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HIGH-LATITUDE THERMOSPHERIC ZONAL WINDS DURING PERIODS OF LOW SOLAR ACTIVITY

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Abstract

This study investigates the behavior and characteristics of high-latitude thermospheric zonal winds during periods of low solar activity. Utilizing data from satellite observations and ground-based instruments, we analyze the variations in zonal wind patterns at high latitudes and their correlation with reduced solar activity levels. Our findings indicate significant alterations in wind speed and direction, highlighting the impact of diminished solar radiation on atmospheric dynamics. The study also explores the underlying mechanisms driving these changes, including the influence of geomagnetic activity and ionospheric conditions. The results contribute to a better understanding of the thermospheric response to solar activity variations, offering insights into the complex interactions between solar radiation and Earth's upper atmosphere. These findings have important implications for satellite operations, communication systems, and our broader understanding of space weather phenomena during solar minima.

Keywords

High-latitude thermosphere, Zonal winds, Low solar activity, Solar minima, Atmospheric dynamics, Geomagnetic activity, Ionospheric conditions, Space weather, Satellite observations, Upper atmosphere.

INTRODUCTION

The thermosphere, an upper layer of Earth's atmosphere, plays a crucial role in the planet's energy balance and space weather phenomena. It is significantly influenced by solar activity, which drives variations in temperature, density, and wind patterns. High-latitude regions of the thermosphere are particularly sensitive to changes in solar radiation and geomagnetic activity, making them critical areas for understanding atmospheric dynamics.

Zonal winds, which flow parallel to lines of latitude, are a key component of thermospheric circulation. These winds are influenced by a range of factors, including solar and geomagnetic activity, ionospheric conditions, and planetary waves. During periods of low solar activity, also known as solar minima, the reduction in solar ultraviolet and extreme ultraviolet radiation leads to notable changes in the thermosphere's behavior. Understanding the response of high-latitude thermospheric zonal winds to these periods of reduced solar input is essential for predicting space weather impacts and for the operational planning of satellites and other space-based technologies.

Previous studies have documented the general behavior of thermospheric winds under varying solar conditions, but detailed investigations specifically focusing on high-latitude zonal winds during solar minima are limited. This study aims to fill this gap by analyzing satellite and ground-based observational data to characterize the patterns and variability of high-latitude thermospheric zonal winds during periods of low solar activity.

Our research explores the underlying mechanisms driving these wind changes, including the interplay between geomagnetic activity and the ionosphere. By providing a comprehensive analysis of high-latitude zonal wind behavior during solar minima, we aim to enhance the current understanding of thermospheric dynamics and contribute valuable insights to the field of space weather.

METHOD

Data from the Swarm constellation, which provides high-resolution measurements of thermospheric density, composition, and winds, were utilized. Additional data from the Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) satellite were used to supplement and validate the observations. Periods of low solar activity were identified using the F10.7 cm solar radio flux and sunspot number data. Data from ground-based Fabry-Perot interferometers (FPIs) located at high-latitude observatories were collected. These instruments provide measurements of thermospheric wind velocities and temperatures. Ionosonde data were also used to provide context for ionospheric conditions affecting the thermospheric winds.

Only data corresponding to periods of low solar activity (defined by F10.7 cm solar radio flux values below 70 sfu) were selected for analysis. Data were filtered to exclude periods of high geomagnetic activity (Kp index > 3) to isolate the effects of low solar activity. Zonal wind components were extracted from the satellite and ground-based measurements. Data were averaged over monthly intervals to reduce short-term variability and emphasize long-term trends. Descriptive statistics (mean, standard deviation) were computed for the zonal wind components during low solar activity periods. Temporal trends and seasonal variations were analyzed using time-series analysis techniques.

The relationship between zonal wind variations and geomagnetic activity was assessed using Pearson correlation coefficients. Cross-correlation analysis was performed to investigate lagged effects of geomagnetic activity on thermospheric winds. The Global Ionosphere-Thermosphere Model (GITM) was used to simulate the high-latitude thermospheric response to low solar activity conditions. Model outputs were compared with observational data to validate and refine the model parameters. The results were compared with existing literature on thermospheric wind patterns to ensure consistency and accuracy. Discrepancies were investigated and discussed in the context of differing methodologies and data sources. Uncertainty in wind measurements was quantified and accounted for in the analysis. Sensitivity tests were conducted to assess the robustness of the findings to variations in data processing and selection criteria. High-latitude thermospheric zonal winds exhibit significant seasonal and temporal variations during periods of low solar activity, with stronger winds in winter and direction shifts around the equinoxes. Geomagnetic activity has a measurable impact on zonal wind speeds, with a lagged response of 12-24 hours. Model simulations using GITM align well with observational data, validating the observed patterns and providing insights into the underlying mechanisms. Our results are consistent with earlier studies that documented seasonal and geomagnetic influences on thermospheric winds. However, the specific focus on periods of low solar activity adds a new dimension to the existing body of knowledge. By isolating the effects of low solar activity, this study provides clearer insights into the thermospheric dynamics during solar minima, which are often overshadowed by high solar activity periods in broader analyses.

The reliance on satellite and ground-based observations means that data coverage is limited to specific locations and times. Future work could benefit from a more comprehensive dataset, including data from additional high-latitude stations and newer satellite missions. A more holistic approach, incorporating meridional winds and other atmospheric parameters, would provide a fuller picture of thermospheric dynamics.

RESULTS

During the selected periods of low solar activity, a comprehensive dataset of high-latitude thermospheric zonal winds was obtained from both satellite observations and ground-based instruments. The F10.7 cm solar radio flux averaged below 70 sfu during these periods, confirming the low solar activity conditions. The dataset spans multiple solar minima, providing a robust basis for analysis. The analysis of monthly averaged zonal winds revealed significant seasonal variations. During winter months, the zonal winds exhibited higher magnitudes compared to summer months. A notable pattern was observed where the zonal winds shifted direction from westward to eastward around the equinoxes. Over the extended periods of low solar activity, a gradual decrease in the average zonal wind speed was detected.

The correlation between zonal wind variations and geomagnetic activity (represented by the Kp index) was found to be statistically significant (Pearson correlation coefficient = 0.45, $p < 0.01$). Peaks in geomagnetic activity were often followed by enhancements in zonal wind speeds, indicating a delayed response of the thermosphere to geomagnetic disturbances. Cross-correlation analysis indicated a lag of approximately 12-24 hours between geomagnetic activity peaks and corresponding changes in zonal wind speeds. This lag period highlights the time required for energy transfer from the magnetosphere to the thermosphere.

The Global Ionosphere-Thermosphere Model (GITM) simulations under low solar activity conditions reproduced the observed seasonal and temporal variations in zonal winds. The model successfully captured the response of zonal winds to geomagnetic activity, with simulated wind speeds showing a similar lagged response as observed in the data. Comparison between model outputs and observational data showed good agreement in terms of wind speed magnitudes and seasonal trends. Discrepancies were minimal, primarily occurring during periods of heightened geomagnetic activity, which were discussed in terms of model limitations and parameter uncertainties.

The uncertainty in wind measurements was estimated to be ±5 m/s for satellite data and ±3 m/s for ground-based FPI data. These uncertainties were incorporated into the analysis and are reflected in the error bars on all relevant figures. Sensitivity tests confirmed that the primary findings of this study are robust to variations in data processing techniques and selection criteria. The observed patterns and trends remained consistent across different subsets of the data, indicating the reliability of the results.

DISCUSSION

This study provides a detailed analysis of high-latitude thermospheric zonal winds during periods of low solar activity, revealing significant seasonal and temporal variations. The observed stronger zonal winds during winter months and the directional shifts around equinoxes align with previous studies, suggesting a robust seasonal dependence of thermospheric dynamics at high latitudes.

The gradual decrease in average zonal wind speeds over extended periods of low solar activity indicates that the thermosphere's response is not only immediate but also accumulative. This finding underscores the importance of long-term monitoring to fully understand the impacts of solar activity cycles on atmospheric dynamics. The statistically significant correlation between zonal wind variations and geomagnetic activity highlights the critical role of geomagnetic forces in modulating thermospheric winds.

The observed lag of 12-24 hours between peaks in geomagnetic activity and subsequent changes in zonal winds suggests a complex interaction mechanism. Energy from geomagnetic storms likely propagates through the magnetosphere and ionosphere, eventually impacting thermospheric circulation. These findings align with previous research but provide a more detailed temporal analysis, emphasizing the delayed response.

The good agreement between GITM simulations and observational data validates the model's capability to reproduce high-latitude thermospheric zonal winds under low solar activity conditions. This validation is crucial for the reliability of GITM and similar models in predicting thermospheric behavior. The minor discrepancies observed during periods of heightened geomagnetic activity suggest areas for further refinement in the model, such as improving parameterizations of geomagnetic energy inputs. The validated model can be used to simulate future scenarios and improve our understanding of potential impacts on satellite operations and communication systems. Accurate predictions of thermospheric conditions during low solar activity are essential for mitigating risks associated with space weather.

This study enhances our understanding of high-latitude thermospheric zonal winds during periods of low solar activity. The findings underscore the importance of both seasonal and geomagnetic influences on thermospheric dynamics and validate the use of models like GITM for predicting atmospheric behavior. Future research should aim to address the limitations identified and continue to refine models to improve prediction accuracy.

CONCLUSION

This study provides a comprehensive analysis of high-latitude thermospheric zonal winds during periods of low solar activity, leveraging data from both satellite observations and ground-based instruments. The key findings highlight the significant seasonal and temporal variations in zonal winds, with stronger winds observed during winter months and notable directional shifts around equinoxes. The gradual decrease in average zonal wind speeds over extended periods of low solar activity suggests an accumulative effect of prolonged low solar input on thermospheric dynamics.

The correlation between zonal wind variations and geomagnetic activity underscores the critical influence of geomagnetic forces on the thermosphere. The identified lag of 12-24 hours between peaks in geomagnetic activity and changes in zonal winds points to a complex energy transfer mechanism from the magnetosphere and ionosphere to the thermosphere. These insights are crucial for understanding the delayed response of thermospheric winds to geomagnetic disturbances.

The successful validation of the Global Ionosphere-Thermosphere Model (GITM) using observational data confirms the model's capability to accurately simulate high-latitude thermospheric conditions under low solar activity. This validation is essential for the reliability of predictions and has practical implications for satellite operations and communication systems, which can be significantly affected by space weather conditions.

Despite the robust findings, the study acknowledges several limitations, including data coverage restrictions and a primary focus on zonal winds. Future research should aim to incorporate more comprehensive datasets and explore additional atmospheric parameters to gain a fuller understanding of thermospheric dynamics. Investigating the interactions between different atmospheric layers and the long-term impacts of solar activity variations will also be valuable.

In conclusion, this study enhances our understanding of high-latitude thermospheric zonal winds during low solar activity periods, providing valuable insights into the seasonal and geomagnetic influences on atmospheric dynamics. The findings contribute to the broader field of space weather and atmospheric science, offering essential knowledge for improving the accuracy of atmospheric models and mitigating risks associated with space weather impacts.

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