Reviewer 1

Review of the manuscript “Reevaluation of EISCAT plasma parameters during the May 2024 geomagnetic storm using O+ ratios from AMIE-driven SD-WACCM-X”

In this manuscript, the authors compare plasma parameters derived from measurements by the EISCAT incoherent scatter radar in Svalbard (ESR), using ion compositions as a prior from the original IRI model and the AMIE-driven WACCM-X model. The results differ with different ion compositions. Based on their analysis, the authors also suggest developing a correlation model to quickly correct the original EISCAT GUISDAP analysis. The authors argue that their method is advanced because it is based on first-principles simulations, and this physics-based approach reduces biases in EISCAT plasma parameter fits compared with standard analyses. However, this argument may not be sufficient based on the current analysis. Additional analysis and discussions are needed. Please see my comments as follows:

Authors:

We thank the reviewer for their evaluation and helpful suggestions.

Major comments:

1. The authors emphasize that their method is advanced because the first-principles model WACCM-X, with AMIE as the driver, is used to provide a more accurate ion composition. However, the question is whether the model itself can reproduce the ionospheric parameters during this May 2024 superstorm, particularly locally at ESR. If significant deviations are observed between the simulation results and ESR measurements, it may not be appropriate to claim that using the simulated ion composition can debias the fitting results. I suggest comparing Ne, Te, and Ti between the simulation outputs and GUISDAP results, with and without the new ion composition.

2. Comment 1 is also associated with a question on the temporal and spatial resolution of simulations. The simulation may provide large-scale distributions; however, it performs poorly under highly dynamic conditions, especially during geomagnetic storms. A discussion of the temporal and spatial scales of ion composition in the model should be conducted.

Authors (combined answer for major comments 1&2):

The advancement of our method is only with reference to applying IRI O+ ratios. Visual comparison to Cai et al., 2026 (see response to comment 4) suggests that the physics-based ion composition matches the BAFIM results better than IRI (though a distinct overestimation of O+ appears to be the case, likely connected to the overall overestimation of O/N2 in WACCM-X). Our method should therefore reduce the bias of EISCAT parameters, even if the plasma temperatures and density are moderately reproduced by the physics-based model. A comparison of model and measurement plasma parameters can be given in the supplementary material, but would, in our opinion, not benefit the study.

A discussion of the temporal and spatial scales is indeed relevant and will be added to the manuscript.

3. The linear correlation model and Equation 2 are based on the assumption that the actual or more accurate O+ ratio is known. Although the authors suggest a “quick correlation” can be applied for a user who is not familiar with EISCAT analysis. However, in practise, the user needs to know the O+ ratio in advance. If a simulation model like WACCM is needed, it will require computational resources and may not be “quick”. Please clarify this if possible.

Authors:

For the existing database of EISCAT measurements, available WACCM-X long-runs can be applied as O+ ratio source (e.g., WACCM-X Simulation of the Atmosphere From 1950 Through 2024 at an Hourly Resolution - Brown - 2026 - Journal of Geophysical Research: Space Physics - Wiley Online Library). For new measurements, additional simulations need to be conducted, which, as the reviewer states correctly, requires computational resources. The applicability of TIE-GCM rather than WACCM-X should be investigated, as it requires fewer computational resources, and the boundary conditions are easier to set to recent conditions.

4. In this study, the ion composition from the model is used to fit the ionospheric parameters of the ISR. On the other hand, the fitted parameters, especially the ion temperature, can affect ion-neutral reactions and hence modify the ion composition. As mentioned in Section 4.2, the BAFIM module with the Ion Density Calculator (IDC) was developed to fit the EISCAT parameters, including the ion composition. One of the advantages of that technique is that it iteratively fits the parameters to ensure that the ion and electron temperatures input to IDC are based on measurements, and that the fitted combination of plasma parameters is reasonable from a chemistry point of view. Hence, that technique is also suitable for rapid changes in ion temperature and composition, which typically occur during active geomagnetic conditions, such as substorms and storms. In addition, a recent study by Cai et al. (2026) used the BAFIM analysis to show the ionospheric responses to the May 2024 superstorm, including changes in ion composition. A discussion on the similarities and differences between the two studies can be made.

Cai, L., Aikio, A., Geethakumari, G. P., Vanhamäki, H., Virtanen, I. I., Oyama, S.-i., et al. (2026). Ionosphere-thermosphere coupling in the Northern polar region during the May 2024 geomagnetic superstorm. Journal of Geophysical Research: Space Physics, 131, e2025JA034495. https://doi.org/10.1029/2025JA034495

Authors:

The mentioned paper was published shortly before the original submission of our manuscript and, hence, is not part of the original discussion. We are thankful for the chance to include it in the now extended discussion and the reviewers' helpful elaborations on the BAFIM technique. We would like to specifically state that the method proposed in our paper is not intended to achieve an accuracy comparable to the BAFIM method, but as an alternative approach applicable in certain cases where a fast debiasing of multiple EISCAT measurement campaigns is required (See comment 3).

Additionally, our proposed method is an initial step towards the application of EISCAT measurements for data assimilation in physics-based models. As the reviewer correctly states, the ion composition affects the ion temperature, in turn affecting the ion composition. Assimilation of EISCAT measurements can therefore only be done meaningfully if the entire

scatter spectra, rather than single parameters, are assimilated. We see this paper as a demonstration of this issue.

As suggested, we added a discussion on the similarities and differences between Cai et al., 2026 and the presented study.

Minor comments:

L30: Could you clarify why to select the May 2024 storm? There are also many publications focusing on this storm. A brief literature review can be conducted of studies of high-latitude electrodynamics during this storm, particularly those associated with incoherent scatter radar analysis.

The missing parameterization of IRI ion compositions with geomagnetic activity is most pronounced during storm conditions. With the availability of multi-day EISCAT measurements and AMIE data assimilation, we chose this event as a favorable example for the proposed method as well as an interesting case study on ISR analysis techniques. We extended the literature review of this event.

L75: Kp exceeded 9

Kp is, by definition, limited to a maximum value of 9, whereas more recently developed indices are allowed to exceed this limit. For historical categorization, Kp still has considerable merits, but we clarified the statement in L75.

L78: In addition to Themens et al., 2024, Cai et al. (2026) studied the polar ionosphere-thermosphere coupling using multiple observations. They showed that both Ti increases and neutral composition changes are important for F-region recombination and hence result in electron density depletion and ion composition changes in the polar region.

We thank the reviewer for the suggestion and have added the proposed statement.

L105: It's unclear during which time period and at which height ranges the data are used for the correlation analysis.

The correlation analysis involves all altitudes and time periods shown in Figure 1. As this study only provides a proof-of-concept, no outlier removal or data filtering has been performed. For the development of an actual debiasing function that uses a larger EISCAT database across diverse geomagnetic conditions, some data cleaning will be required.

L108: ".. except for dNe below the transition altitude." In Figure 4a, there are several linear dependencies between drO+ and dNe when nO+ < 0.5 Ne. Could you discuss why there are several dependencies? Also, similar dependencies are visible in Figure 4c for Te.

Figure 4c shows Ti, which the reviewer presumably means. The different linear dependencies come from different altitude levels. This could indicate that the linear correlation of the O+

difference and the parameter change depends on background conditions, which, of course, vary with altitude. The fact that this is mainly (or rather most dominantly) observed below the transition altitude of the O+ ratio (rO+=0.5) could also indicate that this is related to assumptions about the molecular ion mass. However, at the present stage, we can only speculate, and further investigations will be necessary. We added a brief discussion to the manuscript.

L124: Could you expand the discussion on Figure 5 and Table 1. For example, what is the physics meaning of such relations?

The relations in Table 1 are empirical observations based on Figure 5. We assume they are rather a mathematical consequence of the GUISDAP fitting process and do not carry a physical meaning. However, this is a mere assumption for which we do not feel able to give a reasonable explanation. We expanded the discussion on Figure 5 and Table 1 to adequately state our assumption and the lack of evidence for it.

Figures: Figures 2-7: The font size of the labels is too small to see. Please increase the size. Figures 1,2,5: time ticks are not visible. In addition, it's better to turn on minor ticks to identify times of day.

Done.

Reviewer 2

The manuscript is well written and covers an important topic for incoherent scatter radar (ISR) spectra fitting to obtain plasma parameters, specifically the ion composition estimate used when performing the spectra fits. By using a model run from WACCM-X the authors are able to improve the plasma parameter fits from the Guisdap software package during the May 2024 Superstorm using the EISCAT Svalbard 42m radar. There are 2 runs of the WACCM-X model, one driven by 'Heelis' which is effectively driven by the Kp-Index, and one driven by 'AMIE' which is data driven from an extensive set of different ionospheric and geomagnetic measurements. The authors only use the AMIE driven model when presenting the results.

The authors make suggestions to use the re-analysis technique on the larger EISCAT dataset. This is currently not reinforced by their analysis, though it could be with further analysis and information. The following further analysis is suggested:

G*eneral response by the authors:*

We thank the reviewer for their helpful comments and suggestions. We especially appreciate the very sensible suggestion to either extend the analysis or adapt the conclusions of this study.

We would like to emphasize that we do not suggest using Equation 2 as a correction model and never intended this study to provide a statistically valid debiasing. This study explores ISR analysis techniques on a highly important space weather event and provides a proof of concept for the suggested method of debiasing EISCAT measurements using physics-based O+ ratios. At

the moment, this proof is limited to storm conditions. A statistical investigation of Heelis-driven O+ ratios will be conducted separately, and if possible, include the derivation of a debiasing model. We have adapted the conclusions of the study to reflect this.

1) Using WACCM-X with Heelis to obtain the plasma parameter fits and comparing the results with the WACCM-X AMIE driven model derived fits.

Authors:

Figure 2b shows the Heelis-driven WACCM-X O+ ratios in comparison to AMIE-driven results in Figure 2c. As the relation of O+ ratio to parameter changes is mostly linear, we deemed it unnecessary to show the results for both geomagnetic driving approaches in this initial test. A future study will show fits using Heelis-driven O+ ratios on a wider range of geomagnetic conditions.

2) Using the full profile incoherent scatter fit provided in, e.g., Virtanen et al. 2021, and comparing with the results here. The study presented here is a perfect opportunity to compare the full profile fits to the model driven fits. This would be appreciated by the greater community, with hopefully good agreement between the methods. Virtanen et al., 2021, provides functions that should be usable in the Guisdap software, and it should not be an insurmountable amount of work to re-process this period of data with that software.

Virtanen, I. I., Tesfaw, H. W., Roininen, L., Lasanen, S., & Aikio, A. (2021). Bayesian filtering in incoherent scatter plasma parameter fits. Journal of Geophysical Research: Space Physics, 126, e2020JA028700. https://doi.org/10.1029/2020JA028700

Authors:

This analysis has been conducted by:

Cai, L., Aikio, A., Geethakumari, G. P., Vanhamäki, H., Virtanen, I. I., Oyama, S.-i., et al. (2026). Ionosphere-thermosphere coupling in the Northern polar region during the May 2024 geomagnetic superstorm. Journal of Geophysical Research: Space Physics, 131, e2025JA034495. https://doi.org/10.1029/2025JA034495

Unfortunately, the above-mentioned article was published very shortly before the original submission of our manuscript, which is why it was not discussed in the original version. We added an extensive discussion of their results and a comparison to our method/results (see also answer to reviewer 1).

3) Including a few days with different geomagnetic conditions to determine how the WACCM-X model driven ISR spectra fit results compare with the IRI model spectra fits during less geomagnetically active days.

Authors:

AMIE inputs are manually generated, commonly only for specific space weather events, which usually involve a certain level of geomagnetic activity. A larger database of EISCAT database, including diversified geomagnetic conditions, will be required for developing the actual

debiasing model based on Heelis-driven WACCM-X long-runs (e.g., https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2025JA034630).

It should be stated, that even without this additional analysis the manuscript still has merit. It is only that there is the potential for a much improved study that can be used as a basis for what techniques to use when determining ionospheric parameters from the incoherent scatter spectra when the ion composition is unknown.

Therefore, it is suggested that the authors either present the manuscript as is, and remove some of the suggestions without the proper validation of the statements, or provide an impactful study with some additional figures and comparisons that will be greatly appreciated by the community. It is for this reason that 'Major Revisions' has been suggested.

Please find comments corresponding to the specific lines below.

Lines 91-92: This manuscript is highlighting the re-analysis technique for ISR spectra fitting using the WACCM-X model, and in lines 91-92 it is even mentioned that the Heelis-driven model is more applicable to the re-analysis of the EISCAT measurements in general. The manuscript does not show any results from using the Heelis-driven WACCM-X model though, even though the authors have the data available. It is difficult to determine if the claims of using WACCM-X with Heelis-driving is suitable. Please include the results from Heelis-driven WACCM-X Guisdap spectra fitting and compare with the AMIE-driven WACCM-X Guisdap results.

Authors:

As mentioned above, we are focusing on the presentation of the technique for a single storm case here. For a statistical debiasing model, Heelis-driven O+ ratios as shown in Figure 2b will have to be applied. Heelis-driven O+ ratios show less variability (as expected) but a similar general trend as AMIE-driven O+ ratios. Due to the mostly linear correlation of parameter changes and O+ ratio difference to IRI, conducting the analysis for both Heelis and AMIE would result in similar outcomes, reflecting the differences of Figures 2b and c.

Lines 114-115: The scope of the paper is the May 2024 superstorm, but the manuscript argues for the technique to be applied to the general dataset. More days with different geomagnetic conditions should be investigated before making this claim.

Authors:

We removed this claim and will conduct a statistical study, including quiet time conditions, at a later stage.

Lines 168-169: It is claimed that a validation of BAFIM is difficult, but the data presented here is a great opportunity to compare the techniques and potentially validate both. BAFIM was developed for Guisdap and therefore should be able to be used in the ISR spectra fitting analysis without too much difficulty.

Authors:

An extensive comparison to Cai et al., 2026, who use the BAFIM technique on this campaign, is included in the revised manuscript.

Lines 172-173: The correction function presented has not been sufficiently analysed for different geomagnetic conditions to know if it is suitable. And even then, it potentially only 'corrects' one parameter, T_e. The other parameters do not show such a linear response. Ideally, EISCAT would generate the different incoherent scatter spectra fits with well defined and documented input conditions and make those results available to the users.

Authors:

We agree that an actual correction model requires a thorough statistical analysis. Equation 2 is provided as an example of what a correction function could look like. We have clarified this.

Lines 188-189: It is stated that the Heelis-driven WACCM-X would have to be used for EISCAT ISR spectra corrections but there are no results presented from this, even though the authors have the data available. Further, there is a claim that the correction model would be applicable to all researchers but there are no results showing that such a correction model is viable for different geomagnetic conditions. Please expand the analysis to address these statements.

Authors:

As mentioned above, we present the Heelis-driven O+ ratio in Figure 2b and limit the later results to the AMIE-driven run due to the linear correlation of O+ ratio difference and parameter change.