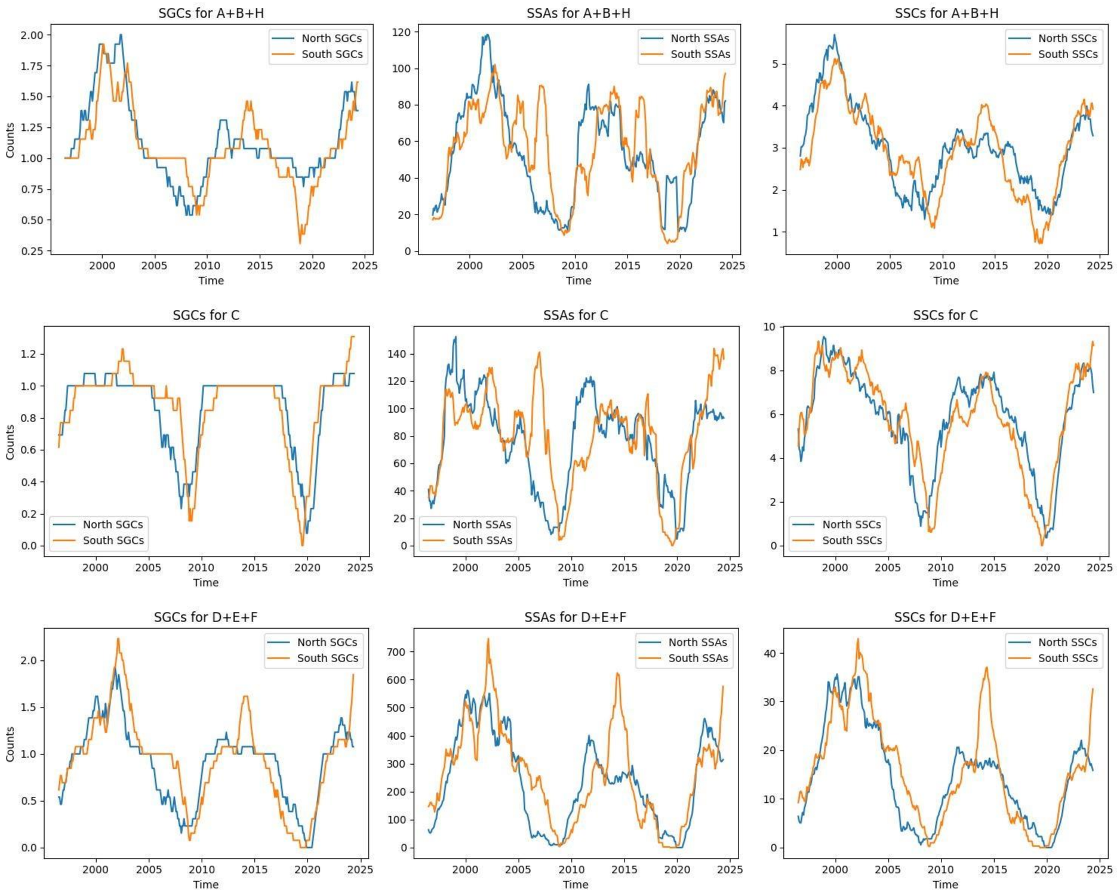

Figure 1. Temporal evolution of sunspot group counts (SGCs, left panels), sunspot areas (SSAs, middle panels), and total sunspot counts (SSCs, right panels) for Small (A+B+H), Medium (C), and Large (D+E+F) sunspot groups, based on 13-month smoothed monthly data from 1996 to 2025. Blue and orange curves denote the northern and southern hemispheres, respectively.

As shown in the middle panel of Figure 1, medium groups display more variable hemispheric behavior. While the ~11-year solar cycle is evident, the timing and intensity of peaks differ between hemispheres. SC23 and SC25 are characterized by stronger activity, whereas SC24 is relatively weak. The asymmetry in medium groups varies with the solar-cycle phase, with AI values ranging from –0.18 to +0.12, indicating alternating hemispheric dominance across cycles. The cross-hemispheric correlations are moderate (r ≈ 0.33–0.47) with variable time lags of up to a few months (–6 to +3 months), suggesting that the leading hemisphere changes between cycles (Tables 1 and 2).

The bottom panel of Figure 1 shows the temporal evolution of large groups. The solar cycle signal is robust across all parameters, with SC23 and SC25 demonstrating strong activity, especially in sunspot areas, while SC24 remains comparatively weak. During SC25, the southern hemisphere exhibits a consistent and pronounced dominance, with AI ≈ –0.16 to –0.18, correlation coefficients up to r ≈ 0.6 (from Tables 1 and 2), and time lags of a few months, indicating that hemispheric asymmetry becomes increasingly significant with larger and more complex groups.

Table 1. Correlation coefficients and their corresponding time delays between northern and southern hemispheres

	A+B+H			C			D+E+F		
	SGC	SSA	SSC	SGC	SSA	SSC	SGC	SSA	SSC
Correlation Coef.	0.41	0.32	0.46	0.47	0.33	0.46	0.53	0.47	0.59
Time Lag (Month)	-8	3	-3	3	3	-6	-4	0	-4

The overall trends are summarized in Table 1, which shows that cross-hemispheric correlations strengthen with increasing group size, while time lags become more systematic, typically with the southern hemisphere leading by several months, indicating enhanced hemispheric coupling in larger structures.

Table 2. Asymmetry index for SC23-SC25

	SC23	SC23	SC23	SC24	SC24	SC24	SC25	SC25	SC25
	SGC	SSA	SSC	SGC	SSA	SSC	SGC	SSA	SSC
A+B+H	0.22	-0.02	-0.01	0.07	0.07	0.06	-0.05	-0.10	-0.07
C	-0.05	-0.02	-0.05	0.09	0.10	0.12	-0.08	-0.18	-0.11
D+E+F	-0.09	-0.10	-0.09	0.04	0.01	0.00	-0.12	-0.16	-0.18

The degree of hemispheric asymmetry, summarized in Table 2, confirms the patterns described above. Small groups (A+B+H) remain nearly symmetric with only minor deviations, medium groups (C) show alternating dominance between cycles, and large groups (D+E+F) display the strongest and most persistent southern dominance, particularly during SC25. Overall, hemispheric asymmetry increases with group size and magnetic complexity, reflecting the dynamic and scale-dependent nature of solar activity.

4. Discussion

In this study, we examined the hemispheric asymmetry of sunspot groups during Solar Cycles 23–25 by analyzing sunspot group counts (SGCs), sunspot areas (SSAs), and total sunspot counts (SSCs) categorized according to the modified Zurich classification. The key findings can be summarized as follows:

- Small sunspot groups (A, B, H) exhibit near symmetry between hemispheres with only minor fluctuations, whereas medium groups (C) reveal alternating dominance that depends on the solar cycle phase, and large groups (D, E, F) display a persistent southern dominance, most notably during SC25.
- The double-peaked structure of the solar cycle reveals that the first peak is generally dominated by the northern hemisphere, whereas the second peak is governed by the southern hemisphere, highlighting phase-dependent hemispheric shifts.
- Cross-correlation analysis confirms stronger hemispheric coupling and systematic time lags in larger groups.
- Asymmetry index values indicate that hemispheric asymmetry intensifies with group size and magnetic complexity.
- The presence of the ~11-year cyclic behavior in all group categories indicates that hemispheric asymmetry evolves in step with the Schwabe cycle, though its magnitude and persistence vary with group size.

The near-symmetric behavior of small groups (A, B, H) suggests that ephemeral and short-lived magnetic structures contribute almost equally to both hemispheres. Their limited lifetimes and simple magnetic configurations likely prevent them from sustaining long-term dominance. Similar conclusions were reported by Kilcik et al. (2011), who found that large groups provide more meaningful insight into solar cycle variability, whereas small groups contribute comparatively little. In contrast, large groups display a persistent southern dominance, especially during SC25, consistent with earlier studies indicating that hemispheric asymmetry is a systematic feature of solar activity rather than random variability (Zou et al. 2014; Nepomnyashchikh et al. 2019). Medium-sized groups show transitional behavior, alternating hemispheric dominance across cycles, suggesting a phase-dependent sensitivity.

The persistent southern dominance of large groups (D, E, F), particularly during SC25, highlights the role of magnetically complex active regions in amplifying hemispheric asymmetry. Such regions are typically associated with enhanced flare productivity and the emergence of strong magnetic flux.

Another key feature is the double-peaked structure of solar cycles, where the first peak is usually dominated by the northern hemisphere and the second by the southern, consistent with recent analyses of SC24 (Joshi & Chandra 2020). These systematic phase lags indicate that the two hemispheres evolve semi-independently, with coupling that is strong but incomplete.

The statistical analyses support these findings: correlation coefficients reveal stronger hemispheric coupling in larger groups, and systematic time lags confirm delayed responses between hemispheres. Similar phase lags were reported by Norton & Gallagher (2010) and Temmer et al. (2006), who emphasized the dynamic, cycle-dependent nature of hemispheric evolution. The AI values obtained here further show that asymmetry strengthens with increasing group size and magnetic complexity, reaching its maximum during SC25, consistent with the general behavior reported by Joshi et al. (2009) for SC23, suggesting that stronger cycles tend to exhibit more pronounced hemispheric asymmetry.

Our findings are consistent with Tirnakci et al. (2025), who demonstrated that higher magnetic complexity enhances flare productivity. Together, these results suggest that hemispheric asymmetry intensifies with group size and magnetic complexity and that phase-dependent hemispheric shifts are linked to quasi-biennial and mid-term periodicities, implying that hemispheric asymmetry is a multi-scale phenomenon.

Overall, the results point to incomplete hemispheric coupling within the solar dynamo, where large and complex magnetic structures amplify existing imbalances. This has important implications for understanding subsurface processes such as meridional flows and flux transport, as well as for improving long-term solar cycle predictions.

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6. References

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