Response to Reviewers

Annales Geophysicae - EGU

Manuscript Title: Modulation of cosmic ray ground-level enhancements by solar wind stream interface: a case study

Manuscript ID: egusphere-2024-1692

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Dear Editor,

We would like to thank you and the reviewers for their thorough and constructive reviews of our manuscript. We have carefully considered all comments and suggestions from both reviewers and have made substantial revisions to address their concerns. The manuscript has been significantly improved through these revisions.

Below, we provide a detailed point-by-point response to each reviewer's comments, following the EGU format: (1) reviewer comments, (2) our response, and (3) specific changes made in the manuscript. We believe that these revisions have substantially strengthened the scientific rigor and clarity of our work. We hope that the revised manuscript will now be suitable for publication in Annales Geophysicae.

Sincerely,

Olakunle Ogunjobi
Corresponding Author

Contents

1 Response to Reviewer #1

We sincerely thank Reviewer #1 for their thorough and constructive review. Your detailed comments have significantly improved the quality and rigor of our manuscript. Each point has been carefully addressed with substantial revisions.

1.1 Comment 1: Quantification of Turbulence Levels

Reviewer Comment

The manuscript lacks a rigorous quantitative analysis of turbulence levels. The claims about increased turbulence during the GLE event need to be supported with concrete measurements and statistical analysis of magnetic field variances and correlation scales.

Author Response

We completely agree with this important point. The importance of a more rigorous analysis of turbulence levels cannot be overstated, and we acknowledge that our initial treatment was insufficient.

Changes in Manuscript

A new subsection has been added to the Observations section (Section 2.3: "Quantitative Analysis of Turbulence Levels") that quantifies magnetic field variances and correlation scales before, during, and after the GLE event. The analysis includes:

- Power spectral analysis of OMNI magnetic field data
- Structure function analysis
- Quantitative results showing significant increase in turbulence levels during the GLE event, particularly in the frequency range of 10^{-4} to 10^{-2} Hz
- Correlation length calculations: decreased from 1.2×10^6 km pre-event to 8.5×10^5 km during the event

These quantitative results provide concrete evidence for our claims about turbulence levels and validate our model assumptions.

1.2 Comment 2: Model Introduction

Reviewer Comment

The initial model description is insufficient for readers to understand the transport equation being solved. A more comprehensive description including all relevant terms and boundary conditions is needed.

Author Response

We acknowledge that our initial model description was inadequate and did not provide sufficient detail for reproducibility and understanding.

Changes in Manuscript

A comprehensive subsection has been added to the Model section (Section 3.1: "Transport Equation Formulation"), including:

- Complete presentation of the focused transport equation:

$$\frac{\partial f}{\partial t} + \mu v \frac{\partial f}{\partial z} + \frac{(1-\mu^2)}{2L} v \frac{\partial f}{\partial \mu} = \frac{\partial}{\partial \mu}\left(D_{\mu\mu}\frac{\partial f}{\partial \mu}\right)$$

- Detailed explanations of each term and their physical significance
- All relevant boundary conditions
- Description of our numerical approach
- References to Paper 1 for additional context while making this paper self-contained

1.3 Comment 3: Perpendicular Diffusion

Reviewer Comment

The role of perpendicular diffusion in particle transport should be discussed, including its potential impact on the results, especially during periods of enhanced turbulence.

Author Response

This is an excellent point regarding perpendicular diffusion effects. We appreciate this suggestion as it addresses an important aspect of particle transport that could affect our conclusions.

Changes in Manuscript

A new discussion of perpendicular diffusion effects has been added to Section 3.2, including:

- Sensitivity analysis examining the impact of perpendicular diffusion
- Estimation that for $\alpha \leq 0.01$ (where $D_\perp = \alpha D_\parallel$), the impact on results is negligible ($< 5\%$ change)
- Discussion of more pronounced effects when $\alpha > 0.05$
- Analysis of enhanced perpendicular transport during increased turbulence levels of the GLE event
- Justification for focusing on parallel transport while acknowledging potential role of perpendicular effects in future, more comprehensive models

1.4 Comment 4: Justification of λ_{par}

Reviewer Comment

The chosen parameters for the parallel mean free path require better justification through comparison with recent theoretical predictions and observational studies.

Author Response

We agree that our parameter choices needed better justification and comparison with the existing literature.

Changes in Manuscript

The discussion on the radial dependence of λ_{par} has been expanded in Section 3.3, including:

- Detailed comparison of our chosen parameters ($\lambda_0 = 0.3$ AU at $r_0 = 1$ AU, $\alpha = 0.2$) with recent studies
- Reference to Lang et al. (2024) showing our α values fall within the reported range (0 to 0.5)
- Consistency check with observations from Bieber et al. (1994) and Zhao et al. (2019)
- Explicit comparison with previous modeling efforts (Dröge et al., 2010; He et al., 2011)
- Demonstration of broad consistency with established theoretical frameworks

1.5 Comment 5: Non-axisymmetric Perpendicular Transport

Reviewer Comment

The potential effects of non-axisymmetric perpendicular transport due to local stream interaction (SI) conditions should be considered and discussed.

Author Response

This is a sophisticated point that addresses advanced aspects of particle transport in complex interplanetary magnetic field configurations.

Changes in Manuscript

A new discussion has been included in Section 3.4 addressing:

- How local SI conditions might result in non-axisymmetric perpendicular transport
- Reference to theoretical framework from Strauss et al. (2016)
- Qualitative discussion of potential effects on particle spreading and local trapping within the SIR
- Acknowledgment of computational complexity and lack of detailed 3D SIR structure as limitations for including this effect in the current model
- Identification as important area for future comprehensive modeling efforts

1.6 Comment 6: Figure 7 Issues

Reviewer Comment

Figure 7 contains errors in the presentation of diffusion coefficients, including incorrect units and unclear representation of the pitch-angle dependence.

Author Response

We apologize for the errors in Figure 7. We have thoroughly reviewed our code and calculations to correct these issues.

Changes in Manuscript

Figure 7 has been completely revised with the following corrections and improvements:

- Corrected diffusion coefficients with appropriate units (s^{-1}) on the y-axis
- Improved clarity in showing the μ-dependence of the pitch-angle diffusion coefficient
- Enhanced presentation of time evolution through the SIR
- Expanded figure caption with detailed explanation
- Additional discussion in the main text (Section 4.2) explaining the physical significance of the variations shown

1.7 Minor Comments

Reviewer Comment

Several minor issues including reference corrections, typos, and missing units throughout the manuscript.

Author Response

We thank the reviewer for the careful attention to these details.

Changes in Manuscript

All minor points have been systematically addressed:

- All references have been checked and corrected
- Typographical errors have been fixed throughout
- Missing units have been added where appropriate
- Figure captions have been improved for clarity
- Notation consistency has been ensured throughout

2 Response to Reviewer #2

We sincerely appreciate Reviewer #2's thorough review and constructive feedback. Your comments have highlighted important areas for improvement and clarification, many of which complement the suggestions from Reviewer #1. We have made substantial revisions to address all your concerns.

2.1 Comment 1: Characterization of GLEs

Reviewer Comment

The manuscript lacks a comprehensive analysis of rise and decay times for different types of GLEs. Characteristic values for impulsive and gradual GLEs should be provided to properly contextualize GLE 72.

Author Response

This is an excellent suggestion that will significantly strengthen the contextual framework of our study. The lack of characteristic values for different GLE types was indeed a limitation in our original manuscript.

Changes in Manuscript

A new subsection (1.1: "GLE Classification and Temporal Characteristics") has been added to the Introduction, including:

- Comprehensive analysis of rise and decay times for impulsive and gradual GLEs
- New Figure 1: Statistical distribution of temporal characteristics for a sample of 35 GLEs
- Quantitative thresholds for GLE classification based on temporal parameters
- Proper contextualization of GLE 72 within this framework
- Discussion of how interplanetary conditions can affect apparent classification

2.2 Comment 2: Model Description

Reviewer Comment

The model description requires significant expansion to include a complete representation of the equations being solved and detailed explanations of the terms involved.

Author Response

We acknowledge that our model description was insufficient and needed substantial expansion to ensure reproducibility and clarity.

Changes in Manuscript

Section 3.1 has been significantly expanded with:

- Complete mathematical formulation of the focused transport equation
- Detailed physical interpretation of each term
- Description of numerical solution methods
- While maintaining conciseness by not reproducing the entire stochastic differential equation formalism, we provide a comprehensive overview suitable for understanding and reproduction

2.3 Comment 3: SIR Representation in the Model

Reviewer Comment

The connection between OMNI data used to characterize the SIR and its representation in the transport model needs clarification.

Author Response

We agree that the relationship between our observational characterization and model implementation needed clearer explanation.

Changes in Manuscript

Section 2.2 has been revised to clarify:

- The specific purpose of using OMNI data for SIR identification and characterization
- How observational parameters inform model parameterization
- The connection between observed SIR properties and their representation in the transport equation
- Added detailed explanation of the data-to-model pipeline

2.4 Comment 4: Figure Issues

Reviewer Comment

Several figures require improvement including Figure 3 (model-observation comparison), Figure 4 (percentile bounds and phase representation), and Figure 7 (pitch angle diffusion coefficient visualization).

Author Response

We acknowledge that several figures needed improvement to better communicate our results and facilitate interpretation.

Changes in Manuscript

Comprehensive figure revisions have been implemented:
Figure 3:

- Updated to clearly show comparison between modeled profile and neutron monitor observations
- Improved legend and axis labels
- Added uncertainty bounds where appropriate

Figure 4:

- Now includes percentile bounds for statistical robustness
- Shows both rise and decay phases with clear temporal markers
- Enhanced color scheme for better visibility

Figure 7:

- Revised to clearly illustrate the sharp increase in pitch angle diffusion coefficient across the stream interface
- Implemented logarithmic scale for better dynamic range representation
- Added quantitative annotations showing the magnitude of change
- Improved temporal resolution to capture rapid variations

2.5 Comment 5: Inconsistency in Mean Free Path Changes

Reviewer Comment

There appears to be an inconsistency between the reported 35% decline during SI crossing and the 60% increase across the SI. This discrepancy needs clarification.

Author Response

This is an important observation that highlights the need for clearer explanation of the temporal evolution of transport parameters throughout the event.

Changes in Manuscript

A new paragraph in Section 3.3 and new Figure 10 have been added to address this apparent discrepancy:

- Detailed temporal analysis showing the evolution of mean free path throughout the entire event
- Clarification of the difference between instantaneous changes during SI crossing versus cumulative changes across the entire SI structure
- New Figure 10: Time series showing the complete evolution of transport parameters
- Enhanced discussion of particle transport dynamics explaining the physical basis for these variations
- Clear distinction between different temporal scales and their respective impacts

2.6 Comment 6: Technical Comments

Reviewer Comment

Several technical issues including figure reference errors, missing subsections, and labeling improvements in figures.

Author Response

We appreciate the careful attention to these technical details that improve the overall quality and readability of the manuscript.

Changes in Manuscript

All technical issues have been systematically addressed:

- Corrected all figure reference errors throughout the manuscript
- Added missing subsection 3.2 as referenced in the text
- Improved labeling in Figure 2 with clearer annotations and legend
- Verified all cross-references and citations
- Enhanced overall document formatting and consistency

3 Summary of Major Changes

The manuscript has undergone substantial revision in response to both reviewers' comments. The major improvements include:

3.1 Enhanced Scientific Rigor

- Quantitative analysis of turbulence levels with statistical measures
- Comprehensive sensitivity analysis for model parameters
- Expanded theoretical framework with complete equation formulations

3.2 Improved Methodology

- Detailed model description enabling reproducibility
- Clear connection between observations and model implementation
- Enhanced discussion of physical assumptions and limitations

3.3 Better Contextualization

- Comprehensive GLE classification framework
- Comparison with existing literature and theoretical predictions
- Proper statistical context for our specific event

3.4 Enhanced Presentation

- Significant improvements to all figures with better clarity and quantitative information
- Resolution of apparent inconsistencies through detailed explanation
- Addition of new figures providing crucial supporting information

4 Conclusion

We believe that these extensive revisions have substantially strengthened our manuscript while maintaining the core scientific contribution: demonstrating how interplanetary structures significantly impact SEP transport during GLEs, potentially affecting their classification based solely on temporal characteristics.

The enhanced quantitative analysis, expanded methodology, and improved presentation address all concerns raised by both reviewers. We are confident that the revised manuscript now meets the high standards of Annales Geophysicae and will make a valuable contribution to the space physics community.

We thank both reviewers for their invaluable feedback that has undoubtedly improved the quality and impact of our work.