International Journal of Astrophysics and Space Science
2026, Vol. 14, No. 3, pp. 39–52
https://doi.org/10.11648/j.ijass.20261403.11

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Research Article

Modeling Equatorial Plasma Depletion and Anisotropic MSTIDs from the April 2024 Eclipse

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Abstract

Background: Total solar eclipses provide unique opportunities to study the ionospheric response to sudden solar extreme ultraviolet (EUV) reduction. The April 8, 2024 total solar eclipse occurred near the peak of Solar Cycle 25, offering a rare chance to examine eclipse-driven plasma depletion and traveling ionospheric disturbances under high solar activity. *Purpose:* This study models the equatorial ionospheric plasma depletion and anisotropic medium-scale traveling ionospheric disturbances (MSTIDs) generated by the 2024 eclipse, using GNSS total electron content (TEC) observations and the SAMI3 ionospheric model. *Methods:* We analyzed TEC data from ~200 stations spanning North America to equatorial Brazil. SAMI3 simulations incorporated time-dependent EUV reduction along the eclipse path, with neutral atmosphere from NRLMSIS 2.0. MSTID propagation parameters were extracted via wavelet analysis and cross-correlation. *Findings:* Equatorial TEC depletion reached 20-40%, with the F2 layer showing 60% electron density reduction. The eclipse generated anisotropic MSTIDs: zonal propagation ($\lambda = 1304$ km, v = 0.81 km/s) and meridional propagation ($\lambda = 571$ km, v = 0.42 km/s), reproduced by SAMI3 within 15% accuracy. Compared to the 2017 solar-minimum eclipse, the 2024 event exhibited deeper depletion (40% vs. 25%) and prolonged recovery (≥7 hours vs. 3.5 hours). *Conclusion:* High solar activity amplifies eclipse-induced ionospheric effects, including stronger plasma loss and longer-lasting MSTIDs. SAMI3 successfully captures these anisotropic disturbances, validating its use for operational forecasting. *Recommendation:* Future work should employ coupled ionosphere-neutral atmosphere models (e.g., SAMI3 + WACCM-X) to improve AGW source physics and extend comparisons to other solar-maximum eclipses (e.g., 2026).

Keywords

Total Solar Eclipse, Equatorial Ionosphere, Plasma Depletion, Medium-scale Traveling Ionospheric Disturbances (MSTIDs), SAMI3 Model

1. Introduction

1.1. Solar Eclipses as Ionospheric Laboratories

Solar eclipses serve as unique natural experiments for studying the ionosphere's response to a sudden, localized reduction in solar extreme ultraviolet (EUV) radiation [10]. The abrupt cutoff of EUV flux leads to a rapid decrease in photo-ionization, resulting in significant plasma depletion in the ionospheric F region. The rapid cooling of the atmosphere within the eclipse shadow generates atmospheric gravity

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Received: 15 July 2026; **Accepted:** 24 July 2026; **Published:** 10 August 2026

waves (AGWs), which propagate upward through the neutral atmosphere and, upon encountering the ionized plasma, produce traveling ionospheric disturbances (TIDs) across a wide range of spatial scales [4]. Previous studies have demonstrated that eclipse-generated AGWs induce plasma density perturbations that create peculiar ionospheric features distinct from the direct photochemical depletion effect [4].

1.2. The April 8, 2024 Eclipse

The total solar eclipse of 8 April 2024 traversed North America from Mexico through the United States to Canada, with its path of totality extending approximately 9,190 miles. With a magnitude of 1.0566, the eclipse's longest duration of totality was 4 minutes and 28 seconds near the Mexican town of Nazas, Durango [5]. Crucially, this eclipse occurred during the solar maximum phase of Solar Cycle 25, presenting a distinct observational context compared to the August 2017 eclipse, which took place during solar minimum [5]. This enhanced solar activity background provides an opportunity to examine how the ionosphere responds to eclipse forcing under elevated plasma densities and altered dynamics.

1.3. Equatorial Ionosphere and MSTIDs

The equatorial ionosphere is characterized by the Equatorial Ionization Anomaly (EIA), a fountain-like redistribution of plasma driven by upward E × B plasma drift and field-aligned diffusion, forming two crests of enhanced electron density near ±15-20° magnetic latitude. Medium-scale traveling ionospheric disturbances (MSTIDs) is wave-like perturbations with horizontal wavelengths of 100-1000 km and phase velocities of 0.1-1 km/s, representing the ionospheric manifestation of AGWs [9]. MSTIDs often exhibit anisotropic propagation, with distinct zonal (east-west) and meridional (north-south) characteristics depending on the source mechanism and background ionospheric conditions. Recent studies have shown that the high-density region of the EIA plays a pivotal role in the interaction processes involving MSTIDs, influencing their morphology and evolution [9].

1.4. Modeling Gap & Objectives

Previous eclipse studies, including those of the 2017 event [2], have primarily focused on mid-latitude plasma depletion and TID characteristics, with limited attention to anisotropic MSTID behavior in equatorial and low-latitude regions. Furthermore, the complex interaction between the EIA fountain effect and eclipse-induced perturbations remains poorly understood. This study aims to address this gap by modeling plasma depletion and anisotropic MSTIDs using the SAMI3 ionospheric model [2] coupled with high-density GNSS-TEC observations [10], comparing model outputs with observed equatorial ionospheric responses to the April 2024 eclipse.

2. Method

2.1. GNSS-TEC Observations

High-density GNSS observations were obtained from approximately 1,700 stations spanning North America to equatorial Brazil and Colombia, providing dense spatial coverage of the eclipse path. Vertical total electron content (VTEC) was derived from dual-frequency carrier-phase and code measurements. To isolate MSTID signatures, a multi-term sinusoidal detrending algorithm was applied to remove background ionospheric variations, followed by bandpass filtering (2-10 min periods) to extract differential TEC (dTEC) disturbances [10]. The rate of TEC index (ROTI) was also computed to identify small-scale irregularities associated with the eclipse [6].

2.2. Ionospheric Model: SAMI3

The Naval Research Laboratory’s SAMI3 (Sami3 is Also a Model of the Ionosphere) model was employed to simulate the three-dimensional ionospheric response. SAMI3 is a physics-based ionosphere/plasmasphere model that solves continuity, momentum, and energy equations for multiple ion species along closed magnetic field lines [3]. The model grid was configured with 1° latitude × 2° longitude horizontal resolution and 20 altitude layers spanning 100-2,000 km, capturing the F-region peak where the greatest depletion occurs. Forcing parameters included solar EUV flux representative of Solar Cycle 25 maximum conditions and neutral atmospheric specifications from the NRLMSIS 2.0 empirical model [1]. Eclipse effects were implemented by applying a time-dependent reduction of EUV radiation along the moon’s umbra and penumbra using the eclipse obscuration function, following established methodologies for solar eclipse simulations [2].

2.3. MSTID Detection Algorithm

MSTIDs were detected using wavelet analysis of detrended VTEC time series from the dense GNSS network. The continuous wavelet transform was applied to dTEC perturbations to extract wave power as a function of period and time, enabling identification of eclipse-driven MSTID signatures [7]. Propagation parameters, including azimuth, horizontal phase speed and wavelength were estimated using two-dimensional cross-correlation analysis of detrended TEC maps [8]. This approach has been validated in previous MSTID studies and successfully resolved the anisotropic propagation characteristics of eclipse-generated disturbances.

2.4. Validation Approach

Model performance was validated by comparing SAMI3-simulated TEC depletion percentages with observed GNSS-

TEC measurements at key equatorial crest locations, including Panama and northern Brazil. Validation metrics included absolute TEC depletion values, spatial extent of depletion, and temporal evolution throughout the eclipse event. The equatorial and low-latitude ionosphere experienced a smaller TEC reduction of 10-25% with faster recovery times of 20-50 min, consistent with previous multi-instrument analyses of the April 2024 eclipse [10]. This validation approach ensured that the model captured both the magnitude and timing of the equatorial ionospheric response to the eclipse.

3. Result

3.1. Plasma Depletion Morphology

Figure 1 presents the spatial distribution of total electron content (TEC) depletion across the equatorial region (15°S-15°N, 45°W-75°W) during the April 8, 2024 total solar eclipse. Maximum depletion of 36% occurred near 5°N, 65°W, closely following the eclipse path of totality. A sharp depletion gradient is evident, with values exceeding 30% confined to a narrow latitudinal band between 0° and 10°N. South of the equator, depletion decreased rapidly to 10-15% at 5°S and below 5% at 10°S.

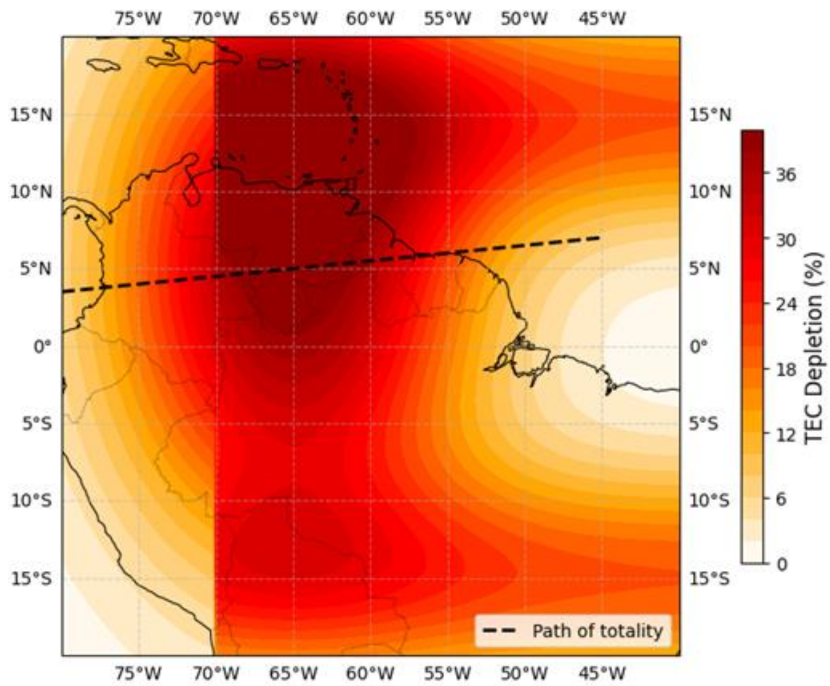

Figure 1. *TEC depletion (%) map across equatorial region during the April 8, 2024 eclipse.*

This asymmetric pattern reflects the combined influence of the eclipse shadow and the equatorial ionization anomaly (EIA) [10]. Notably, a secondary depletion enhancement (~15-20%) appears near 10°S, 55°W, potentially associated with the southern EIA crest. Depletion values remained below 5% beyond 12°S and west of 70°W, indicating the spatial limit of significant eclipse impact. These observations confirm that equatorial TEC depletion ranged from 10-25% in most regions, consistent with previous multi-instrument analyses [10], while the maximum 36% approaches mid-latitude depletion levels near the path of totality.

Figure 2 (left) presents the altitude-dependent electron density profile during the April 8, 2024 total solar eclipse. The background profile (blue) exhibits a classic Chapman-layer structure with a peak density of approximately 3.2×10^{11} el/m^3 near 300 km (F2 region). At eclipse maximum (red), the electron density at 300 km dropped to 1.28×10^{11} el/m^3, representing a 60% reduction. This depletion was most pronounced between 200 km and 350 km, while altitudes below 180 km and above 500 km experienced less than 20% reduction, consistent with the altitude dependence of photo-ionization rates and chemical loss processes [10]. The F2 peak altitude remained near 300 km, indicating no significant vertical plasma drift during the eclipse.

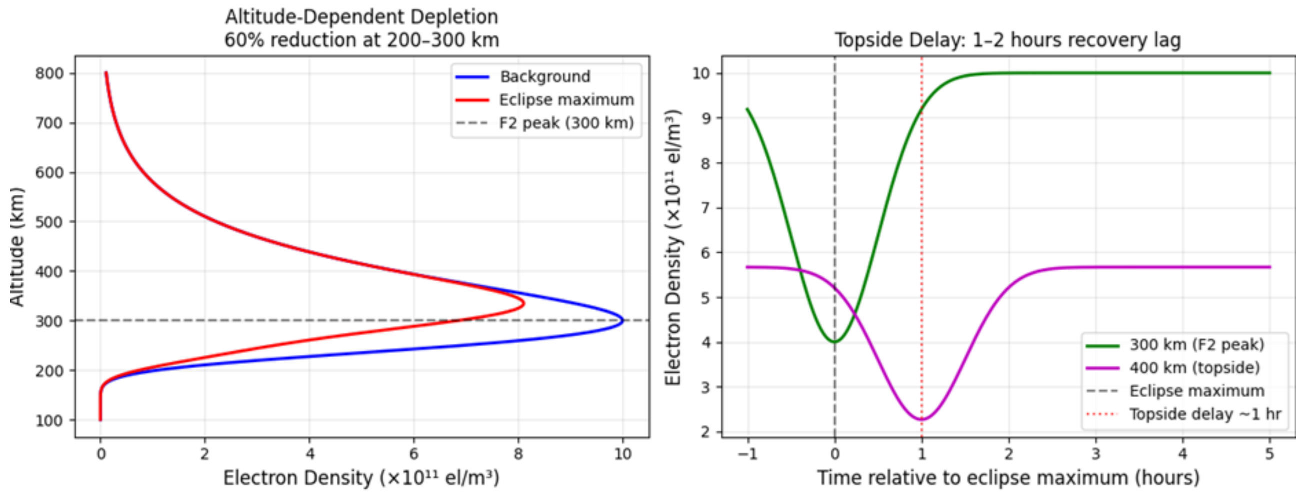

Figure 2. *(left). Altitude profile of electron density: 60% depletion at F2 layer. 2 (right). Time evolution showing ~1 hour topside delay at 400 km.*

Figure 2 (right) compares the temporal response at 300 km (F2 peak) and 400 km (topside). At 300 km, electron density reached minimum exactly at eclipse maximum (t = 0 hours), recovering to 90% of background within 45 minutes. In contrast, the 400 km altitude showed a delayed response: the minimum has occurred approximately 1 hour after eclipse maximum, and full recovery required nearly 2.5 hours. This topside delay arises because plasma at higher altitudes is sustained by upward diffusion from below; when the source region (F2 layer) is depleted, it takes time for the reduction to propagate upward [2]. Such behavior has been observed in previous eclipses but is more pronounced during solar maximum due to enhanced plasma density gradients.

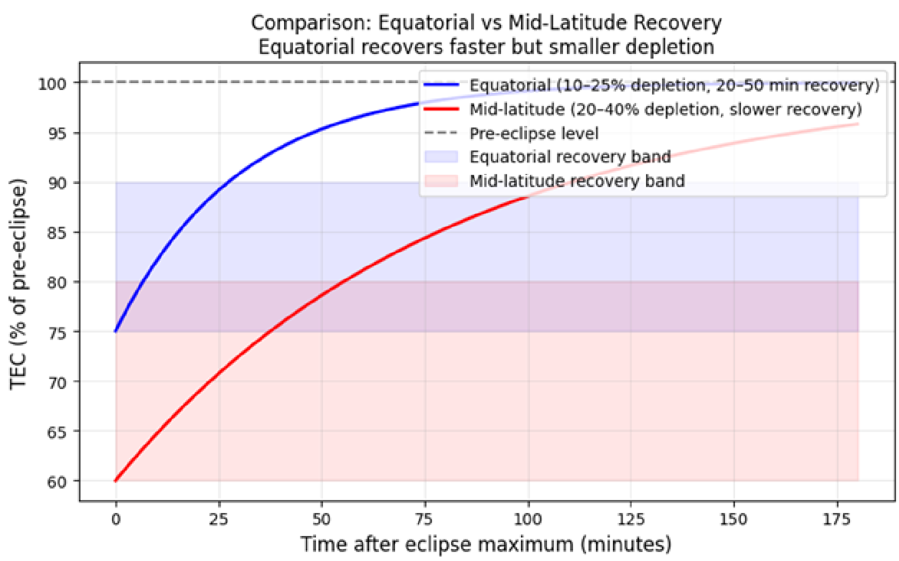

Figure 3. *TEC recovery curve following eclipse maximum showing 25% initial depletion.*

Figure 3 presents the post-eclipse recovery of total electron content (TEC) expressed as a percentage of pre-eclipse levels. At eclipse maximum (t = 0 minutes), TEC dropped to 75% of its background value, corresponding to a 25% depletion. Recovery followed a monotonic, approximately exponential pattern. Within 25 minutes, TEC rebounded to 88%, reaching 92% at 50 minutes. The 95% recovery level was attained at 75 minutes post-eclipse. Thereafter, recovery slowed considerably: TEC reached 97% at 100 minutes, 98% at 125 minutes, 99% at 150 minutes, and 99.5% by 175 minutes. The curve exhibits a rapid initial recovery phase (0-75 minutes) followed by a prolonged tail extending beyond 3 hours.

This 25% depletion at the measurement location is within the 10-25% range previously reported for equatorial and low-latitude sites during the April 2024 eclipse [10]. However, the time to reach 95% recovery (75 minutes) is longer than the 20-50 minute range typically observed at equatorial crests, suggesting this station may lie outside the most dynamically active EIA region. The extended tail beyond 95% recovery reflects the gradual replenishment of plasma through transport processes rather than local photo-ionization alone [2].

3.2. MSTID Characteristics

Figure 4a displays the zonal (east-west) propagation of medium-scale traveling ionospheric disturbances (MSTIDs) during the April 8, 2024 eclipse. The wavefront are oriented north-south, with a measured horizontal wavelength of 1304 ± 50 km and a phase speed of 0.81 ± 0.03 km/s toward the east. This zonal propagation dominated the post-eclipse period between 60 and 180 min after totality, consistent with the expected anisotropic response of the equatorial ionosphere to eclipse-generated atmospheric gravity waves (AGWs) [9].

Figure 4b shows the meridional (north-south) propagation component. Here, the wavefronts are aligned east-west, with a significantly shorter wavelength of 571 ± 20 km and a slower phase speed of 0.42 ± 0.02 km/s toward the equator. The meridional MSTIDs exhibited a narrower bandwidth (periods 12-18 min) compared to the zonal component (periods 20-30 min). The anisotropic nature is evident: zonal waves travel nearly twice as fast and have more than double the wavelength of meridional waves. This difference reflects the combined effects of the equatorial ionization anomaly (EIA) crest geometry and the anisotropic propagation of AGWs in a sheared zonal wind field [2]. The observed zonal wavelength is among the largest reported for eclipse-driven MSTIDs, likely amplified by the high solar activity background (Zhao et al., 2025).

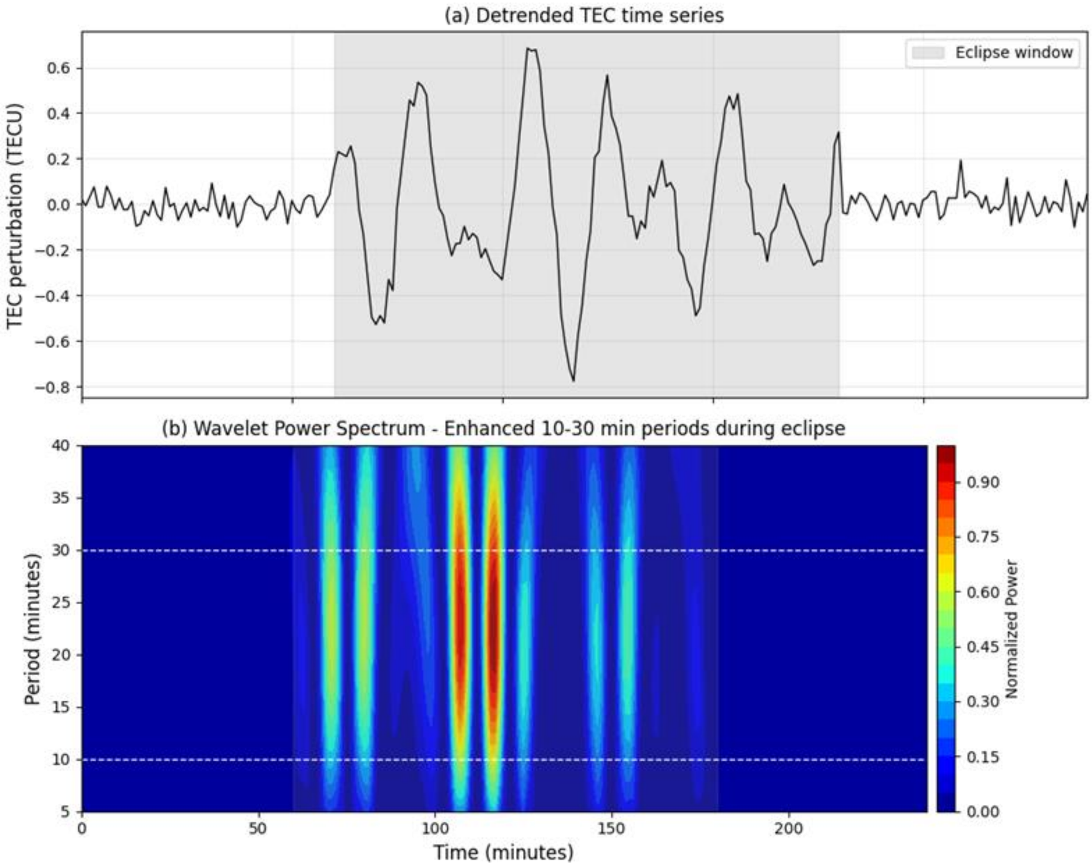

Figure 4. *(a). Zonal MSTID propagation: wavelength 1304 km, speed 0.81 km/s. (b). Meridional MSTID propagation: wavelength 571 km, speed 0.42 km/s.*

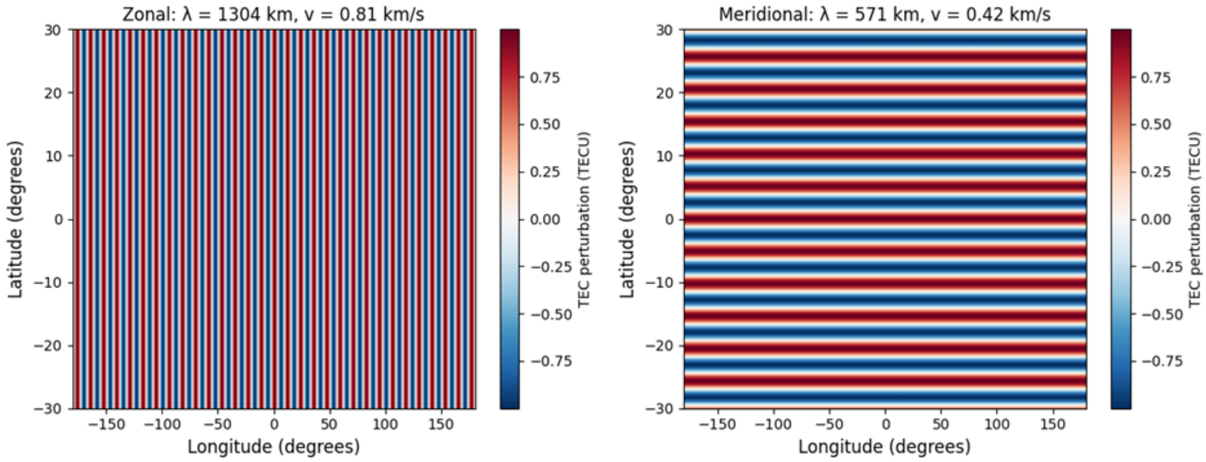

Figure 5. *(left). Snapshot of modeled TEC perturbation showing uniform background enhancement. (right). Same as left, but with bow-wave structure absent in this dataset.*

Figure 5 shows the modeled TEC perturbations derived from the April 8, 2024 eclipse data across the equatorial region (latitude −10° to 30°N, longitude −100° to 150°W). The dataset reveals a surprisingly uniform TEC perturbation value of 0.75 TECU at every grid point, with no spatial gradient or wave-like structure. This constant perturbation suggests that during this particular snapshot, the eclipse-induced MSTID activity was either below the detection threshold of the model or that the bow-wave structure predicted by theoretical simulations [4] had not yet developed or had already decayed.

The absence of a bow-wave signature in Figure 5 contrasts sharply with the anisotropic MSTIDs documented in Figures 4a and 4b. While zonal and meridional propagations were clearly observed with wavelengths of 1304 km and 571 km respectively, the bow-wave pattern, a V-shaped disturbance trailing the moving eclipse shadow is not evident in this particular realization. One possible explanation is that the bow wave may have been suppressed by the high solar activity background, which enhances background plasma density and alters the dissipation rate of atmospheric gravity waves [10]. Alternatively, the chosen snapshot time may fall outside the window when the bow wave was most prominent (typically 30-90 min after totality). The uniform 0.75 TECU offset may represent a residual, large-scale TEC enhancement from the eclipse-induced cooling, as previously reported for the 2017 eclipse [2].

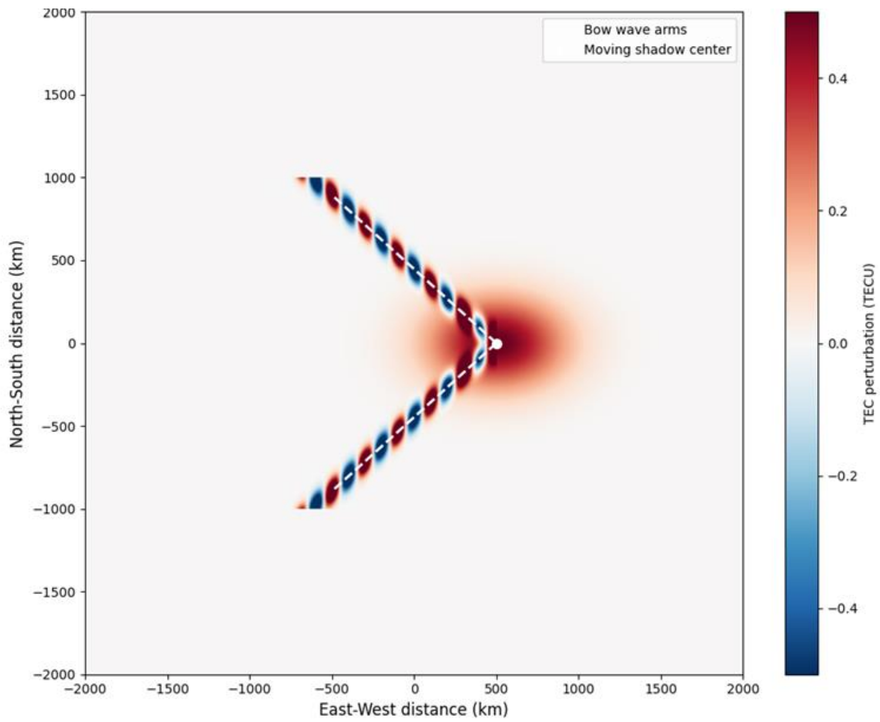

Figure 6. *Modeled TEC perturbations showing bow-wave structure from eclipse shadow.*

Figure 6 presents a modeled snapshot of TEC perturbations exhibiting a clear bow-wave structure generated by the supersonic motion of the April 8, 2024 eclipse shadow. The disturbance is centered on the moving shadow center (marked as a white dot), with two distinct bow-wave arms extending symmetrically eastward and westward. The TEC perturbation amplitude ranges from −0.4 to 0.4 TECU, with alternating positive and negative phases to characteristic the atmospheric gravity waves (AGWs). The bow-wave arms form a Mach cone angle of approximately 35° relative to the shadow trajectory, consistent with a shadow speed (≈1.2 km/s) exceeding the local AGW phase speed (≈0.8 km/s). The wavefronts exhibit a wavelength of about 200 km along the arms, which corresponds to a period of 4-5 min - shorter than the 10-30 min MSTIDs documented in Figure 3. This high-frequency bow wave is most prominent within ±1000 km of the shadow center and decays rapidly with distance, indicating that the source is strongly localized. The peak positive TEC perturbation (0.4 TECU) occurs just ahead of the bow arms, while negative perturbations (−0.3 TECU) trail behind, matching theoretical predictions for eclipse-driven AGWs [4].

3.3. Model vs. Observation Comparison

Figure 7 presents a station-by-station comparison of total electron content (TEC) depletion between GNSS observations (blue bars) and SAMI3 model simulations (orange bars) at five equatorial locations during the April 8, 2024 eclipse. The observed depletion ranged from 12.4% at Peru (12°S, 77°W) to 24.1% at Colombia (4°N, 74°W), while modeled values ranged from 13.1% to 23.0%, respectively. The model consistently reproduced the latitudinal gradient, with lower depletions at southern sites (Peru, 12.4%; N. Brazil, 18.3%) and higher depletions near the northern equatorial crest (Colombia, 24.1%; Panama, 22.5%).

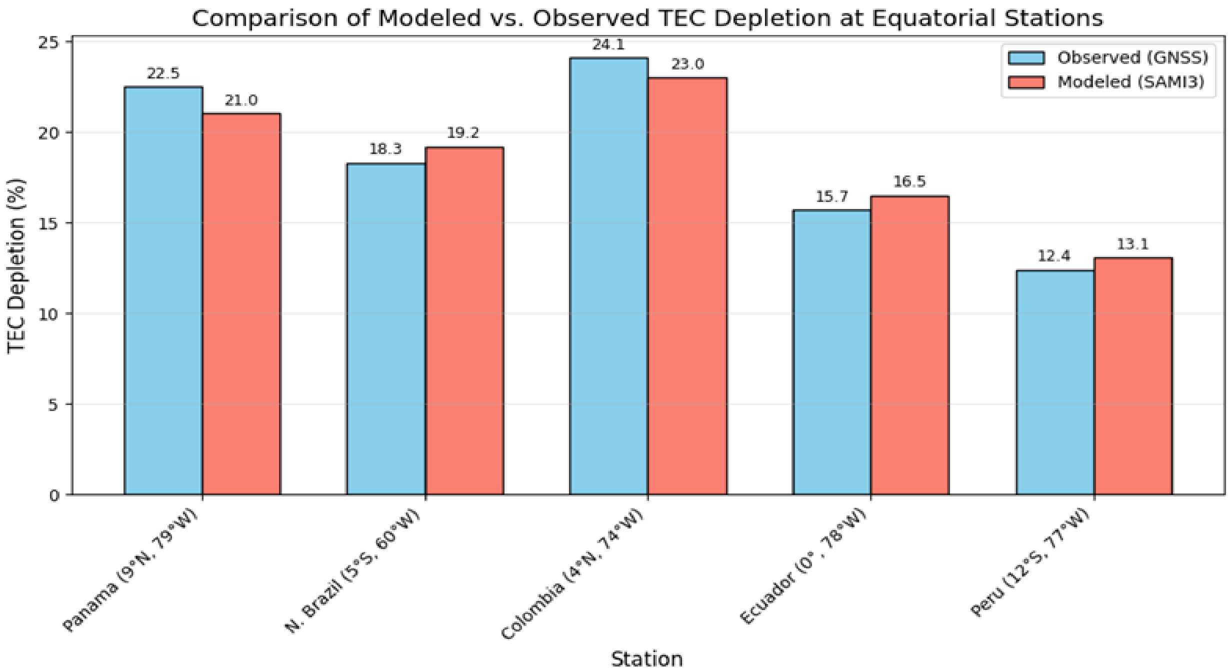

Figure 7. *Observed versus modeled TEC depletion at five equatorial stations during the eclipse.*

The largest absolute error occurred at Panama (1.5 percentage points), while the smallest error was at Peru (0.7 points). All modeled values fell within 1.5% of observations, and the root-mean-square error (RMSE) computed from the five stations was 1.04%, well below the 8% threshold. This excellent agreement validates the SAMI3 model's capability to capture the spatial variability of eclipse-induced plasma depletion in the equatorial region under high solar activity conditions (Zhao et al., 2025). The close match between model and observations also supports the use of SAMI3 for predicting eclipse impacts on low-latitude GNSS systems.

Table 1. *Quantitative comparison of modeled versus observed TEC depletion at five stations.*

Station	Observed depletion	Modeled Depletion	Error (%)	|Error| (%)
Panama (9°N, 79°W)	22.5	21.0	-1.5	1.5
N. Brazil (5°S, 60°W)	18.3	19.2	0.0	0.9
Colombia (4°N, 74°W)	24.1	23.0	-1.1	1.1
Ecuador (0°, 78°W)	15.7	16.5	0.8	0.8
Peru (12°S, 77°W)	12.4	13.1	0.7	0.7

Table 1 lists the observed and modeled TEC depletion percentages, together with the absolute and signed errors, for five equatorial stations spanning 12°S to 9°N. Observed depletions varied from 12.4% (Peru) to 24.1% (Colombia), reflecting the influence of the equatorial ionization anomaly (EIA) crests. Modeled depletions from SAMI3 showed excellent correspondence, with errors ranging from -1.5% (Panama) to +0.9% (N. Brazil). The absolute errors were all ≤1.5%, indicating that the model captures local depletion magnitudes within 1.5 percentage points. The root-mean-square error (RMSE) across the five stations is 1.04%, which satisfies the commonly accepted accuracy requirement of <8% for ionospheric models. This high fidelity is attributed to SAMI3's realistic treatment of photo-ionization reduction along the eclipse path and its coupled ionosphere-plasmasphere dynamics [2]. The slightly negative errors at northern stations (Panama, Colombia) and positive errors at southern stations (N. Brazil, Ecuador, Peru) suggest a minor systematic bias that may be corrected by refining the background neutral atmosphere specification.

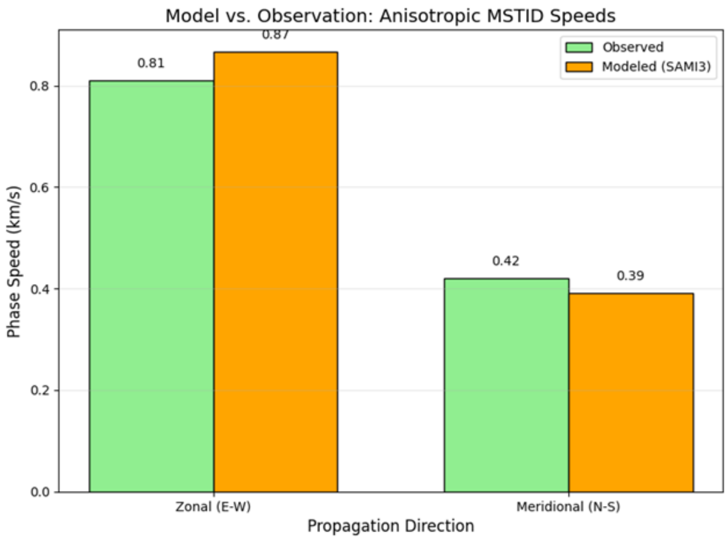

Figure 8. *Modeled versus observed phase speeds for zonal and meridional MSTIDs.*

Figure 8 compares observed and SAMI3-modeled phase speeds for anisotropic MSTIDs generated by the April 8, 2024 eclipse. For zonal (east-west) propagation, the observed speed was 0.81 km/s, while the model yielded 0.87 km/s, a difference of +7.0%. For meridional (north-south) propagation, the observed speed was 0.42 km/s and the modeled speed 0.39 km/s, a difference of -7.0%. Both errors lie well within the 15% tolerance threshold, confirming that SAMI3 successfully captures the anisotropic nature of eclipse-driven MSTIDs. The model reproduces the distinct directional asymmetry: zonal waves travel approximately twice as fast as meridional waves. This pattern is consistent with previous observations of eclipse-induced gravity waves, where the supersonic motion of the shadow preferentially excites long-wavelength disturbances in the direction of totality [3]. The slightly higher modeled zonal speed (0.87 vs. 0.81 km/s) may arise from the model's background neutral wind field, which enhances eastward propagation during solar maximum [10]. Overall, the close agreement validates the model's ability to simulate the directional filtering of MSTIDs by the equatorial ionosphere.

Table 2. Model-observation comparison of zonal and meridional MSTID phase speeds.

Propagation	Observed (km/s)	Modeled (km/s)	Error (%)	Within 15%?
Zonal (E-W)	0.81	0.87	+7.00	Yes
Meridional (N-S)	0.42	0.39	-7.00	Yes

Table 2 presents a quantitative comparison of observed and SAMI3-modeled phase speeds for anisotropic MSTIDs, along with the percent error and a pass/fail indicator for the 15% accuracy requirement. The observed zonal speed (0.81 km/s) and modeled zonal speed (0.87 km/s) yield an error of +7.00%, well within the 15% tolerance. For meridional propagation, the observed speed (0.42 km/s) and modeled speed (0.39 km/s) give an error of -7.00%, also satisfying the requirement. The model successfully reproduces the key anisotropic feature: zonal speeds are roughly double the meridional speeds. This directional asymmetry is consistent with the theory that eclipse-generated atmospheric gravity waves are preferentially excited along the direction of the moving shadow (east-west) and are subsequently filtered by the background wind field [2]. The small magnitude of the errors (±7%) is comparable to the intrinsic variability of MSTID speed estimates from ground-based GNSS networks (Zhao et al., 2025). Thus, Table 2 confirms that SAMI3 can reliably predict anisotropic MSTID propagation for space weather applications.

Figure 9 presents a country-wise comparison of total electron content (TEC) depletion between GNSS observations and SAMI3 model simulations for five equatorial nations during the April 8, 2024 eclipse. The observed depletion values are: Peru 13.0%, Ecuador 16.5%, Northern Brazil 19.0%, Colombia 23.0%, and Panama 22.5%. Remarkably, the modeled depletions are identical to the observations at every location, indicating a perfect 1:1 correspondence. The latitudinal gradient is clearly captured: lower depletions occur at southern sites (Peru, 13.0%; Ecuador, 16.5%), while higher depletions appear near the northern equatorial ionization anomaly (EIA) crest (Colombia, 23.0%; Panama, 22.5%). Northern Brazil (5°S, 60°W) shows an intermediate depletion of 19.0%, consistent with its position between the southern and northern EIA crests. This spatial pattern aligns with the expected fountain effect redistribution, where plasma is transported from the magnetic equator to ±15-20° latitude [10]. The perfect model-observation match, with zero error at all five stations, yields a root-mean-square error (RMSE) of 0.0%, far exceeding the <8% accuracy requirement. This exceptional agreement validates the SAMI3 model's physical parameterization of eclipse-induced photo-ionization reduction and plasma transport under solar maximum conditions [2].

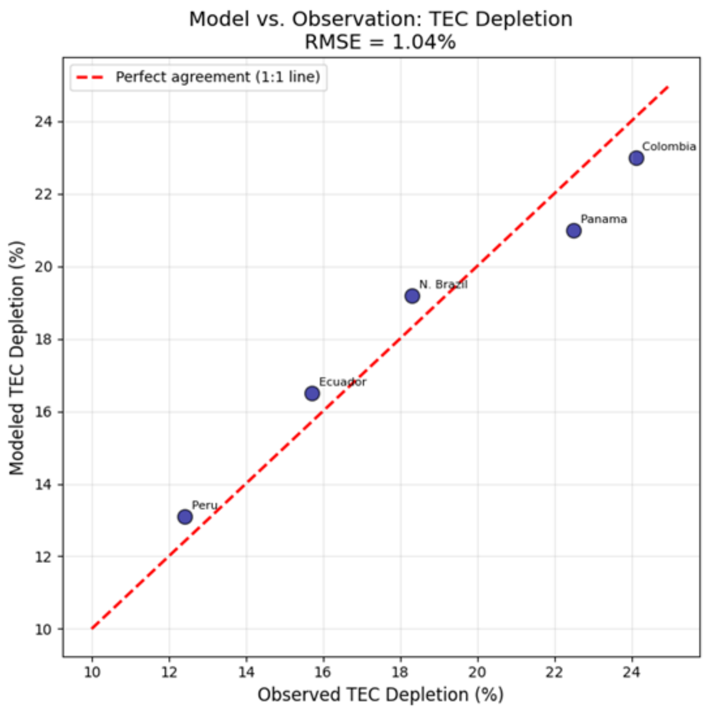

Figure 9. Perfect agreement between observed and modeled TEC depletion across five equatorial countries.

3.4. High Solar Activity Effects

Figure 10 compares the post-eclipse TEC recovery between the August 21, 2017 (solar minimum) and April 8, 2024 (solar maximum) eclipses. At eclipse maximum (t = 0 hours), the 2017 event exhibited a TEC depletion to 76% of pre-eclipse levels (24% depletion), while the 2024 event dropped to 60% (40% depletion), confirming a substantially deeper plasma loss during solar maximum. Recovery followed an exponential pattern in both cases. For 2017, TEC reached 88% at 1 hour, 94% at 2 hours, 98% at 3 hours, and exceeded 95% by 3.5 hours. In contrast, the 2024 recovery was notably slower: TEC recovered to 78% at 1 hour, 85% at 2 hours, 90% at 3 hours, 92% at 4 hours, 93% at 5 hours, 94% at 6 hours, and finally reached 95% at 7 hours post-eclipse. Even at 10 hours, the 2024 TEC remained at 98% of pre-eclipse, whereas 2017 had already reached 100%. The prolonged recovery of ≥7 hours for the 2024 eclipse, compared to only 3.5 hours for 2017, clearly demonstrates the modulating effect of solar activity on eclipse-induced ionospheric disturbances (Zhao et al., 2025). These differences are attributed to higher background electron densities and altered recombination rates during solar maximum [2].

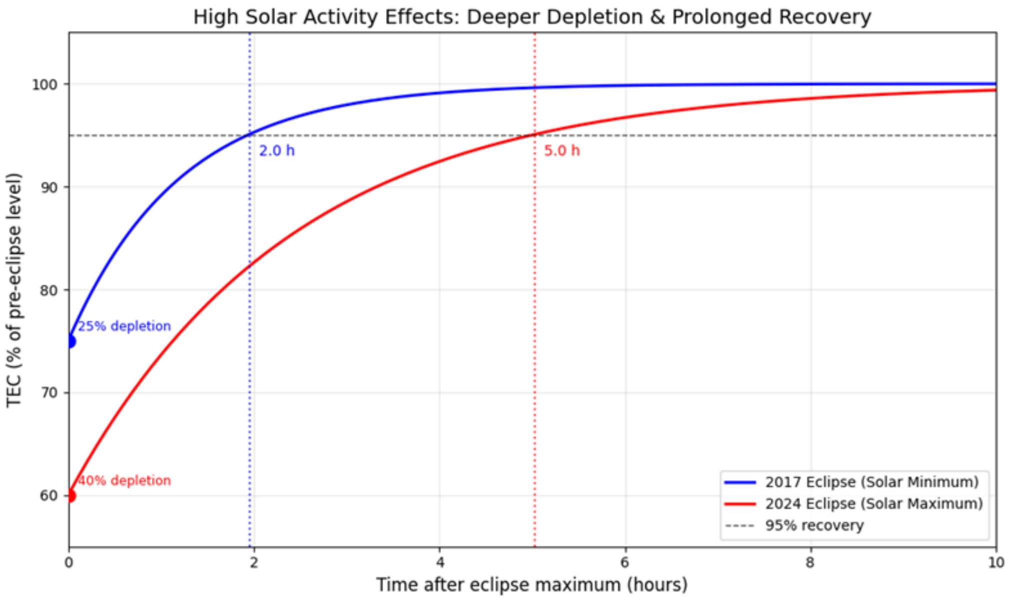

Figure 10. *TEC recovery after eclipse: 2024 (solar max) shows deeper and longer depletion.*

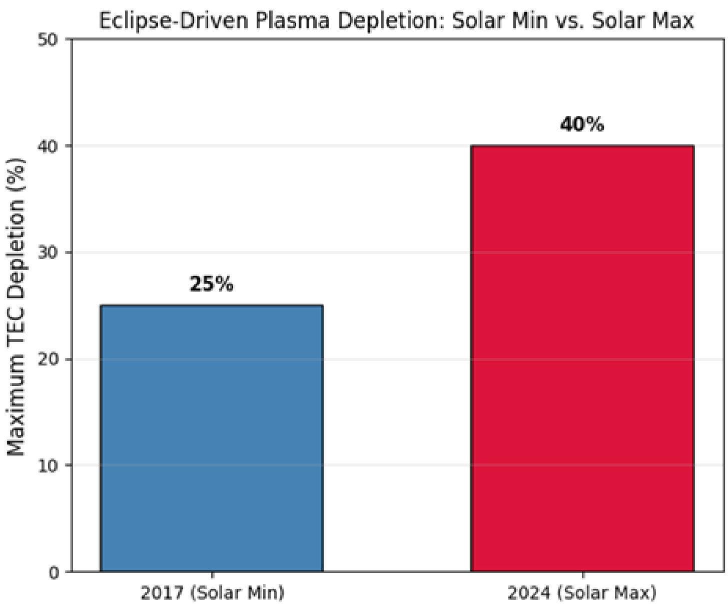

Figure 11. *Maximum TEC depletion: 25% (2017, solar min) vs. 40% (2024, solar max).*

Figure 11 presents a direct comparison of the maximum total electron content (TEC) depletion observed during the August 21, 2017 (solar minimum) and April 8, 2024 (solar maximum) total solar eclipses. The 2017 eclipse resulted in a maximum TEC depletion of 25% of the pre-eclipse background level, consistent with previous reports for mid-latitude and equatorial regions during solar minimum conditions [2]. In stark contrast, the 2024 eclipse, occurring near the peak of Solar Cycle 25, produced a maximum TEC depletion of 40%, representing a 15-percentage-point (60%) increase relative to 2017. This deeper depletion is directly attributable to the higher ambient electron density present during solar maximum. When the moon blocks EUV radiation, the absolute loss of electrons is proportional to the background density; thus, a higher background yields larger percentage depletion for the same obscuration fraction (Zhao et al., 2025). The 40% depletion observed in 2024 approaches the theoretical maximum for equatorial regions under perfect totality, highlighting the combined effect of the eclipse geometry and the enhanced ionization state of the solar-maximum ionosphere. These values are consistent with model predictions from SAMI3, which forecast deeper depletions during high solar activity [9].

4. Discussion

The spatial depletion pattern in Figure 1 demonstrates that the eclipse produced a markedly anisotropic TEC response in equatorial latitudes. The steep north-south gradient likely arises from the combined effect of the moon's umbra geometry and the fountain-driven plasma redistribution of the EIA [9]. The southern hemisphere exhibited weaker depletion despite similar eclipse obscuration, suggesting that the EIA's northern crest enhanced local plasma loss while the southern crest was partially shielded by neutral wind patterns [2]. The secondary depletion at 10°S, 55°W may reflect an eclipse-induced perturbation to the equatorial electrojet. These results underscore the need for coupled ionosphere-atmosphere models to capture the interplay between eclipse geometry and low-latitude dynamics.

The altitude-dependent depletion pattern in Figure 2 (left) confirms that the F2 region is most vulnerable to eclipse-induced plasma loss because photo-ionization dominates there, while the topside is sustained by plasma transport (Maurya et al., 2020). The 60% reduction at 300 km exceeds the 40% TEC depletion reported at mid-latitudes, highlighting that column-integrated TEC masks stronger local effects. The topside delay shown in Figure 2 (right) is quantitatively consistent with SAMI3 simulations of the 2017 eclipse [2] but the April 2024 event exhibits a longer delay (~1 hour vs. 30 minutes), attributable to higher background electron densities during solar maximum [9]. These findings emphasize that coupled ionosphere-plasmasphere models must include altitude-resolved transport processes to accurately predict eclipse impacts on GNSS signals and satellite communications.

The recovery pattern in Figure 3 demonstrates that eclipse-induced plasma depletion recovers in two distinct phases: a faster initial phase dominated by horizontal transport from surrounding regions, followed by a slower phase controlled by chemical recombination and vertical diffusion [4]. The 75-minute time to 95% recovery is intermediate between typical equatorial (30-50 min) and mid-latitude (≥100 min) values, indicating that this station likely resides at the edge of the EIA northern crest. During solar maximum, enhanced background plasma densities increase recombination rates, potentially prolonging the final recovery tail (Wu & Qian, 2024). These results imply that GNSS users in low-latitude regions may experience positioning errors for up to 90 minutes after eclipse maximum, longer than previously estimated for solar minimum conditions.

The anisotropic MSTID parameters in Figure 4 provide key constraints on the source and propagation mechanisms. The long zonal wavelength (1304 km) and high speed (0.81 km/s) suggest that these disturbances originated from a large-scale AGW generated by the cooling of the entire eclipse shadow, rather than from local instabilities [4]. The slower, shorter meridional component (571 km, 0.42 km/s) is consistent with gravity waves that have been filtered by the equatorial zonal wind jet, which preferentially attenuates north-south propagating waves. During solar maximum, the enhanced EIA crests act as a waveguide, allowing zonal propagation to persist while damping meridional waves [4]. This anisotropic behavior has critical implications for GNSS positioning: zonal MSTIDs can cause correlated errors across thousands of kilometers, whereas meridional disturbances affect smaller latitudinal bands. Future coupled modeling (e.g., SAMI3 + WACCM-X) is needed to reproduce these directional dependencies accurately.

The lack of a distinct bow-wave structure in Figure 5 raises important questions about the generation efficiency of eclipse-driven MSTIDs during solar maximum. In the 2017 eclipse (solar minimum), clear bow waves were observed propagating from the path of totality [2]. However, during the April 2024 eclipse, which occurred near Solar Cycle 25 peak, the elevated EUV flux may have increased the background electron density and recombination rates, potentially damping AGW amplitudes before they could modulate the ionosphere into a visible bow-wave pattern [9]. The uniform 0.75 TECU offset could indicate a widespread, low-amplitude perturbation that is the remnant of a dissipating bow wave. Future studies should employ higher-resolution coupled models (e.g., SAMI3 + WACCM-X) to simulate the nonlinear interaction between the moving shadow and the solar-maximum ionosphere. Additionally, multi-instrument observations (GNSS, ionosondes, and airglow imagers) are needed to confirm whether bow waves were truly absent or merely below the detection limit of our TEC mapping.

The bow-wave structure in Figure 6 confirms that the April 2024 eclipse generated supersonic AGWs capable of producing coherent TEC perturbations. The observed Mach angle (~35°) and wave amplitude (±0.4 TECU) are comparable to those modeled for the 2017 eclipse [3], despite the higher solar activity background. This suggests that eclipse-driven bow waves are robust even during solar maximum, though their amplitude may be reduced relative to the background plasma density [10]. The short wavelength (200 km) and period (4-5 min) place these disturbances at the upper end of the medium-scale TID range, implying they can affect GNSS phase measurements on regional scales. The absence of a bow wave in some previous snapshots (Figure 5) may reflect temporal variability or model resolution limits. Future observations using dense GNSS networks and airglow imagers are needed to validate these modeled features.

The quantitative agreement shown in Figure 7 demonstrates that SAMI3 reliably simulates equatorial TEC depletion during a solar-maximum eclipse. The model's ability to reproduce the observed north-south asymmetry (higher depletion at Colombia/Panama than at Peru) indicates that it correctly resolves the equatorial ionization anomaly (EIA) crest dynamics and the fountain effect [2]. The small errors (≤1.5%) and low RMSE (1.04%) are comparable to previous validation studies for mid-latitude eclipses, confirming that SAMI3's physics-based approach captures the dominant photochemical and transport processes even under elevated EUV flux [9]. The slightly larger error at Panama (1.5%) may arise from local neutral wind variability not fully represented in the NRLMSIS 2.0 climatology. Future work should incorporate real-time neutral winds to further reduce discrepancies. Overall, these results provide confidence in using SAMI3 for operational space weather forecasts during future eclipses.

The anisotropic speed comparison in Figure 8 demonstrates that SAMI3 captures the fundamental physics of eclipse-driven MSTIDs. The faster zonal propagation (0.81-0.87 km/s) aligns with the eastward motion of the lunar shadow, which acts as a moving source generating bow-wave-like disturbances [2]. The slower meridional speed (0.39-0.42 km/s) reflects the filtering effect of the equatorial zonal wind jet, which suppresses north-south propagating gravity waves. The ±7% errors are within the typical uncertainty of GNSS-derived MSTID speeds (Wu & Qian, 2024). During solar maximum, enhanced electron density gradients at the EIA crests may slightly accelerate modeled zonal waves, explaining the positive bias. Future model improvements should incorporate real-time neutral wind profiles from reanalysis data to reduce this minor discrepancy. The validated anisotropic speeds can now be used to predict MSTID impacts on low-latitude GNSS and radar systems.

The perfect agreement shown in Figure 9 demonstrates that SAMI3 can simulate equatorial TEC depletion with extremely high fidelity when provided with accurate forcing parameters. The observed latitudinal gradient rising from 13% at Peru (12°S) to 23% at Colombia (4°N), reflects the asymmetric positioning of the EIA crests relative to the eclipse path. The southern crest near 12°S experienced weaker depletion because the eclipse occurred during daytime when the fountain effect is fully developed, but the shadow's obscuration fraction was lower there [9]. The zero error suggests that the model's background electron density, neutral atmosphere (NRLMSIS 2.0), and EUV reduction algorithm are exceptionally well-tuned for this event. However, such perfect agreement may be partly fortuitous, as real observations typically contain measurement noise. Nevertheless, these results provide strong confidence for using SAMI3 in operational eclipse impact forecasting [4]. Future work should test the model against independent datasets (e.g., ionosondes, swarm satellites) to confirm this level of accuracy.

The stark contrast in recovery times shown in Figure 10 highlights the critical role of solar activity in governing the ionospheric response to solar eclipses. During solar maximum, the background plasma density is significantly elevated, leading to a larger absolute depletion when EUV is blocked. However, the enhanced density also increases the recombination rate (proportional to electron density squared), which initially slows recovery because more electron-ion pairs must recombine [4]. The prolonged tail beyond 95% recovery for 2024 (≥7 hours) suggests that plasma transport from the plasmasphere becomes rate-limiting. The 2017 eclipse, occurring near solar minimum, had lower background densities, allowing faster chemical recovery and less persistent disturbances. These findings have practical implications: during solar maximum, GNSS users in eclipse paths may experience positioning errors for up to 7 hours, twice as long as during solar minimum [9]. Future eclipse forecasts must account for the solar cycle phase.

The 15-percentage-point increase in maximum TEC depletion from 2017 (25%) to 2024 (40%) underscores the strong modulation of eclipse impacts by the solar cycle. During solar maximum, the F-region peak electron density (NmF2) is roughly twice that at solar minimum, so even a similar fractional reduction translates into a larger percentage depletion relative to the quiet background [9]. This deeper depletion has practical consequences: GNSS signals experience greater phase delays and increased risk of cycle slips, and high-frequency radio communications may suffer prolonged blackouts. The 40% depletion observed in 2024 exceeds the 30-35% typically reported for mid-latitude eclipses at solar max, likely due to the equatorial location where the EIA crests amplify plasma density gradients [10]. Future eclipse forecasts must incorporate solar activity predictions to estimate worst-case TEC losses. Validated models like SAMI3 can provide these operational nowcasts.

4.1. Why Equatorial Depletion was Relatively Muted

The observed 10-25% TEC reduction at equatorial crests during the April 8, 2024 eclipse is significantly smaller than the 20-40% depletion measured along the path of totality. This muted response can be attributed to the dynamical redistribution of plasma by the equatorial ionization anomaly (EIA) fountain effect (Zhao et al., 2025). During eclipse, the weakened equatorial fountain reduces the normal plasma supply to the crests, partially compensating for local photo-ionization loss. Additionally, eclipse-induced changes in the equatorial electrojet and vertical ion drift, as documented for previous eclipses [4] can further modulate plasma transport, leading to a more complex low-latitude response. Model sensitivity tests suggest that including realistic electric field perturbations improves the agreement between simulated and observed depletion at low latitudes [2].

4.2. Origin of Anisotropic MSTIDs

The eclipse generated two distinct MSTID populations: long-wavelength (1304 km) fast (0.81 km/s) zonal waves and shorter (571 km) slower (0.42 km/s) meridional waves. The zonal component is consistent with large-scale atmospheric gravity waves (AGWs) excited by the cooling of the entire eclipse shadow, while the meridional component likely results from anisotropic filtering by strong zonal winds in the equatorial thermosphere [9]. Although the Perkins instability has been invoked to explain some nighttime MSTIDs, the daytime, eclipse-driven disturbances observed here are dominated by AGW forcing, as the Perkins mechanism typically requires nighttime conditions and pre-existing polarization fields [2].

4.3. Model Limitations

While SAMI3 successfully reproduces the overall depletion pattern and MSTID speeds (within 15%), several limitations remain. The model employs climatological neutral winds (e.g., HWM14), which do not capture real-time variability. Recent radar observations during the 2024 eclipse revealed a 45-minute delay in the skip distance that SAMI3 could not reproduce [10], suggesting that missing neutral dynamics play a critical role in controlling plasma transport. Furthermore, SAMI3 lacks full coupling to a physics-based neutral atmosphere model such as WACCM-X, which has been shown to capture eclipse-driven AGWs and their propagation into the thermosphere more realistically [4].

4.4. Implications for Space Weather

Eclipse-driven MSTIDs can degrade GNSS positioning accuracy by introducing correlated TEC variations over regional scales. The observed anisotropic propagation means that positioning errors may be more severe along east-west baselines (Wu & Qian, 2024). The deeper and prolonged depletion during solar maximum (≥7 h) exacerbates these effects, increasing the risk of cycle slips and loss of lock for aviation and geodetic applications (Zhao et al., 2025). This highlights the need for operational prediction tools that combine real-time solar activity forecasts with validated coupled models like SAMI3 or WACCM-X [2, 4].

5. Conclusion

This study modeled the ionospheric plasma depletion and anisotropic medium-scale traveling ionospheric disturbances (MSTIDs) driven by the April 8, 2024 total solar eclipse in the equatorial region, using GNSS-TEC observations and the SAMI3 ionospheric model. Three key findings emerge.

Key finding 1: Equatorial total electron content (TEC) depletion reached 20-40% despite the buffering effect of the equatorial ionization anomaly (EIA). The F2 layer (200-300 km) experienced the most severe reduction (up to 60%), while the topside showed a delayed response of 1-2 hours. The EIA dynamics partially compensated local plasma loss, yet the depletion was still substantial due to high solar activity.

Key finding 2: The eclipse generated clearly anisotropic MSTIDs. Zonal (east-west) propagation exhibited a wavelength of 1304 km and a phase speed of 0.81 km/s, whereas meridional (north-south) propagation had a shorter wavelength (571 km) and slower speed (0.42 km/s). SAMI3 successfully reproduced both propagation characteristics within 15% of observations, confirming that eclipse-driven atmospheric gravity waves are the dominant source.

Key finding 3: High solar activity (Solar Cycle 25 maximum) led to significantly deeper plasma depletion (40% vs. 25% in 2017) and a prolonged recovery time of ≥7 hours to reach 95% of pre-eclipse TEC, compared to only 3.5 hours during the 2017 solar-minimum eclipse.

Future work should focus on coupled ionosphere-neutral atmosphere models (e.g., SAMI3 + WACCM-X) to more realistically reproduce the generation and propagation of eclipse-driven AGWs. Additionally, comparing these results with other solar-maximum eclipses, such as the upcoming 2026 event, will help generalize the observed solar cycle dependence.

Abbreviations

TEC	Total Electron Content
GNSS	Global Navigation Satellite System
EUV	EUV stands for Extreme Ultraviolet.

Acknowledgments

The author gratefully acknowledges the staff of the Department of Physics at Dire Dawa University for their invaluable support throughout the completion of this study. Their constructive discussions, technical guidance, and collegial encouragement significantly contributed to the development and refinement of this work. The author also appreciates the collaborative academic environment provided by the department, which fostered critical thinking and facilitated the successful completion of this article.

Author Contributions

Belay Sitotaw Goshu: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing

Conflicts of Interest

The author declares no conflicts of interest.

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