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Reviewer #1

Q: Eclipse effects on thermosphere-ionosphere-magnetosphere coupling processes were mentioned, but this topic was not pursued in any detail in the manuscript. There was the mention of geomagnetic activity, but only as it related to non-eclipse induced effects away from the path of totality.

A: We discussed the effect of disturbed thermospheric winds being impacted by the passage of the totality in paragraphs 280, 300, 325, 425, and which in turn affect the electron densities in the ionosphere. These changes are directly related to the eclipse and are due to thermosphere-ionosphere coupling. We do agree with the reviewers that the component of magnetospheric coupling was not included, and thus we will remove it from the first paragraph of the introduction.

Q: The main goals of the study are (1) to accurately identify eclipse-induced variations in Ne, Te, Ti over central to eastern North America, and (2) to discuss observed features that challenge current understanding of ionosphere-thermosphere coupling processes. Goal (1) was extensively addressed in the text, but I did not find a clear statement of the unanswered questions arising from the observations.

A: We appreciate the reviewer’s suggestions and will include additional information in the discussion section as described below.

Most of the prior reports of ISR-based observations have focused on vertical variations of multiple ionospheric state parameters. In this study, we extend our understanding into the horizontal domain, highlighting spatially varying ionospheric responses to the varying eclipse obscuration. Additionally, the results show that unique eclipse induced ion temperature cooling occurred and reached 225 K, among the largest ion temperature drops reported during an eclipse. Furthermore, Millstone Hill radar data revealed that simulations that show an increase with altitude in the eclipse-driven reduction in mid-latitude ion temperature do not match observations. Specifically, altitudinal variation of Ti decreases shows a clear peak (not a monotonic decrease) at 260-325 km altitude, above which there is decreased cooling at altitudes above ~350 km.

This result extends beyond the vertical-only study of the August 2017 eclipse by Goncharenko et al [2018], which also showed a similar altitude dependence in ion temperature decrease. In aggregate, this points to needed improvements in energetics for full profile modeling attempts to understand ionospheric thermodynamics and its connections to ionosphere-thermosphere coupling. These future modeling improvements, e.g. more realistic upper boundary conditions or more correct light neutral and ion species (H, He, H+, He+), could resolve the discrepancy.

Reviewer #2

Q.: The manuscript presents the results of a comprehensive study of a number of ionospheric characteristics over the eastern part of the USA during the total solar eclipse of 8 August 2024. The authors conducted extensive investigations and identified distinctive features of ionospheric behavior over a large portion of the region. This was made possible through the employment of the incoherent scatter technique with wide-field scans. This technique is unique in that it simultaneously provides a suite of ionospheric parameters for specific altitudes and locations. The reported findings have strong potential to improve our understanding of the complex atmospheric and ionospheric processes occurring during solar eclipses and to enhance the predictive capability of numerous ionospheric models.

My main concerns are related to the reliability of the retrieved ionospheric characteristics, especially the electron and ion temperatures. My estimates indicate that the range to the scattering volume is about 1500 – 3500 km for altitudes of 200 – 400 km. Taking into account that the echo signal power is inversely proportional to the square of the range, I have serious concerns about the ability to retrieve these parameters with acceptable accuracy, despite the operation in uncoded, very long transmitted pulse mode. I fully realize that these concerns might be resolved by reading the tens of publications cited by the authors. However, the manuscript itself should provide sufficiently comprehensive methodological information, without requiring the reader to refer the external sources unless absolutely necessary.

A: We respectfully disagree with the reviewer. The technique of collective Thomson or incoherent scatter radar as a full-altitude probe of the ionospheric state has a history stretching back to the first practical measurements in the late 1950s after a landmark paper by W. E. Gordon of Cornell University. A robust theory tied to a plasma physics based first-principles model has existed through several independent derivations since the late 1950s and early 1960s. A good summary of the technique is contained in Evans [1969, 2005]. The forward plasma physics model used in fitting radar spectra to yield plasma parameters allows the data uncertainties measured through power spectral or autocorrelation analysis (e.g. Farley et al, 1969) to map directly into quantitative uncertainties on the plasma parameters at each measured range using standard inverse analysis methods. These quantitative uncertainties are used as inputs in the applied methods described in the study.

Q: The description of the applied methods in the manuscript is currently insufficient and requires expansion in order to address potential questions from readers.The major comments presented below are mostly based on the above concerns and call for stronger emphasis on the key factors necessary to improve the clarity of the reported results.

1. *The authors do not provide information on the errors (in percentage) associated with the electron density and plasma temperature measurements during the solar eclipse observations. In addition, it would be very useful if the authors could present representative range profiles for the pre-obscuration, obscuration, and post-obscuration intervals. If any measures were taken to reduce these errors, they should be briefly highlighted in the manuscript.*

A : Thank you for the suggestion. We have observed that wide-field measurements with the Millstone Hill steerable 46 meter antenna at low elevations using 2 msec long uncoded pulses provide sufficiently low uncertainties on plasma parameters to conduct the applied methods described. In Figures 1 and 2 below, we present these experimental uncertainties.

Figure 1 below shows the uncertainties associated with each of the parameters (Ne, Te, and Ti) for a single azimuth ~ -93 degrees over range profiles (shown in altitude measurements) on April 8th, 2024. Each of the panels shows the profiles 2 hours before maximum obscuration over the scanning region, during maximum obscuration over the scanning region, and 2 hours after maximum obscuration. As we can see, errors associated with measurements from 200 - 400 km are low, typically hovering in the single digit percentage range. Additionally, to train the polynomial regression model, we retained data that had uncertainties no greater than 3%. This is described in the Methods section:
"Several filters are also applied to MISA data before training the model. First, the data selected above is organized into 6.5◦ azimuth ×28 km altitude bins and resampled every 30 min. Missing data points are forward-filled to maintain continuity. Second, any data with an experimental uncertainty greater than 3%, and with values that fall outside the 5-95th percentile is rejected. Early morning data before 10 LT was excluded due to high levels of uncertainty."

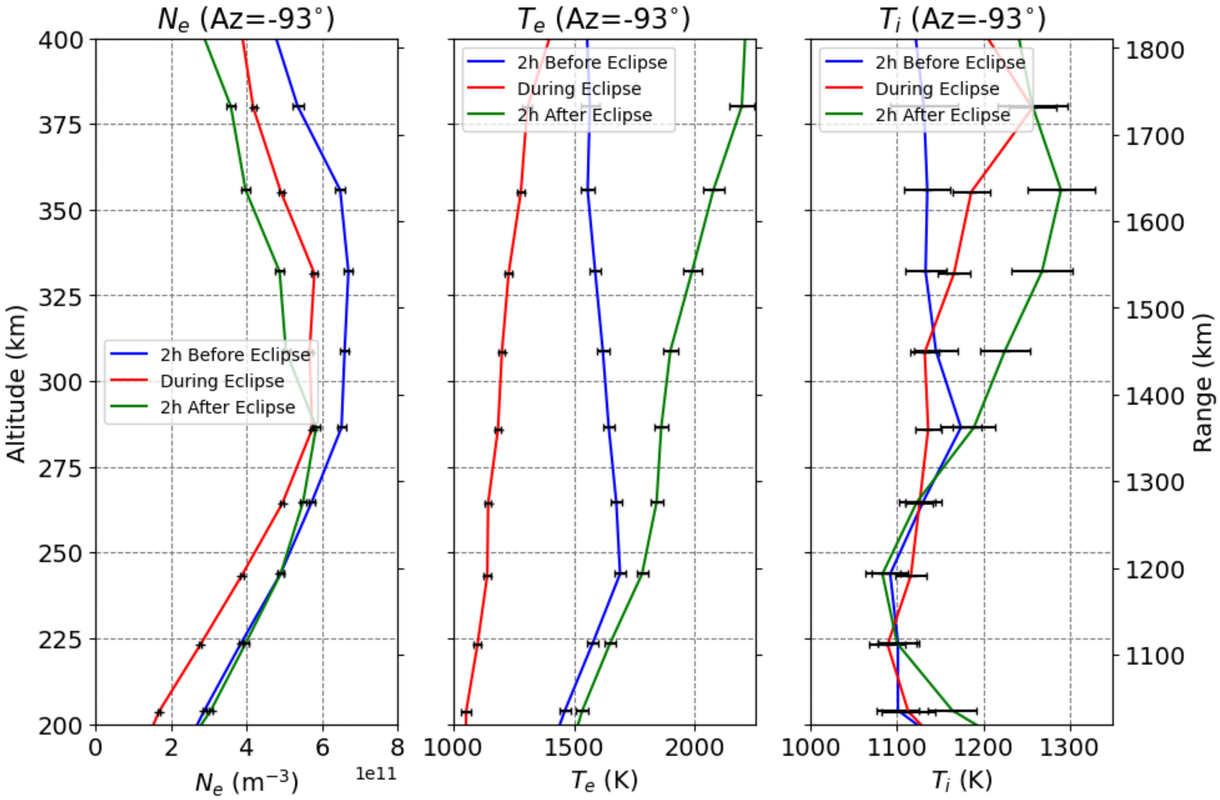

Figure 1. Altitude profiles of the observed Ne (left), Te (middle) and Ti (right) 2 hrs prior to the eclipse (blue), during the eclipse (red) and 2 hrs after the eclipse (green).

Figure 2 below shows the average of ALL errors both absolute and relative from 15 - 20 UT and averaged across all azimuths. As we can see, the relative error is quite low for all parameters from 200 - 400 km.

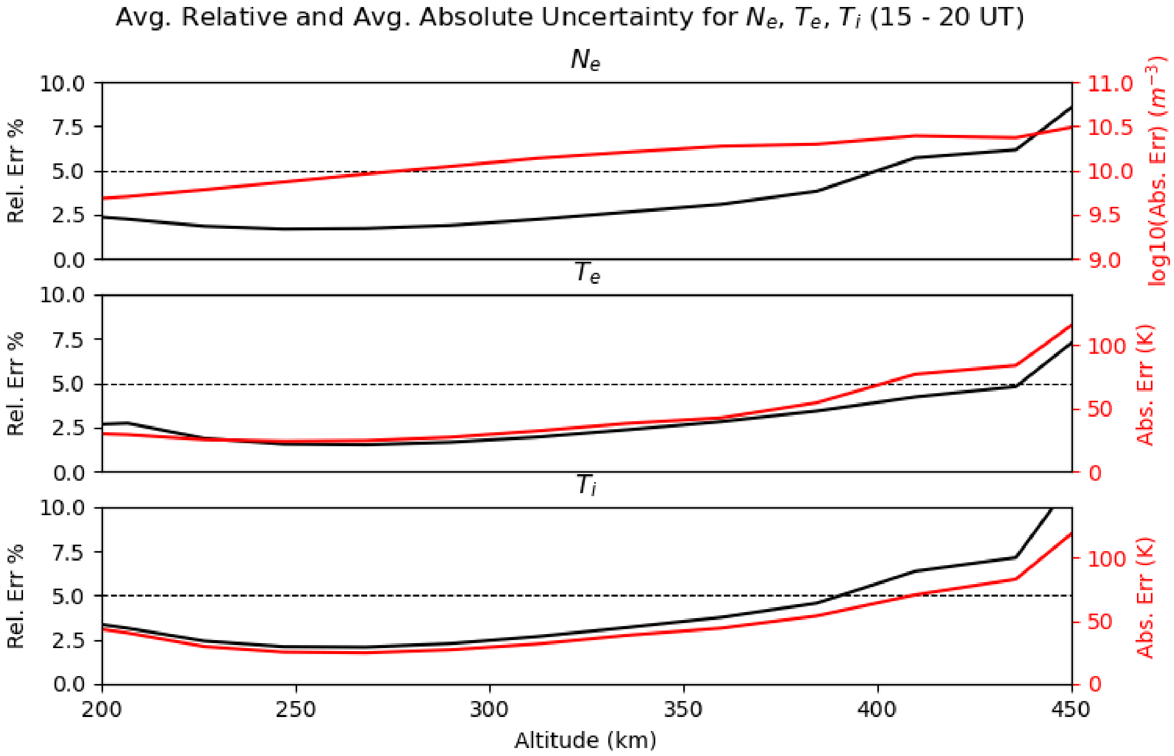

Figure 2. Altitude profiles of relative (in black) and absolute errors (in red) of Ne, Te, and Ti averaged over 15 - 20 UT and across all azimuths.

Q.:

2. *The ion-acoustic power spectra method does not directly yield absolute electron density values unless calibration coefficient or external data for calibration are applied. It is therefore unclear which calibration methodology was used in this study. I strongly recommend that the authors provide electron density values obtained by independent techniques (e.g., ionosonde and/or Swarm data) for cross-validation.*

A: Altitude profiles of electron density are obtained from collective Thomson / incoherent scatter radar theory (many papers; e.g. see above paper - Evans, 1969) using a volumetric target radar equation, including a term connecting radar signal power to electron density through a calibration factor. This calibration constant is determined by direct comparison of measurements of signal power from the F-region electron density peak with plasma line / Langmuir mode measurements of peak electron density. Measurement of the plasma line return (frequency of scattered energy) at the F region peak directly connects electron density to fundamental physical constants. Since a frequency is measured as opposed to an area under a curve, accuracy of the resulting plasma line derived electron density is well under 1%.

Electron density has been routinely calibrated at Millstone Hill using the plasma line technique since Jan 1, 2016. Descriptions can be found, for example, in Shammat 2023; Shammat et al., 2024, with the latter describing the overall calibration procedure. Numerous other studies utilized Millstone Hill ISR plasma line calibrated data (Wang et al., 2019, Figure 2, during the 2017 solar eclipse; Zhang et al., 2019, Figure 14, during a solar flare; Zhang et al., 2021, two traveling ionospheric disturbances events)

Q:

3. *The authors provide Equation (1) illustrating the applied Tikhonov regularization. However, the manuscript does not specify the chosen values of the regularization coefficient α, nor does it justify the criteria used for selecting these values.*

A: Thank you for your suggestion and we will include an additional explanation in the Methods section. The regularization coefficient α was selected via empirical tuning to minimize the mean percentage error on test data. The alpha coefficients used vary from 0.5 - 2 among altitude bins. In parallel, a k-fold cross-validation analysis was also performed across $\alpha \in [10^{-4}, 10^{4}]$ at each altitude bin, for sampled logarithmically with 1000 candidate values. Optimal α coefficients found using this method resulted in very minimal performance gains and the coefficients found using empirical tuning were retained for simplicity.

Q.:

4. *Using the 2 ms uncoded transmitted pulse with a 6° elevation angle yields a horizontal resolution of about 280 km. During the motion of the Moon’s shadow, horizontal gradients in electron density and temperature can arise at spatial scales smaller than 300 km. How were such horizontal gradients accounted for in the retrieval of ionospheric characteristics?*

A.: This is a good point. Because of the use of a 2 msec long pulse at low elevation, the horizontal resolution of the variations resolved by the radar is unavoidably larger than 300 km, and any ionospheric variation within the pulse length is being averaged. Therefore, the study analysis focuses on the comparisons of large scale ionospheric variations such as across the broad areas of the near topside and the F region or over large longitudinal spans.

Q.:

5. The Discussion section should be extended to address potential sources of distortion in ionospheric characteristics when the incoherent scatter technique is used. In particular, the negative effect of “space debris” at altitudes above 200 km cannot be completely excluded by filtering. Such contamination can introduce significant bias in the retrieval of electron and ion temperatures.

A.: We agree with the reviewer in extending the Discussion section to include a brief discussion on the topic of space debris. From our present analyses of MISA ISR data, the main difficulty presented by “hard target” space debris comes from in-beam reflections due to the Starlink operational belt at 550 km altitude. The much larger cross-section of the satellite bodies themselves, combined with any debris in the orbit plane, yields a heavily distorted signal and prevents any incoherent scatter measurements.
However, Millstone Hill observations show that this does not prove an operational problem for realistic ionospheric parameter profiles at altitudes significantly away from the Starlink orbital shell, and with the steerable MISA antenna at off-vertical directions (6 degree elevation) as is used in our study. These conclusions are based on comparisons during non-eclipse conditions to empirical based models of ionospheric parameters (e.g. Zhang and Holt, 2008) and to the standard IRI model. (Adding these comparisons to the paper is considered beyond its scope.) In particular, the wide field results from the steerable MISA antenna do not show any hard target distortions to beyond the sensitivity range of even the longest radar pulse used. Detailed calculations of the relative cross-section of ionospheric Thomson scatter versus satellite debris are beyond the scope of this paper, and are not relevant or even possible at present as the flux of 34 cm debris is not sufficiently characterized in orbit.

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