REVIEWER'S REPORT

Manuscript No.: IJAR-56266

Title: Superposed epoch analysis of Magnetospheric Convection Electric Field during geomagnetic storms due to High Speed Solar Wind during solar cycle 24

Recommendation:
<mark>Accept as it is</mark>

Rating	Excel.	Good	Fair	Po
Originality		√		
Techn. Quality		√		
Clarity		√		
Significance			√	

Reviewer Name: Dr. Manju M

Detailed Reviewer's Report

1. Objective of the Study

The primary objective is to examine how the magnetospheric convection electric field varies across storm phases. The analysis aims to link these variations to solar wind parameters. Particular attention is given to the role of IMF Bz orientation and solar wind velocity. Another goal is to quantify how input energy evolves throughout storm progression. By integrating statistical methods, the study seeks average patterns rather than isolated cases. This improves reliability of conclusions. Ultimately, the objective is to clarify phase-dependent magnetospheric behavior

2. Study Background and Scientific Context

Geomagnetic storms represent large-scale disturbances in near-Earth space caused by solar wind–magnetosphere coupling. Understanding their internal dynamics is essential for predicting space-weather hazards. During solar cycle 24, high-speed solar wind streams became frequent drivers of moderate storms. These storms differ fundamentally from CME-driven events in structure and temporal evolution. Their prolonged interaction with Earth's magnetosphere produces distinct electric field behavior. Investigating these processes provides insight into magnetospheric energy circulation. This study therefore focuses specifically on storms linked to high-speed solar wind conditions.

3. Research Motivation

Previous research has extensively analyzed CME-driven storms, leaving high-speed stream storms comparatively understudied. Yet these events occur more frequently during declining solar cycle phases. Their moderate intensity and long duration make them important for cumulative magnetospheric effects. Scientific gaps remain regarding their electric field evolution and energy transfer efficiency. Addressing

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this gap enhances predictive understanding of magnetospheric convection. The work responds directly to this need by applying a phase-resolved statistical method. This ensures systematic evaluation of storm dynamics.

4. Significance of Investigating MCEF

The convection electric field governs large-scale plasma circulation inside the magnetosphere. Variations in this field directly influence particle transport and auroral processes. Understanding MCEF evolution helps interpret magnetospheric energy redistribution. It also supports modeling of radiation belt dynamics. Since electric fields respond rapidly to solar wind changes, they are excellent diagnostic parameters. Studying them during storms reveals internal system responses. Therefore, MCEF analysis provides a sensitive indicator of magnetospheric state.

5. Selection of Solar Cycle 24 Period

The investigation covers years 2008–2018, corresponding to solar cycle 24. This cycle displayed relatively low overall activity but frequent high-speed streams. Such conditions are ideal for isolating HSSW-driven storms. Using an entire cycle ensures statistical representativeness. It avoids bias from short-term solar variability. The selected period also includes both maximum and declining phases. This enables comparison across different solar conditions. Thus, the time span strengthens reliability of results.

6. Data Sources and Reliability

All solar wind and geomagnetic parameters were obtained from a standardized space-physics database. These datasets provide consistent time resolution and calibrated measurements. High temporal resolution ensures accurate storm phase identification. Using established databases guarantees reproducibility. It also allows comparison with earlier studies. Data integrity is crucial for statistical analysis. Therefore, careful selection of validated datasets underpins the study's credibility.

7. Parameters Used in Analysis

Key parameters include solar wind velocity, IMF Bz, electric field Ey, particle density, AE index, and SymH index. Each variable represents a different physical aspect of solar-terrestrial interaction. Velocity measures driving strength, while Bz controls reconnection conditions. Particle density indicates plasma supply. AE tracks auroral activity, and SymH reflects ring current intensity. Combining them gives a multidimensional view of storms. This integrated parameter set enables comprehensive interpretation.

8. Storm Identification Criteria

Storms were defined using quantitative SymH thresholds. The beginning was marked by values below −60 nT, and the end above −20 nT. This ensured consistent event selection. Applying strict criteria reduced ambiguity in classification. It also guaranteed that only significant disturbances were included.

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Uniform thresholds allow meaningful statistical averaging. Such methodological rigor strengthens the validity of comparisons. Consequently, identified storms represent true geomagnetic events.

9. Storm Intensity Classification

Events were categorized into low, moderate, intense, and superstorm classes. This classification relied on minimum SymH values. Most selected events fell into low or moderate categories. This matches expectations for HSSW-driven storms. Including intensity grouping helps interpret parameter responses. It also enables comparison across strength levels. Such stratification clarifies how storm magnitude influences magnetospheric dynamics.

10. Filtering for High-Speed Solar Wind Events

To isolate HSSW storms, events were cross-checked with independent catalogs of solar wind structures. Storms linked primarily to CMEs were excluded. This ensured the sample represented only high-speed stream influences. Such filtering avoids mixed-driver contamination. It also improves physical interpretation of results. Restricting the dataset strengthens cause-effect relationships. Thus, conclusions specifically describe HSSW storm behavior.

11. Storm Phase Segmentation

Each storm was divided into initial, main, and recovery phases. These phases correspond to characteristic SymH variations. Segmenting events allows phase-specific analysis. Different physical processes dominate each stage. For instance, energy injection peaks during the main phase. Recovery reflects gradual system relaxation. Phase division therefore provides a structured analytical framework. It enables detailed temporal interpretation.

12. Challenge of Variable Storm Durations

Storms differ greatly in length and intensity. Direct averaging would distort trends because timelines do not align. This variability complicates statistical comparisons. Without normalization, early or late phases could be misrepresented. A method was therefore required to standardize time scales. Addressing this issue is essential for meaningful ensemble analysis. The chosen solution was superposed epoch analysis with normalization.

13. Principle of Superposed Epoch Analysis

Superposed epoch analysis aligns multiple events relative to a common reference time. Each storm is rescaled to a standard interval. This allows averaging across many events simultaneously. The technique highlights common patterns while suppressing noise. It is widely used in space physics. Applying it here ensures robust statistical trends. Thus, it provides a powerful framework for storm comparison.

14. Time Normalization Procedure

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Each phase interval was mathematically transformed into a 0–1 scale. This process converts different durations into comparable segments. A value of zero represents phase start, and one represents its end. Normalization allows direct alignment of storm phases. It also preserves relative temporal evolution. This step is crucial for consistent binning. Consequently, it standardizes all events for analysis.

15. Binning Strategy for Statistical Calculation

Normalized intervals were divided into equally spaced bins. Each bin represents a portion of phase evolution. Statistical measures such as mean and median were calculated for each bin. This approach smooths fluctuations while preserving trends. Separate bin counts were used for different runs. This ensured appropriate resolution for each phase comparison. The binning method therefore supports precise statistical evaluation.

16. Multiple Analytical Runs

Four separate runs were conducted to compare different phase combinations. These included IP–MP, MP–RP, IP+MP–RP, and IP–(MP+RP). Each run highlights distinct physical transitions. Comparing outputs reveals how parameters evolve across boundaries. Multiple perspectives reduce interpretational bias. They also uncover hidden relationships. Running several configurations thus enriches the analysis.

17. Determination of MCEF Values

The convection electric field was calculated from interplanetary electric field components. A validated empirical relationship was applied. This formula links Ey and solar wind speed with IMF Bz. Using an established expression ensures accuracy. It also allows comparison with earlier literature. Derived MCEF values therefore represent realistic magnetospheric conditions. Reliable calculation is fundamental for subsequent interpretation.

18. Calculation of Energy Input Components

Energy transferred from solar wind to magnetosphere was computed using a coupling function. This function incorporates density, velocity, magnetic field magnitude, and clock angle. The total energy was separated into reconnection and other contributions. This decomposition reveals different transfer mechanisms. Reconnection dominates when IMF is southward. Other processes act when IMF is northward. Such separation clarifies physical drivers.

19. Results from Initial–Main Phase Analysis

During the initial phase, most parameters remained near zero, indicating quiet conditions. As Bz turned southward, all parameters rose sharply. This marked entry into the main phase. Particle density peaked briefly before declining. The decline suggests particle loss from the magnetosphere. Meanwhile, electric field and energy increased gradually. These patterns illustrate the onset of storm-driven convection.

20. Behavior During Main–Recovery Transition

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At the minimum SymH value, the main phase ended and recovery began. Parameters such as AE and MCEF reached maximum values shortly before this transition. During recovery, they decreased steadily. However, they did not return fully to pre-storm levels. This indicates residual convection. Remaining energy persists after storm peak. Thus, recovery is slower than energy injection.

21. Combined Initial–Main Versus Recovery Analysis

When initial and main phases were analyzed together, parameters increased simultaneously. During recovery, they decreased in parallel. This synchronized behavior indicates coordinated system response. The magnetosphere acts as an integrated system rather than independent regions. Notably, post-storm values remained above pre-storm levels. This suggests incomplete relaxation. Hence, storms leave lasting magnetospheric signatures.

22. Full-Storm Evolution Findings

Across the entire storm timeline, parameter peaks coincided with Bz turning southward. Auroral activity intensified immediately. Energy input components rose rapidly. Particle density peaked earlier than other parameters. During recovery, all variables declined gradually. Nevertheless, stabilization occurred above initial baselines. This confirms that storms modify magnetospheric conditions. Their influence persists beyond the event.

23. Evidence of Substorm Activity

Sharp increases in auroral electrojet index indicated substorm onset. These occurred mainly during the main phase. Such timing confirms theoretical expectations. Substorms represent rapid energy release episodes. Their presence explains sudden parameter fluctuations. Observations therefore validate established magnetospheric models. Substorm detection strengthens interpretation of electric field variations.

24. Interpretation of Energy Dissipation

Analysis shows that injected energy is not fully dissipated by storm end. Residual values persist into late recovery. This implies slow internal redistribution processes. Tail reconnection and particle transport contribute to gradual relaxation. The magnetosphere therefore retains memory of disturbances. Such persistence is important for space-weather forecasting. It indicates delayed system stabilization.

25. Scientific Significance of Findings

The study demonstrates that HSSW-driven storms produce distinct electric field patterns. Their convection persists longer than expected. Results confirm that storm phase strongly controls parameter behavior. They also highlight the importance of IMF orientation. These insights improve understanding of solar wind coupling. They contribute to theoretical modeling. Overall, the findings advance knowledge of magnetospheric dynamics.

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26. Recommendations and Future Work

Future studies should include larger storm samples for stronger statistics. Incorporating satellite observations could refine spatial interpretation. Extending analysis to additional solar cycles would test universality. Coupling results with numerical simulations may reveal causal mechanisms. Monitoring residual energy after storms is especially important. Improved modeling could enhance forecasting accuracy. Continued research will deepen understanding of solar-terrestrial interactions.