Reply#1

We sincerely appreciate and are honored to receive your insightful comments, which have significantly improved the quality and clarity of our manuscript. We have diligently addressed all the raised concerns and our detailed responses are presented as follows:

(0) Line 23: The term "Rocket Exhausted Depletions (REDs)" is awkward and ambiguous. A better term would be "Holes in the Ionosphere from Rocket Exhaust (HIREs)"

Response:We agree that the term "Rocket Exhausted Depletions (REDs)" is awkward and ambiguous. Accordingly, we have replaced it throughout the manuscript with the clearer and more descriptive term "Holes in the Ionosphere from Rocket Exhaust (HIREs)."

(1) Line 32: The statement "The study contributes to a deeper understanding of the formation and development of artificial ionospheric plasma bubbles." is misleading. The word bubbles refers to equatorial structures that rise in altitude. The plasma depletions produce by rocket exhaust do not "bubble" up but just stay at a fixed altitude. Please replace "bubbles" by "hollow-tubes".

Response: We appreciate this important clarification. To avoid confusion between the term "bubbles" and equatorial plasma bubbles, and to better reflect the structures observed in this study, we have replaced "bubbles" with "hollow-tubes" in the revised manuscript.

(2) Line 57 has "Bernhardt et al., 1961, 2001". Bernhardt was not writing papers in 1961. Please use the correct date and that check this paper is in the references.

Response: We sincerely apologize for the citation error. The reference to 1961 was mistakenly attributed to Bernhardt; the correct 1961 reference is Booker and is already cited elsewhere in the 11manuscript. We have corrected "Bernhardt et al., 1961, 2001" to "Bernhardt et al., 2001" in Line 57. During this revision, we also rechecked the references and corrected the other inconsistency.

(3) Line 413 has "This study first utilizes COSMIC-1 occultation data to resolve the vertical structure of REDs, integrates Swarm and GNSS-TEC observations, and reconstructs its 3D hollow-tube morphology." should be replaced with "This is the first study that utilizes COSMIC-1 occultation data to resolve the vertical structure of REDs, integrates Swarm and GNSS-TEC observations, and reconstructs its 3D hollowtube morphology."

Response: Thank you for helping us improve the clarity of our wording. The sentence in Line 413 has been revised as suggested:"This is the first study that utilizes COSMIC-1 occultation data to resolve the vertical structure of HIREs, integrates Swa rm and GNSS-TEC observations, and reconstructs their 3D hollow-tube morphology."

Once again, we sincerely thank the reviewer for the careful reading and constructive feedback.

Reply#2

We are grateful and honored to have received your valuable feedback, which will enhance the quality of our manuscript and the expression of research innovation. We have carefully addressed all raised concerns, with specific responses as follows:

1. Lines 85-89, authors state that "Park et al. (2022) also utilized the GOLD imager, Madrigal TEC, and multiple Low-Earth-Orbit satellites, with COSMIC-2 data revealing an increase in ionospheric slab thickness at the depletion center, indirectly supporting vertical structure analysis. However, the 3D structure of rocket-exhausted electron density depletion remains unclear." Also, in Lines 111-112, it is stated "The gridded data products derived from COSMIC occultation observations have been used in rocket-induced depletion (RED) studies (Park et al., 2022)."

I think the authors miss out what the COSMIC-2 data were utilized in Park et al. (2022). It was the data assimilation data product of COSMIC-2, which has 3-D structure of the ionosphere. As Park et al. (2022) did provide altitudinal variations of REDs for their event, it is not for the first time the authors provide the 3-D results. In fact the Abel inversion of the electron density profile provided by the standard data output of COSMIC might be errouneous at lower altitudes (lower than ~250 km altitudes) due to its assumptions of spherical symmetry over a wide area of ionosphere (Yue et al., 2010; Liu et al., 2010). The RED generation of the density depltion on the other hand is an asymmetry density structure and therefore the actual depth/strength of the RED might not be precised using Abel inversion of the radio occultation observations. This altitude is also roughly similar to that the authors reported, so some cautious or discussion is also necessary.

1. Response:We sincerely thank the reviewer for raising this important issue.

(1a) Park et al. (2022) employed GOLD imagery, Madrigal TEC data, and multiple low-Earth-orbit satellites to monitor REDs. Although they utilized the COSMIC-2 GIS gridded product for three-dimensional analysis of the depletion, the spatial resolution of the GIS product is insufficient for resolving the precise three-dimensional structure and evolution of the electron density hole. Specifically, the GIS grid has a horizontal resolution of 5° × 2.5° in latitude–longitude and a vertical resolution of 20 km, which is coarse relative to the typical horizontal scale of REDs (~500 km). Moreover, GIS products rely on the underlying COSMIC observations; if the occultation data capture the depletion, the GIS product may reflect its three-dimensional morphology. However, given the sparse coverage of COSMIC data and the relatively small spatial scale of REDs, the representation of depletion structures in the GIS product may contain considerable uncertainties.

We have revised the original text in Lines 85–89 and Lines 111–112 accordingly. The original statements: "Park et al. (2022) also utilized the GOLD imager, Madrigal TEC, and multiple Low-Earth-Orbit satellites, with COSMIC-2 data revealing an increase in ionospheric slab thickness at the depletion center, indirectly supporting vertical structure analysis. However, the 3D structure of rocket-exhausted electron density depletion remains unclear." and "The gridded data products derived from COSMIC occultation observations have been used in rocket-induced depletion (RED) studies (Park et al., 2022)."

have been revised as follows:

"Park et al. (2022) also utilized the GOLD imager, Madrigal TEC, and multiple low-Earth-orbit satellites, with COSMIC-2 data revealing an increase in ionospheric slab thickness at the depletion center, indirectly supporting vertical structure analysis, while the COSMIC-2 Gridded Ionospheric Specification (GIS) gridded product provides indirect evidence for the three-dimensional distribution of electron density depletions. However, due to the insufficient spatiotemporal resolution of the GIS data (5°×2.5° in latitude and longitude, 1-hour temporal resolution), which is coarse relative to the typical ~500 km width of rocket-induced depletions, the fine three-dimensional structure and evolutionary process remain poorly resolved."

(1b) Regarding the uncertainty in the electron density profiles derived from standard COSMIC data: The electron density profiles obtained from COSMIC standard data products are derived using the Abel inversion method, which assumes large-scale spherical symmetry of the ionosphere (Yue et al., 2010; Liu et al., 2010). This assumption may introduce errors in the lower altitudes (below ~250 km), and in some cases, even produce artificial cavity structures. Given that REDs are characterized by strongly asymmetric spatial distributions, the actual depth and intensity of the depletion may not be precisely captured by the Abel inversion method. Therefore, to avoid the uncertainties associated with the inverted electron density profiles, we instead used the original podTEC data in subsequent comparisons. As shown in the Figure R1, the RED signatures were extracted from the podTEC data using the method of Pradipta et al. (2015). Previous studies have shown that the typical uncertainty of podTEC data derived from Low-Earth-Orbit radio occultation is about 2-3 TECU (Yue, 2011). In comparison, the depletion magnitudes observed in these two occultation events are significantly larger than this uncertainty range, indicating that the observed signals are not due to measurement errors but rather represent a genuine physical phenomenon.

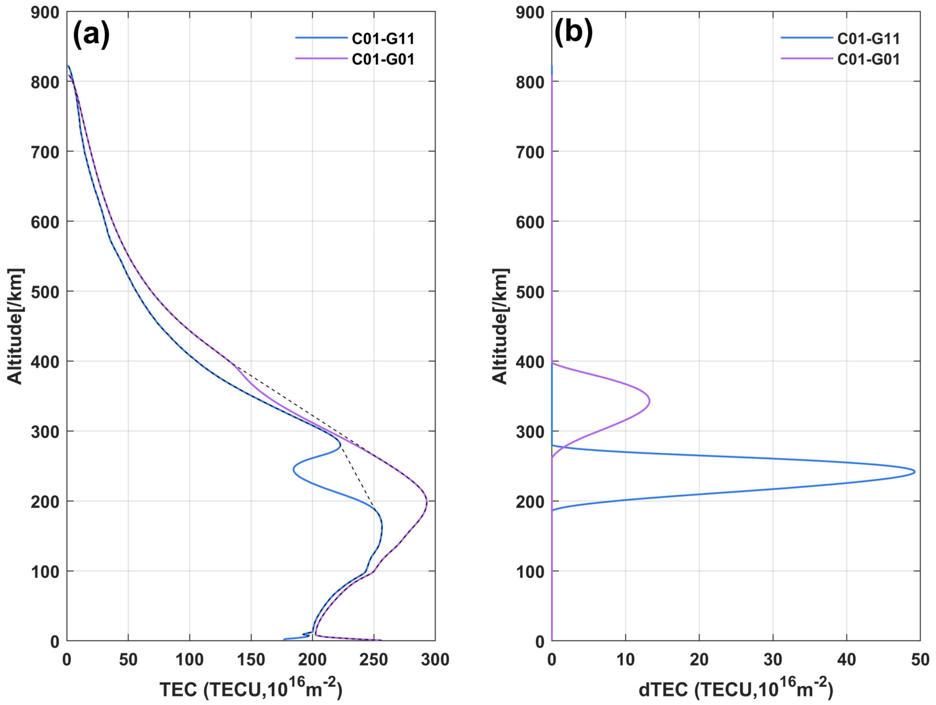

Figure R1. (a) COS TEC height profile of the occulted star; (b) dTEC value extracted by the method from Pradipta et al.,(2015)

We have added a detailed discussion of this uncertainty in the revised manuscript, including the following additions:

"Both COSMIC-1 radio occultation events occurred within 50 minutes after the rocket launch, and the observed depletion regions were located within approximately 300 km of the rocket trajectory. This temporal and spatial proximity indicates that the observed ionospheric depletion was very likely caused by the rocket launch. For event C01-G11, the TEC depletion was about 50 TECU, with a corresponding electron density reduction exceeding 75%; in contrast, event C01-G01 showed a weaker depletion, with a TEC decrease of about 13 TECU and an electron density reduction of less than 20%. Previous studies have shown that the typical uncertainty of podTEC data derived from low Earth orbit radio occultation is about 2-3 TECU (Yue, 2011). In comparison, the depletion magnitudes observed in these two events are significantly larger than this uncertainty range, suggesting that the observed TEC depletions were mainly caused by rocket exhaust. "

Ref:

Pradipta, R., Valladares, C. E., and Doherty, P. H.: An effective TEC data detrending method for the study of equatorial plasma bubbles and traveling ionospheric disturbances, J. Geophys. Res. Space Physics, 120, 11,048–11,055, https://doi.org/10.1002/2015JA021723, 2015.

Xu X., Hong Z., Guo P., Liu R. Retrieval and validation of ionospheric measurements from COSMIC radio occultation[J]. Acta Physica Sinica, 59(3): 2163-2168. https:/doi.org/10.7498/aps.59.2163.2010.

Yue, X., Schreiner, W., Hunt, D., Rocken, C., & Kuo, Y., Quantitative evaluation of the low Earth orbit satellite based slant total electron content determination, Space Weather, 9, S09001, https://doi.org/10.1029/2011SW000687, 2011.

2. Lines 115-116, the authors claimed that "A detailed assessment of the feasibility and reliability of COSMIC occultation data can be found in Yan et al. (2022). In this study, we utilize the electron density and total electron content (TEC)." I assume they refer to this one from their Reference list.

Yan, X., Yu, T., and Xia, C.: Limb Sounders Tracking Tsunami-Induced Perturbations from the Stratosphere to the Ionosphere. Remote Sensing, 14(21), 5543. https://doi.org/10.3390/rs14215543, 2022.

However, this one is clearly not for validation of COSMIC radio occultation, two more suitable references validating COSMIC-1 and COSMIC-2 are provided as follows.

For COSMIC-1:

Lei, J., et al. (2007), Comparison of COSMIC ionospheric measurements with ground-based observations and model predictions: Preliminary results, J. Geophys. Res., 112, A07308, doi:10.1029/2006JA012240.

COSMIC-2:

Lin, C.-Y., Lin, C. C.-H., Liu, J.-Y., Rajesh, P. K., Matsuo, T., Chou, M.-Y., et al. (2020). The early results and validation of FORMOSAT-7/COSMIC-2 space weather products: Global ionospheric specification and Ne-aided Abel electron density profile. Journal of Geophysical Research: Space Physics, 125, e2020JA028028. https://doi.org/10.1029/2020JA028028

Response: We appreciate the reviewer providing more suitable references for validating COSMIC data. After reviewing the suggested literature, we have added these references to the revised manuscript:

3. In the comparison of the simulations and the observed RED, the discrepancy between observation

and simulation was attributed to the background ionosphere applied in the simulation, which is from IRI. It is well understood that IRI output would not match to realistic ionosphere. But a good comparison can be made by percentage of the depletion. Also, the assumption of the H2O diffusion shall be different from reality. I think a better comparison shall be made by the authors by performing various simulation task to find out what the most suitable diffusion parameter might be for the density depletion to better agree with the observation. In this way, the authors or the readers could know how far off the assumption of diffusion given by Bernhardt (1976) to the reality. In the current version, simply compare the simulation with observation and give hypothesis to the discrepancy is actually not very helpful to better understandings of the underlying physics.

Response: We sincerely thank the reviewer for highlighting this important aspect. In our manuscript, the diffusion coefficient is not treated as a fixed parameter but is explicitly calculated based on the background neutral atmosphere composition and temperature. The expressions used are as follows:

$$D_{H_2O}=[\frac{n_O}{8.46\times10^{17}T_n^{0.5}}+\frac{n_{N_2}}{2.04\times10^{17}T_n^{0.632}}+\frac{n_{O_2}}{2.02\times10^{17}T_n^{0.632}}]^{-1}cm^2\cdot s^{-1}$$

$$D_{H_2}=[\frac{n_O}{2.97\times10^{18}T_n^{0.5}}+\frac{n_{N_2}}{2.8\times10^{17}T_n^{0.740}}+\frac{n_{O_2}}{3.06\times10^{17}T_n^{0.732}}]^{-1}cm^2\cdot s^{-1}$$

Here, n_i denotes the number densities of O, N2, and O2, and T_n is the neutral atmospheric temperature. This formulation, which is derived from Mendillo (1993), enables the diffusion coefficient to vary across the simulation domain according to the local neutral composition and temperature. It provides higher fidelity compared to the anisotropic diffusion approach used in Heki (2008), which approximated diffusion using only a few points. We agree that differences between empirical models (such as IRI and NRLMSISE) and the actual atmosphere inevitably lead to discrepancies between simulated and observed results. To improve the analysis, we have added a more detailed comparison between simulation and observations, along with a discussion of the contributing factors.

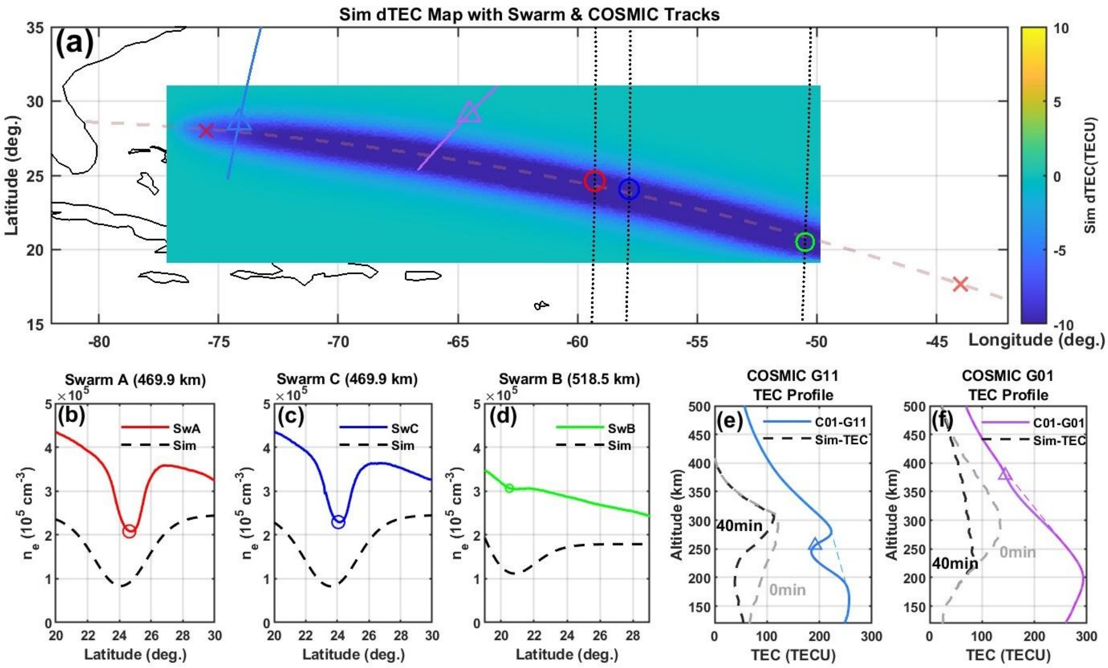

Figure 4 Comparison of the simulated dTEC calculation at the 40th minute with observational data. (a) The variation in the vertical integral of the simulated electron density, dTEC; (b–d) Comparison of electron

density between Swarm satellites and simulations; (e–f) Comparison of the integral of electron density along the simulated COSMIC radio occultation ray path with the podTEC from occultation observations.

In the simulation results, Figure 4a shown the distribution of the vertical TEC variation. The simulated TEC variation intensity is approximately 10 TECU, and the simulated depletion is primarily distributed along the release trajectory, with a horizontal width perpendicular to the trajectory of about 500 km. Figures 4(bcd) present a comparison of electron density between the Swarm A, Swarm C, and Swarm B satellites and the simulations. The simulation results show that at the location corresponding to Swarm A, the electron density reduction amplitude is 1.6×10^6 cm^{-3} (with an observed reduction of 1.9×10^6 cm^{-3}), and the background change rates are 65.6% and 65.7%, respectively, significantly higher than the depletion amplitudes of 45% and 39% observed by Swarm A and Swarm C. The background electron density observed by the satellites is significantly higher than that output by the IRI model; this discrepancy affects the chemical reaction efficiency and extent, representing a primary reason for the differences between the simulation and observations. Figures 4(ef) show a comparison between the integral of electron density along the simulated COSMIC radio occultation ray path and the podTEC from occultation observations. The simulated TEC variation is about 40 TECU, and the depletion altitude ranges are 120-305 km and 220-450 km, respectively, which are broader than those observed in the two occultation events. The background TEC is significantly lower than the observed values, primarily due to the combined effects of the occultation ray path geometry and errors in the background electron density from the IRI model.

And The newly added text includes：

“ By integrating the simulated vertical electron density, the equivalent vTEC as observed by ground-based GNSS can be obtained. In this study, equivalent observational integrals were also performed along the ray paths of two COSMIC radio occultation events, and the simulation results were compared with electron density measurements from the Swarm satellites, as shown in Figure 4. The simulated vTEC depletion amplitude and spatial scale are generally consistent with ground-based GNSS observations; the discrepancies between the simulation and Swarm satellite observations primarily arise from the fact that the background electron density output by the IRI model is significantly lower than the observed values. In the chemical process of depletion formation, the recombination efficiency ($\Delta n_i = k_i \cdot n_A \cdot n_A \Delta t$)is related not only to the reaction rate constant k_i but also to the concentrations of the reacting species. A higher background electron density leads to a higher chemical recombination efficiency, resulting in a greater magnitude of electron density loss.The broader depletion range output from the simulation along the occultation ray path, compared to actual observations, is closely related to the diffusion coefficient of the released species. The diffusion coefficient is influenced by background atmospheric parameters, and the atmospheric component concentrations provided by the NRLMSISE model deviate from actual values, with a root mean square error of approximately 30% and up to 100% in extreme cases (Doornbos et al., 2008). This deviation affects the diffusion coefficient of the released species and further influences the concentration distribution of the diffusing species. Additionally, the IRI model exhibits errors in the background electron density and oxygen ion (O^+) conditions, which further affect the efficiency and extent of the chemical reactions. The diffusion coefficient varies with altitude and local time, modulated by background atmospheric composition and temperature; lower atmospheric molecular concentrations or higher temperatures result in faster diffusion and broader distribution of the released species, leading to larger depletion scales (both width and thickness), but the accompanying concentration reduction results in a smaller depletion amplitude. Therefore, the primary mechanisms governing the characteristics of REDs can be attributed to the diffusion coefficient and background constituent concentrations, both of which are determined by the background conditions of the exhaust release."

Ref:

Doornbos E. ,Klinkrad H.,Visser P. , Use of two-line element data for thermosphere neutral density model calibration, Advances in Space Research, Volume 41, Issue 7, 2008, Pages 1115-1122, ISSN 0273-1177, https://doi.org/10.1016/j.asr.2006.12.025.

4. Furuya and Heki (2008) did perform similar simulation and compare their results to observations of GNSS-TEC. Any new insights from this study on top of Furuya and Heki (2008)? The authors may state the differences between the then study to this latest one to better describe the novelty of this study. Maybe the modeling is more comprehensive in this study? Maybe the electrodynamics is included in this study? What is the advantage of this study to the one published in 2008?

Response: We sincerely thank the reviewer for this constructive suggestion.

(1) Firstly, the core contribution of this study lies in integrating multi-source observational data (including vertical profiles from COSMIC, in-situ measurements from Swarm satellites, and ground-based GNSS data) with high-resolution numerical simulations to reconstruct the 3-D tubular electron density depletion structure of REDs. The more comprehensive numerical model we developed serves, on the one hand, to reconstruct the three-dimensional tubular structure of REDs, and on the other hand, to validate and compare with the observed depletions. Previous studies have mainly focused on the horizontal distribution of REDs using GNSS TEC data, with limited vertical information. Although some GIS products can reflect three-dimensional grid structures, their resolution remains insufficient to resolve the tubular morphology of the ionospheric depletion.

(2) Comprehensiveness of the modeling: Our modeling approach is more comprehensive in two respects. First, the mathematical formulation incorporates not only the neutral diffusion and chemical processes but also the effects of electrodynamics, including background electric and magnetic fields, which influence plasma transport. Second, we reconstruct the realistic rocket launch scenario. Recognizing that the release trajectory plays a crucial role (Feng et al., 2021), we incorporate the three-dimensional rocket trajectory and calculate the exhaust mass flow rate based on engine parameters to more accurately represent the release process.

(3) Inclusion of electrodynamics: The plasma diffusion process is explicitly included in our model. Plasma diffusion, distinct from neutral diffusion, is an important physical process in the ionosphere that persists throughout the neutral release and chemical reaction phases and governs the drift and evolution of the depletion structure.

(4) Advantages over the 2008 study: (4a) Our model is more comprehensive and offers higher parametric accuracy. It includes the plasma diffusion process, which is physically distinct from neutral diffusion. In addition, the diffusion coefficient is computed using high-resolution neutral composition and temperature, allowing a more accurate representation of neutral species diffusion. (4b) The observational data used in this study are more diverse, including vertical profile data from COSMIC and in situ measurements from Swarm satellites, providing both vertical and horizontal constraints on the depletion structure. (4c) The three-dimensional tubular structure of the electron density depletion is reconstructed through observation-constrained numerical simulation, rather than being solely a

simulation product. This integration of observations and simulation yields a more robust depiction of the depletion morphology.
We will revise the manuscript accordingly to better highlight these distinctions and the novelty of this work.

Once again, we sincerely thank the reviewer for the careful reading and constructive feedback.