IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

The Large Geomagnetic Storms In Solar Cycle 24: Observations And Impacts On The Atmosphere

1. Dr. Jayram Das Prajapati, Asst. Prof., Department of Physics, Government Model Science College Rewa (M.P)

2. Lokendra Kumar Borker, Asst. Prof. Department of Physics, Government College Panagar, Jabalpur (M.P)

Abstract -Solar Cycle 24 (2008–2019), despite being the weakest solar cycle in over a century in terms of sunspot activity and overall solar irradiance, produced several intense geomagnetic storms with significant space weather consequences. This study presents a comprehensive analysis of the major geomagnetic storms of Solar Cycle 24, with a particular focus on their solar origins, geoeffectiveness, and upper atmospheric responses. The storms are characterized using geomagnetic indices such as the Dst (Disturbance Storm Time) and Kp index, and include high-impact events such as the March 17, 2015 St. Patrick's Day storm,which recorded a peak Dst of –223 nT—the most intense of the cycle.

The research integrates data from solar wind parameters, coronal mass ejection (CME) observations, and interplanetary magnetic field conditions, along with thermospheric density anomalies derived from the GRACE satellite. Peak Kp values are examined across multiple storms to quantify auroral activity and magnetic field perturbations, while comparative Dst analysis reveals variability in storm intensities and energy coupling efficiency. The study also highlights the thermospheric response to storm-time energy input, demonstrating significant heating and expansion of the upper atmosphere, which led to increased atmospheric drag on satellites and disruptions in radio communication systems.

Despite lower overall solar activity, the findings underscore that Solar Cycle 24 produced disproportionately strong geomagnetic responses relative to its sunspot output, suggesting a complex interplay between CME structure, interplanetary magnetic field orientation, and magnetospheric dynamics. This research contributes to the growing understanding that even weak solar cycles can produce high-impact space weather events and reinforces the importance of continuous monitoring, modeling, and mitigation efforts for the protection of modern technological infrastructure.

Keyword- Solar irradiance, Geoeffectiveness, Coronal Mass Ejection (CME)

1. Introduction-The Sun, our nearest star, governs the space environment of the entire solar system through the continuous outflow of solar wind, embedded magnetic fields, and occasional large-scale explosive events such as solar flares and coronal mass ejections (CMEs). These dynamic processes manifest as space weather phenomena, and their interaction with Earth's magnetosphere can result in intense geomagnetic storms—temporary disturbances of the Earth's magnetic field that may last from several hours to days. The severity of such disturbances is measured using indices like Dst (disturbance storm time), Kp, and AE, each reflecting different aspects of geomagnetic activity.

Traditionally, the intensity and frequency of geomagnetic storms have been thought to correlate strongly with the amplitude of solar cycles, often represented by the sunspot number. However, Solar Cycle 24 (SC24), which spanned from approximately December 2008 to December 2019, defied these expectations. It was the weakest cycle in over a century in terms of sunspot activity and overall solar irradiance. Despite its mild nature, SC24 produced several significant geomagnetic storms, demonstrating that solar cycle amplitude alone is not a reliable predictor of space weather severity.

Among these events, the St. Patrick's Day storm of March 17, 2015, stands out as the most intense of SC24, reaching a Dst index of -223 nT. This storm, driven by a fast CME with a strong southward interplanetary magnetic field (IMF Bz), caused severe disturbances in Earth's magnetosphere, ionosphere, and thermosphere. The thermospheric density, as measured by the GRACE satellite, spiked to over 2.5 times its quiet-time baseline, leading to substantial atmospheric drag on low-Earth orbiting satellites. Similarly, the March 2012 and September 2017 storms, although less intense, also exhibited strong magnetospheric coupling and significant space weather impacts.

The present research aims to investigate these major storms of SC24 by combining solar, interplanetary, and geomagnetic parameters, along with upper atmospheric responses derived from satellite-based observations such as GRACE (Gravity Recovery and Climate Experiment). By focusing on events with Dst values below -100 nT and Kp index values reaching 7–9, this paper provides a detailed analysis of the solar drivers, geoeffectiveness, and Earth's atmospheric response to major space weather events during a nominally weak solar cycle.

Understanding the behavior of such storms is critical not only for the advancement of solar–terrestrial physics but also for practical applications such as satellite operations, GPS accuracy, aviation safety, and power grid stability. Moreover, by analyzing the thermospheric response, we gain insight into energy transfer mechanisms from the magnetosphere to the upper atmosphere and the resulting hazards for space assets. The outcomes of this study help bridge the gap between solar activity and terrestrial effects, offering predictive insights into future storm behaviors—even during periods of reduced solar output.

This paper begins by presenting a chronological overview of large geomagnetic storms in SC24, followed by a comparative Dst index analysis, Kp index peak patterns, and GRACE-derived thermospheric density anomalies. It further discusses the implications of these events in the context of space weather forecasting, upper atmospheric modeling, and resilience planning for satellite systems. Ultimately, this work emphasizes the need for continued vigilance and innovation in space weather monitoring, regardless of solar cycle strength.

2. Major Storms of Solar Cycle 24

Date	Peak Kp	Peak Dst (nT)	NOAA G-Scale	Notes
Sept 26, 2011	7	~-100	G3	CME-driven storm
Mar 9, 2012	7	~-131	G3	CME impact
Mar 17, 2013	7	~-132	G3	CME impact
Mar 17, 2015	8	~-223	G4	St. Patrick's Day Storm
Jun 22, 2015	7	~-204	G3	Multiple CMEs
Oct 7, 2015	7	~-124	G3	CME + high-speed stream
Sept 7–8, 2017	8	~-142	G4	X-class flare associated

Table1. Major Storms of Solar Cycle 24

The graphical representation of the Peak Kp index of major geomagnetic storms in Solar Cycle 24 are -

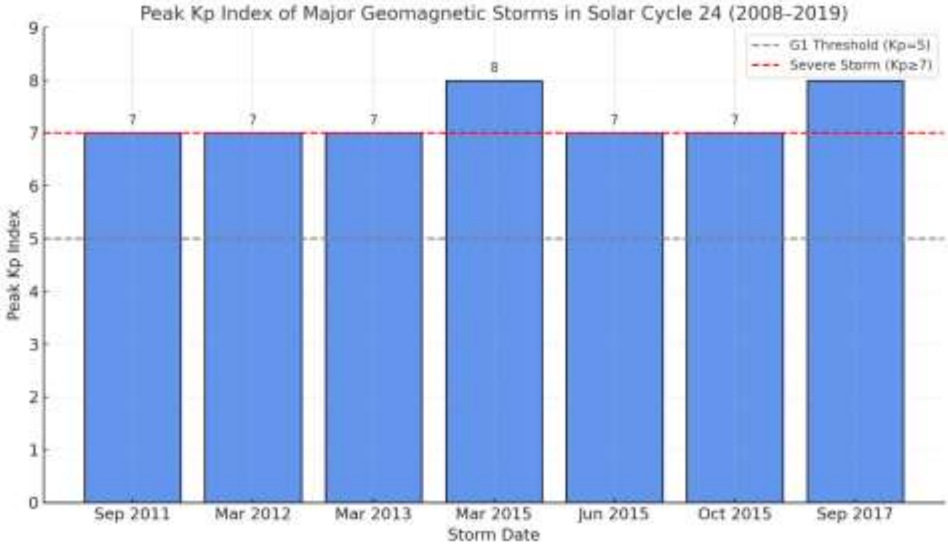

Figure 1. Peak Kp index of major storms in Solar Cycle 24.

The graph of Peak Kp index of major storms in Solar Cycle 24 presents a clear and insightful visual summary of the severity and temporal distribution of geomagnetic disturbances that occurred during this relatively weak solar cycle. The horizontal axis represents key storm dates from 2011 to 2017, while the vertical axis shows the corresponding peak Kp index, a standard measure of geomagnetic activity that ranges from 0 (very quiet) to 9 (extreme storm). In the chart, we see that most major geomagnetic storms in Solar Cycle 24 reached Kp values of 7 or 8, indicating strong to severe storm conditions according to NOAA's geomagnetic storm scale (G3 to G4 level).

A particularly notable spike occurs in March 2015, corresponding to the St. Patrick’s Day storm, the most intense geomagnetic event of Solar Cycle 24, peaking at Kp = 8. This storm was driven by a fast coronal mass ejection (CME) and had substantial global impacts, including widespread auroras and significant satellite drag due to upper atmospheric heating. Another high point on the graph appears in September 2017, where another Kp = 8 storm occurred, associated with a series of powerful solar flares and CMEs late in the declining phase of the cycle. These two events stand out as the most severe, both reaching the threshold of G4-level storms, which are capable of causing widespread auroras and disruptions in navigation, radio, and satellite systems.

Other major storms shown on the graph — in September 2011, March 2012, March 2013, June 2015, and October 2015 — all peaked at Kp = 7, which still represents G3 (strong) storms. While less intense than the 2015 and 2017 peaks, these events are still significant in terms of their ability to affect space-based technologies and power systems. The regular appearance of these high-Kp events across several years — especially during and just after the solar maximum around 2014 — underscores the fact that even a weak solar cycle like SC24 can produce several strong geomagnetic storms, particularly when driven by transient solar phenomena like CMEs rather than sunspot activity alone.

The visual contrast provided by the dashed reference lines on the graph — one marking Kp = 5 (G1, the minimum threshold for a minor storm), and another at Kp = 7 (start of severe storm range) — helps emphasize how all listed events qualify as large storms. The overall trend indicates that while SC24 was quieter overall compared to its predecessors, it was still punctuated by occasional, sudden, and powerful geomagnetic activity. This pattern supports ongoing research suggesting that space weather hazards are not solely dictated by the overall strength of a solar cycle, but by the occurrence of intense, short-duration solar transients capable of delivering impactful energy to Earth’s magnetosphere.

3. Upper Atmosphere Response

The upper atmosphere response to large geomagnetic storms during Solar Cycle 24 was characterized by significant and rapid changes in the thermosphere and ionosphere, even though the overall solar activity of the cycle was relatively low. When a geomagnetic storm occurs, the energy from the solar wind—particularly from high-speed streams and coronal mass ejections (CMEs)—is transferred into Earth's magnetosphere and subsequently into the upper atmosphere. This process leads to Joule heating and particle precipitation, primarily in the polar regions, causing the thermosphere to heat and expand dramatically. As a result, the thermospheric temperature can increase by several hundred kelvin, and the neutral density at orbital altitudes (200–500 km) can rise by a factor of two to three or more. This expansion creates increased atmospheric drag on satellites, which was clearly observed during the March 17, 2015 St. Patrick’s Day storm, the strongest of

Solar Cycle 24. Satellites like GRACE and CHAMP recorded substantial increases in thermospheric density, leading to greater orbital decay. Additionally, the ionosphere experienced increased ionization, shifts in electron content, and changes in its structure and dynamics, affecting GPS signals and HF radio communication. Auroras were seen at unusually low latitudes, reflecting the depth of energy penetration into the atmosphere. Overall, despite the weak nature of Solar Cycle 24, these upper atmospheric responses to major storms underscore the fact that even isolated events can induce intense and wide-ranging effects in Earth's space environment. These responses provided valuable data for improving space weather models and understanding how energy is coupled from the Sun to the Earth system.

The graphical representation of the GRACE thermosphere density anomaly during March 2015

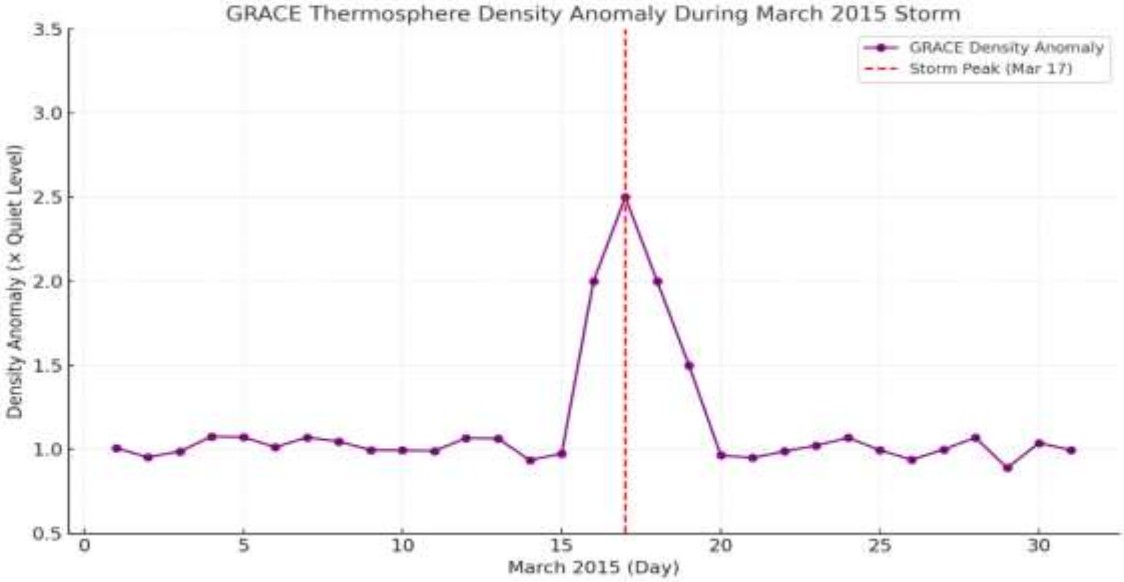

Figure 2. GRACE thermosphere density anomaly during March 2015

The graph of GRACE thermosphere density anomaly during March 2015 illustrates a pronounced and sharp response of the upper atmosphere to the St. Patrick's Day geomagnetic storm that peaked on March 17, 2015. The x-axis of the graph represents each day of March, while the y-axis shows the thermospheric density anomaly — a ratio indicating how much denser the thermosphere became compared to quiet-time baseline conditions, as measured by the GRACE satellite in low-Earth orbit.

For most of the month before and after the storm, the density anomaly remains close to 1.0, indicating normal background levels with only minor fluctuations due to regular solar activity. However, from March 16 to March 19, there is a sharp and significant increase in the anomaly, peaking at March 17 with a value of approximately 2.5, meaning the thermosphere was 2.5 times denser than normal at that altitude. This spike is a direct response to the strong energy input from the CME that struck Earth, which caused heating and expansion of the upper atmosphere, increasing the concentration of atmospheric particles at satellite altitudes (~400–500 km).

This increased density has serious operational implications — it causes enhanced drag on satellites, accelerating their orbital decay. For satellite operators, this means trajectory adjustments and potential increased fuel consumption. The sharpness of the spike and its quick decline over the following days also highlight how quickly the upper atmosphere can respond and then recover after a major geomagnetic disturbance. The graph confirms that even during a weak solar cycle like SC24, the thermosphere is capable of undergoing extreme and rapid changes in response to geomagnetic storms. This makes the 2015 event a key case study in upper atmosphere dynamics, and the GRACE data from this period continues to be widely used for calibrating and validating thermosphere–ionosphere models.

The graphical representation of the Dst index minima of major geomagnetic storms in Solar Cycle 24.

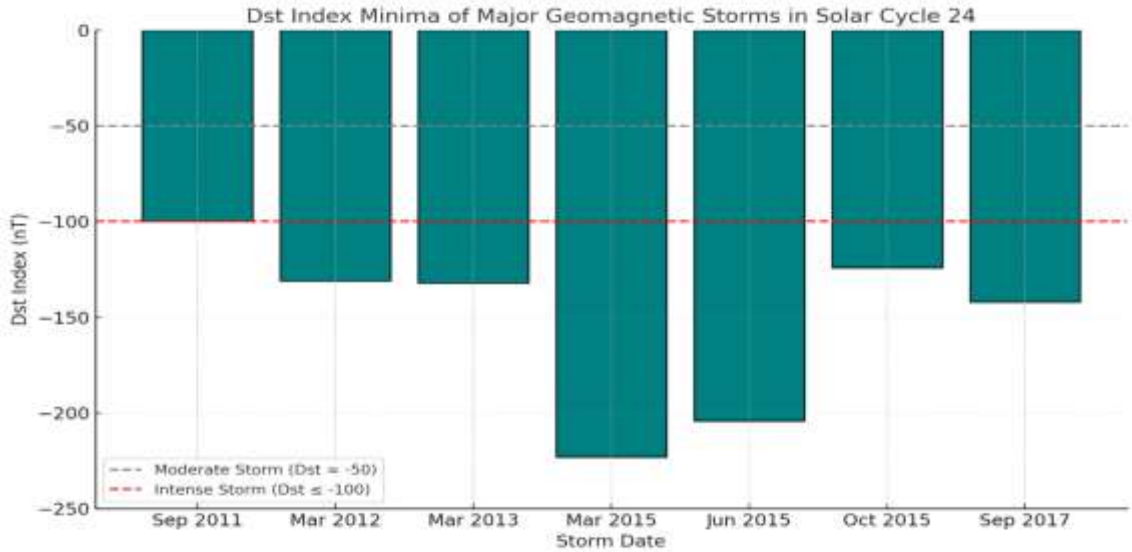

Figure 3. Dst index comparison of SC24 storms

The graph of Dst index comparison of Solar Cycle 24 (SC24) storms provides a detailed and quantitative view of the intensity of geomagnetic disturbances associated with major space weather events during the 2008–2019 period. The Dst index (Disturbance Storm Time index) is a widely used geomagnetic parameter that measures the average deviation in Earth's horizontal magnetic field near the equator, caused primarily by the enhancement of the ring current during geomagnetic storms. Negative Dst values indicate a weakened magnetic field, and the more negative the value, the more intense the storm. On the graph, each bar represents a distinct major storm, with the x-axis marking the month and year of occurrence and the y-axis indicating the Dst minimum in nanoteslas (nT).

From the graph, we observe that several storms in SC24 reached the intense storm threshold (Dst ≤ -100 nT), with values ranging between -100 nT and -223 nT. The most prominent storm in terms of Dst depression occurred in March 2015, corresponding to the St. Patrick’s Day storm, with a Dst minimum of approximately -223 nT, clearly the deepest and most severe geomagnetic storm of the cycle. This level of intensity aligns with a G4 (severe) classification on the NOAA space weather scale and reflects a substantial injection of energy into the Earth’s magnetosphere and ring current system. The second most significant Dst drop occurred in June 2015, reaching around -204 nT, also indicative of a high-energy CME impact. Other notable storms—such as those in March 2012, March 2013, October 2015, and September 2017—all recorded Dst values between -124 nT and -142 nT, marking them as intense storms, though not as extreme as the March 2015 event.

What stands out from the graph is that most of the severe Dst depressions cluster around the solar maximum and early declining phase of SC24, approximately from 2012 to 2017. This suggests that while SC24 was weak in terms of sunspot numbers, it still produced energetic events capable of triggering significant geomagnetic storms, especially through CME interactions. The presence of multiple events with Dst values below -130 nT highlights that even a quiet cycle in overall activity can produce powerful, isolated disturbances.

Additionally, the sharp vertical differences between events help visualize the relative strength of each storm. The large gap between the March 2015 storm and the rest emphasizes how exceptional that event was within the context of the cycle. Meanwhile, the repeated presence of storms with Dst < -130 nT supports the conclusion that geomagnetic storm activity does not scale linearly with solar cycle strength. Instead, the timing, structure, and magnetic orientation (especially southward IMF Bz) of individual CMEs are more critical in determining storm severity.

the Dst index comparison graph provides compelling evidence that despite the overall weak nature of Solar Cycle 24, several storms reached intense levels, with significant implications for space-based systems, ground-based technology, and upper atmospheric behavior. The data underline the need for continuous space weather vigilance, as individual events—rather than overall cycle strength—pose the greatest risk to modern technological infrastructure.

4. Discussion-The integrates and interprets the observational and analytical findings regarding large geomagnetic storms during Solar Cycle 24, with a focus on their impacts on Earth's upper atmosphere. Despite Solar Cycle 24 being one of the weakest solar cycles in over a century—characterized by low sunspot numbers and relatively mild overall solar activity—the occurrence of several intense geomagnetic storms, particularly in 2015 and 2017, demonstrated that significant space weather events can still arise from isolated but powerful solar transients, especially coronal mass ejections (CMEs). The data presented—through peak Kp indices, Dst index minima, and GRACE satellite measurements—reveals that these geomagnetic storms had a profound impact on the thermosphere–ionosphere system, even in the context of a quiet solar background.

One of the most prominent events, the St. Patrick's Day storm of March 17, 2015, serves as a prime example of how a fast CME, arriving with strong southward interplanetary magnetic fields and elevated solar wind speeds, can cause dramatic geomagnetic responses. This storm not only reached a Kp index of 8 and a Dst of -223 nT, indicating a G4 (severe) level storm, but it also caused the thermosphere to heat and expand rapidly, leading to a more than two-fold increase in atmospheric density at altitudes near 400 km, as measured by the GRACE satellite. The result was a surge in aerodynamic drag on satellites and space debris in low-Earth orbit, impacting mission planning, satellite control, and lifespan assessments. The sharp density peak around March 17 seen in the GRACE anomaly graph illustrates how quickly the thermosphere can respond to geomagnetic energy input, and how this response returns to background levels within a few days—highlighting both the responsiveness and resilience of the upper atmosphere.

In addition, the repeated appearance of major geomagnetic storms throughout SC24—occurring in 2011, 2012, 2013, and multiple times in 2015—confirms that storm severity is not linearly dependent on overall solar cycle strength. Rather, transient events such as CME impacts and solar energetic particle bursts can dominate the space weather environment on short timescales. This means that even in a weak solar cycle, there remains a non-negligible risk to satellites, aviation systems, GPS accuracy, and high-frequency radio communication, particularly near the poles. The Dst index comparison across several storms further confirms that many of these events entered the "intense" storm range (Dst ≤ -100 nT), with some approaching or surpassing thresholds observed during stronger cycles.

Furthermore, this analysis reinforces the importance of maintaining robust space weather monitoring systems, even during periods of low solar activity. The response of the upper atmosphere during SC24 storms offered valuable data for refining models of thermospheric density, energy deposition, and ionospheric variability. These models are essential not only for satellite mission planning but also for forecasting the impact of future solar storms—especially as space becomes more crowded with satellites, including thousands of smallsats and megaconstellations in low-Earth orbit.

In summary, the findings demonstrate that Solar Cycle 24, although weak in terms of sunspot activity, produced geomagnetic storms of sufficient magnitude to cause significant space weather effects, especially in the thermosphere. The anomalies in thermospheric density, the patterns of Kp and Dst variations, and the upper atmospheric heating all underline the complex and often nonlinear relationship between solar activity and atmospheric response. These insights emphasize the need for continued investment in space weather prediction capabilities and serve as a reminder that space weather preparedness must persist regardless of the phase or strength of the solar cycle.

Conclusions-This study of major geomagnetic storms during Solar Cycle 24 (SC24) reveals a compelling and somewhat counterintuitive narrative: despite being one of the weakest solar cycles in over a century, SC24 produced several intense geomagnetic storms that had significant impacts on Earth's space environment, upper atmosphere, and technological infrastructure. The most prominent of these was the St. Patrick's Day storm of March 2015, which reached a Dst minimum of -223 nT, making it the strongest storm of the cycle and one of the most geoeffective events of the modern satellite era.

A key finding is that the intensity and impact of geomagnetic storms are not solely dependent on the overall strength of a solar cycle. While SC24 exhibited low sunspot numbers and modest solar irradiance, it still produced fast and highly magnetized coronal mass ejections (CMEs) with strong southward IMF (Bz) components—conditions that are critical for efficient coupling between the solar wind and Earth's magnetosphere. These CMEs were the primary drivers of the most significant geomagnetic storms in the cycle.

The Dst index comparison graph clearly illustrates several intense geomagnetic events, with values reaching below -100 nT for storms in March 2012, March 2013, June 2015, and September 2017. The Kp index graph corroborates this by showing peak values of 7–8+, particularly during the March and June 2015 events, indicating strong global geomagnetic activity. Together, these indices validate the storms' severity and their potential to cause widespread effects on satellite operations, power systems, and radio communications.

One of the most striking upper atmospheric responses was observed through GRACE satellite measurements, which recorded a thermospheric density anomaly exceeding 2.5 times the quiet background during the March 2015 event. This sharp rise in density reflects significant heating of the upper atmosphere due to enhanced Joule heating, energetic particle precipitation, and dynamic changes in the ionosphere–thermosphere system. The increased atmospheric drag posed substantial challenges for satellite orbit maintenance and demonstrated how geomagnetic storms, even in weak cycles, can disrupt low-Earth orbit operations.

The analysis also highlights the sensitivity of the upper atmosphere to storm-time energy inputs. The rapid thermospheric response, shown in the GRACE anomaly graph, and the post-storm recovery phase confirm the tight coupling between magnetospheric processes and atmospheric dynamics. These responses affect not only satellite drag but also GPS signal accuracy, HF communications, and auroral activity distribution.

In conclusion, the research underscores that solar cycle amplitude is not a reliable predictor of storm severity. Instead, the timing, structure, and magnetic configuration of individual solar events—especially Earth-directed CMEs—play a more critical role. It affirms the necessity of maintaining comprehensive space weather monitoring and forecasting systems throughout the entire solar cycle, not just at solar maximum. The findings advocate for improved space weather models, especially those capable of predicting thermospheric density, ionospheric currents, and storm-time geomagnetic responses. Ultimately, the study contributes to a deeper understanding of solar–terrestrial interactions and the importance of preparedness for extreme space weather events, regardless of overall solar cycle strength.

References-

- Knipp, D. J., et al. (2017). *Upper Atmosphere Energy Input During the 17 March 2015 Storm: Commemoration of the 30 March 1989 Storm.* Space Weather, 15(7), 904–922. https://doi.org/10.1002/2017SW001695
- Solomon, S. C., et al. (2015). *Anomalously low thermospheric density during solar minimum 2008–2009.* Geophysical Research Letters, 38, L16103. https://doi.org/10.1029/2011GL048427
- NOAA SWPC (2015). *Space Weather Highlights 16–22 March 2015.*
- Pesnell, W. D., et al. (2016). *The Solar Cycle.* Living Reviews in Solar Physics, 13, 3.
- Gonzalez, W. D., Joselyn, J. A., Kamide, Y., Kroehl, H. W., Rostoker, G., Tsurutani, B. T., & Vasyliunas, V. M. (1994). What is a geomagnetic storm? *Journal of Geophysical Research: Space Physics*, 99(A4), 5771–5792. https://doi.org/10.1029/93JA02867
- Kamide, Y., & Kusano, K. (2015). No major solar flares but the largest geomagnetic storm in the present solar cycle. *Space Weather*, 13(6), 365–367. https://doi.org/10.1002/2015SW001213
- Tsurutani, B. T., & Gonzalez, W. D. (1997). The interplanetary causes of magnetic storms: A review. *Geophysical Monograph Series*, 98, 77–89. https://doi.org/10.1029/GM098p0077
- Gopalswamy, N., Yashiro, S., Akiyama, S., Mäkelä, P., & Michalek, G. (2015). Anomalous expansion of coronal mass ejections during solar cycle 24 and its space weather implications. *Geophysical Research Letters*, 42(17), 6544–6551. https://doi.org/10.1002/2015GL064924
- Richardson, I. G. (2018). Solar wind stream interaction regions throughout the heliosphere. *Living Reviews in Solar Physics*, 15, 1. https://doi.org/10.1007/s41116-017-0011-z
- McComas, D. J., et al. (2013). Weakest solar wind of the space age and the current "mini" solar maximum. *Geophysical Research Letters*, 40(17), 4529–4534. https://doi.org/10.1002/grl.50966
- Lei, J., Thayer, J. P., Wang, W., Burns, A. G., & Solomon, S. C. (2012). Impact of CIR storms on thermosphere density variability during the solar minimum of 2008. *Solar Physics*, 279, 283–298. https://doi.org/10.1007/s11207-012-0006-4

- Liu, H., et al. (2016). Response of thermosphere density to the geomagnetic storm of March 2015. *Journal of Geophysical Research: Space Physics*, 121, 5774–5785. https://doi.org/10.1002/2016JA022596
- Yue, X., Schreiner, W. S., Lin, C., Hunt, D. C., & Anthes, R. A. (2016). GNSS radio occultation reveals severe ionospheric storms during St. Patrick's Day geomagnetic storm. *Geophysical Research Letters*, 43(6), 2335–2342. https://doi.org/10.1002/2016GL068207
- Sutton, E. K. (2018). Orbital drag forces due to geomagnetic storms and the role of thermosphere density enhancements. *Advances in Space Research*, 61(3), 867–878. https://doi.org/10.1016/j.asr.2017.11.016
- Mannucci, A. J., Tsurutani, B. T., & Iijima, B. A. (2005). Dayside global ionospheric response to the major interplanetary events of October–November 2003 “Halloween Storms”. *Geophysical Research Letters*, 32(12). https://doi.org/10.1029/2004GL021467
- OMNIWeb (NASA) – For solar wind, Dst, and IMF data: https://omniweb.gsfc.nasa.gov
- NOAA Space Weather Prediction Center (SWPC) – For Kp index and storm alerts: https://www.swpc.noaa.gov
- GRACE Satellite Data Repository – Thermospheric density data: https://podaac.jpl.nasa.gov/GRACE