We thank the reviewer for a very thorough evaluation of the manuscript and for very constructive comments. In the revised manuscript we have responded to all comments, which led to a significantly improved paper. In the following, our responses to the reviewers' comments are marked in blue italics, whereas the additions to the manuscript are marked in blue. Lines (L) in the answers refer to lines in the revised document.

Reviewer #1 Evaluations:

The paper "Storm-time energy budget in the high latitude lower thermosphere-ionosphere: Quantification of energy exchange and comparison of different drivers in TIE-GCM" provides a detailed assessment of TIE-GSM heating and cooling terms relevant for neutrals, ions, and electrons, during a major geomagnetic storm. Two simulation runs are compared, one driven by the Weimer (2005) model of high latitude electric potential, the other by AMIE data.

Understanding and properly quantifying the energy budget in the ionosphere-thermosphere is certainly a major topic, likewise the related improvement of the simulation codes and boundary conditions. As soon as the few issues listed below and in the attached annotated manuscript are fixed, I shall be happy to recommend publication.

1. As far as I can judge, the main point that requires clarification is the direct Joule heating of the neutrals. This is invoked several times, as well as indicated in Figures 2 and 3. I am a bit confused, since Joule heating implies the effect of the electric field, which is obviously not directly felt by the neutrals. As aptly mentioned by the authors, the energy is passed to the ions by Joule heating, then transferred to the neutrals by collisions. But obviously there is also another mechanism, indicated in Figure 2 by the direct red arrow between the q_J box (q_\Omega in the figure - typo?) and in Figure 3 by the gray 'Joule heating' box (incidentally, the 'Joule heating' and 'Ions' boxes have somewhat different mutual roles in Figure 3 compared to Figure 2). I presume that the 'direct Joule heating' to neutrals and the Joule heating via ions are indeed related to specific terms of TIE-GCM. Perhaps the 'direct Joule heating' is related to the neutral wind term of Eq. (5), u_n \times B, i.e., to the (macroscopic) convection motion of the neutrals, whereas the ion term, related to the temperature difference (pointed out by the authors), is rather a (microscopic) conduction effect? Or, as suggested by Eq. (11), there is a 'prompt' energy transfer (the 'direct' Joule heating of neutrals?) versus a 'delayed' transfer (see the annotated pdf)? Please clarify.

We thank the reviewer for bringing this point up, that allows us to clarify this important point. Joule heating arises from the frictional dissipation of ion motion driven by the electric field, where collisions with neutrals convert this kinetic energy into thermal energy. A substantial portion of this energy is deposited into the neutral gas, with additional energy initially increasing ion temperature and then being transferred to the neutrals via collisional coupling. This collisional energy transfer mechanism plays an important role in the thermospheric energy balance in the lower thermosphere, where ion–neutral collision frequencies are high. We agree with the reviewer's comment that, as suggested by Eq. (11), there is a 'prompt' energy transfer (the 'direct' Joule heating of neutrals) versus a 'delayed' transfer. We further discuss this point in the responses to comments ***A26***, ***A28***, ***A53***, ***A54***, ***A55*** *(Eq. 11),* ***A56***, ***A60***, ***A64***, ***A65***, ***A67****. Below we have added suggestions for corresponding changes to the manuscript to clarify this point.*

2. Another point that I regard as important is the reason behind the difference of the Weimer and AMIE results, in particular at / near the maximum phase of the storm (Figure 1). This is attributed mainly to the sub-grid variability, apparently better captured by AMIE, because of better spatial resolution (e.g., L567-569, 576-578). The better capturing of the actual conditions by AMIE is at least as important and should

be emphasized better. To my understanding, AMIE takes (much?) better into account the actual conditions, as compared to a statistical model, like Weimer (2005), which provides some sort of 'average ' behavior. The more disturbed are the conditions, the farther off are the various parameters from some 'average' and the more important is to drive the simulation by (as close as possible to) actual boundary conditions. I think that some elaboration of the discussion and conclusions would be welcomed.

*We agree that the AMIE model generally captures the actual conditions better than Weimer, as it incorporates time-dependent observations and thus better reflects the actual, event-specific electrodynamic state of the system. This comment is also further discussed in our responses to comments **A01**, **A12**, **A14**, **A69**, **A95**, **A101**.*

3. Besides the two points above, please see the annotated manuscript, attached, for various other remarks, mostly minor issues.

We thank the reviewer for the thorough review; all comments have been addressed, as discussed below.

Annotated Comments on Manuscript

A1. L12: Not surprising, AMIE will provide better / more trustful results, since it reflects actual, not average conditions - see point 2 of the Report. Clearly visible in Figure 1, where the AMIE Joule heating is well above Weimer and empirical - since these both are average statistical results.

Response: *As also discussed above, we agree with the reviewer that the AMIE model generally captures the actual conditions better than Weimer. This is included together with the small-scale variability in the text in the Summary and Conclusions section, as follows:*

L681-693: "Together with the above issues related to spatial resolution of the models, the discrepancies are also related to the fundamental differences of the forcing models: whereas the Weimer (2005) model represents a statistical, climatological average response to given solar wind and IMF conditions, the AMIE model incorporates time-dependent observations and thus better reflects the actual, event-specific electrodynamic state of the system. During the storm maximum, when the magnetosphere–ionosphere system departs significantly from an average behavior, deviations from climatological patterns become substantial. Under such highly disturbed conditions, the use of boundary conditions that closely represent the instantaneous electrodynamics becomes particularly critical. The enhanced Joule heating in the AMIE-driven simulation therefore likely reflects a more realistic representation of the storm-time energy input.

The quantification of the various energy terms, their variability, and the discrepancies between models, highlights the need for the accurate quantification of Joule heating, as the single most important term with the highest magnitude and highest variability, both during the evolution of the storm-time event that was simulated, but also when different model runs are inter-compared. This has significant implications for our knowledge and understanding of the storm-time response of the LTI tothe external forcing"

A2. L24: "which can greatly exceed the energy input from solar EUV radiation"

Does it? Perhaps locally, but not globally? Provide some numbers? To my knowledge, the solar wind carries of the order of 1 millionth of the energy flux in the solar radiation. If that's roughly true, it would be hard to compete, even under extremey disturbed geomagnetic conditions. Perhaps the authors mean the contribution to the dynamics? Geomagnetic variations are certainly more important for the dynamics than the variations of the solar radiation (on considerably longer time scales).

Response: *Even though Joule heating in not known quantitatively, and even though there are large discrepancies between models, the fact that during geomagnetic storms Joule heating can exceed the largest energy source for the system, which is the solar EUV radiation, has been reported in past studies (e.g., Knipp et al. 2005, Verkhoglyadova et al 2016). This can also be observed in Figure 3, where in the left-hand side plot EUV is the largest heating term, whereas in the right-hand side Joule heating is much larger. These references were added together with a related comment in the text as follows:*

L33-34: *It is thought that, during active times, the effects of Joule heating on the upper atmosphere are more significant than those of EUV or energetic and auroral particle precipitation (e.g., Verkhoglyadova et al. (2016), Knipp et al. (2005)).*

A3: L29: 'Joule heating is the most thermodynamically important process" Provide Ref? This is an outcome of the paper, but it would be good to point also to prior work, in the Intro.

Response: *See response to A2 above. The above-mentioned references to Knipp et al. (2005) and Verkhoglyadova et al (2016) have been added in the text at line **L34**.*

A4: L31-32: 'It is thought that, during active times, the effects of Joule heating on the upper atmosphere are more significant than those of EUV or energetic and auroral particle precipitation (e.g., Zhang et al. (2017))'. In absolute terms this surprises me a bit, see above L24.

Response: *See responses to A2 and A3 above. The above-mentioned references to Knipp et al. (2005) and Verkhoglyadova et al (2016) have been added in the text. The reference to Zhang et al. (2017) has been removed, as the above references are more appropriate.*

A5. L70: "commonly used models" → "common models"

Response: *Changed according to the reviewer's comment (**L73**).*

A6. L71: "effects in the energetics" → effects ON the energetics

Response: *Changed according to the reviewer's comment (**L74**).*

A7-A8. L81-81: 'minimum Dst index of approximately -223 nT". L86: 'A minimum Dst of -190.7 nT'. -190 or -223 ?

Response: Indeed the -190.7 nT was a typo. The minimum value of Dst during St Patrick's storm was at -223nT. Corrected accordingly ***(L89)***.

A9. L126: 'Consequently' → 'Subsequently'

Response: *Changed according to the reviewer's comment (**L129**)*

A10. L131 'are kept…" → remained

Response: *Changed according to the reviewer's comment (**L134**).*

A11. L133: “WEIMER” → Weimer driver?

Response: *Changed according to the reviewer's comment (**L136**).*

A12. L133: ‘While there are large differences…” See comment at o. 1 and point 2 of the Report

Response: *See response to comment A1 above.*

A13. L133: “model resutls” → model results

Response: *Corrected **(L137).***

A14. L135: “it has high correlation with the Joule heating calculated with the AMIE run.”→ Not surprising, both capture the actual state - unlike the empirical and Weimer results, based on statistics.

Response: *See response to comment A1 above.*

A15. L136: “which is closer..” → closest

Response: *Changed according to the reviewer's comment (**L139**).*

A16. L160: Weimer 2005 → Weimer-2005

Response: *Changed according to the reviewer's comment (**L163**).*

A17. L160: ‘(Weimer (2005))” → (Weimer, 2005) => use \citep instead of (\cite) to avoid double brackets. I guess this depends on your local LaTeX environment, but \citep is easy to get by one of the standard packages. The same for quite a few references below (some of which are highlighted) showing double brackets - (name (year)).

Response: *Changed to \citep according to the reviewer's comment (**L163**).*

A18. L169: (Weimer (2005))

Response: *Changed to \citep according to the reviewer's comment (**L172**).*

A19. L171: (Richmond and Kamide (1988))

Response: *Changed to \citep according to the reviewer's comment (**L174**).*

A20. L174: “ionospheric” → as well as ionopsheric

Response: *Changed according to the reviewer's comment (**L176-177**).*

A21. L174: “self-consisting” → self-consistent

Response: *Changed according to the reviewer's comment (**L176**).*

A22. L197: “owever” → However

Response: *Corrected **(L219).***

A23: Figure 2: Replace q_\Omega by q_Joule

Response: *Indeed, this is a typo; it has been corrected in **Figure 2** in the revised manuscript.*

A24: Figure 2: Please expand a bit, to ease the read of the figure.

Response: *We have expanded the text to describe Figure 2 as follows:*

L203-214: “In brief, these processes include external heating processes, energy transfer between the neutrals, ions and electrons, and heating or cooling of the neutrals due to various other Thermosphere processes. External heating processes include Joule heating, which is deposited to the neutrals either promptly during active times, or indirectly through the initial heating of the ions and the subsequent energy exchange between ions and neutrals; Energetic Particle Precipitation, including energetic protons, which deposits energy directly to the neutrals, and energetic electrons, which ionize the neutral particles and create photoelectrons which subsequently get thermalized; solar extreme ultraviolet (EUV) radiation, which is the most significant heating energy source in the LTI, on long-term averages. Energy transfer can occur from the ions to the neutrals, between ions and electrons, and from the electrons to the neutrals. Finally, other neutral heating processes include molecular diffusion, ion chemistry, O_2 recombination, photo-electron heating, horizontal diffusion; eddy diffusion, horizontal advection and adiabatic heating, which can lead to either heating or cooling; radiative cooling from CO_2, NO and O(3P); and cooling due to conduction to the middle atmosphere.”

A25: L211: (Vasyliunas and Song (2005))

Response: *Changed to \citep according to the reviewer's comment (**L232**).*

A26: L215: “Joule heating is deposited directly into the neutral gas…”. See point 1 of the Report.

Response: *We agree with the reviewer's comment that, as also suggested by Eq. (12), there is a ‘prompt’ energy transfer (the ‘direct’ Joule heating of neutrals) versus a ‘delayed’ transfer. This has been changed into “Joule heating is deposited promptly …”, as discussed above reviewers' general comment #1. Thus, Joule heating is deposited promptly into the neutral gas, which is shown in Figures 2 and 3 as a direct arrows from Joule heating (qJ) to the neutrals, whereas an additional amount of energy is initially deposited to the ions, increasing ion temperature, and is subsequently transferred to the neutrals via collisional coupling; this is shown in Figure 2 as a red arrow initially from qJ to the ions and subsequently from the ions to the neutrals, and in Figure 3 as a red arrow from the ions to the neutrals. The calculation of this term in TIEGCM is done according to Eq. (12) (**L236**).*

A27: L217: 'represented" → derived

Response: *Changed to \citep according to the reviewer's comment (**L237**).*

A28: L222: "..to the neutrals either directly or…" -→ What is the direct way? See also above L215.

Response: *See response to comment A26 above; "directly" and "indirectly" have been removed, and this has been changed in the text as:*

"either promptly, or through the heating …" *(**L243**).*

A29: L228: "as discussed in…" → as discussed by…

Response: *Changed according to the reviewer's comment (**L249**).*

A30: L230: "…in Tourgaidis et al. (2025a)." → by Tourgaidis et al. (2025a).

Response: *Changed according to the reviewer's comment (**L251**).*

A31: L233: "Together with heating.." → Joule heating?

Response: *Changed according to the reviewer's comment (**L253**).*

A32: L234-235: (Verronnen et al. (2015))

Response: *Changed to \citep according to the reviewer's comment (**L255-256**).*

A33: L235: "and this heats.." → and this also heats

Response: *Changed according to the reviewer's comment (**L256**).*

A34: L263-264: "and thus on altitude dependent in the LTI..." → Please rephrase

Response: *Changed as follows"*

" and consequently to altitude in the LTI" *(**L287-288**).*

A35: L275-276: "..if electrons do not drift far enough…" → Don't understand, please clarify.

Response: *This refers to the eastward drift of electrons vs. westward drift of the ions after, e.g., a substorm injection in the midnight or pre-midnght regions; however this discussion is too detailed for this paper, and we have decided to remove it, and merge with the following sentence. This now reads as follows:*

L298-301: "Nevertheless, it has been found that, at times, proton precipitation can dominate over electrons in some regions; furthermore, studies have shown that medium-energy (10s of kev) precipitating protons can carry more energy flux than electrons (Tian et al., 2020)".

A36: L286: EUV radiation and also…” → delete and

Response: *Changed according to the reviewer's comment (**L313**).*

A37: L287: "..indirect processes that driven by" → delete that?

Response: *Changed according to the reviewer's comment (**L314**).*

A38: L292: "heating source in a global scale" → "heating source on a global scale"

Response: *Changed according to the reviewer's comment (**L319**).*

A39: L306: "else Te>Ti>Tn" → Namely Te>Ti>Tn

Response: *Changed according to the reviewer's comment (**L340**).*

A40: L308-309: "The ion-neutral heat transfer rate is given by:" → add reference

Response: *The following reference has been added:*

"see Eq. 14 in Sarris et al., 2023b" ***(L345)***

Sarris TE, Tourgaidis S, Pirnaris P, Baloukidis D, Papadakis K, et al., (2023b) Daedalus MASE (mission assessment through simulation exercise): A toolset for analysis of in situ missions and for processing global circulation model outputs in the lower thermosphere-ionosphere. Front. Astron. Space Sci. 9:1048318. doi: 10.3389/fspas.2022.1048318

A41: L315: "..to a lack of a quantitative …" → "..to a lack of quantitative …"

Response: *Changed according to the reviewer's comment (**L349-350**).*

A42: L325 " according to:…" → add reference

Response: *The following reference has been added:*

"see Eq. 15 in Sarris et al., 2023b" ***(L361)**.*

A43: L327: "..is given by:" →add reference

Response: *The following reference has been added:*

"see Eq. 16 in Sarris et al., 2023b" ***(L364)**.*

A44: L342-343: "are included and are presented below." → are included. (delete "and are presented below")

Response: *Changed according to the reviewer's comment (**L377**).*

A45: L353: "…up and down…" → Up and down is a bit at odds with horizontal winds. Parallel and anti-parallel? Along and against?

Response: *Indeed, we agree that "up and down" sounds strange for horizontal winds; this has been changed in the text as:*

"along and against" *(**L394**).*

A46: L368: "according to equation:" → add reference

Response: *The following reference to the TIEGCM manual has been added:*

TIEGCM Model Description: TIEGCM V1.94 Model Description, Tech. rep., HAO/NCAR, Boulder, CO, USA, https://www.hao.ucar.edu/modeling/tgcm/doc/description/model_description.pdf, version 1.94 documentation, 2018.

A47: L377: "by the by the Earth's magnetic field" → delete second "by the"

Response: *Changed according to the reviewer's comment (**L417-418**).*

A48: L377: "At the **heat** of the significance.." → At the **heart** the heat of the significance

Response: *Changed according to the reviewer's comment (**L418**).*

A49: L378: "from low density to high density…" → Usually it works in the opposite direction, from high to low density (against the gradient).

Response: *Indeed, that was a typo; this has been corrected in the manuscript.* ***(L419).***

A50: L391: "…primarily in the…" → primarily at the or primarily near the

Response: *This has been changed to*

"primarily near.." *(**L432**).*

A51: L395: "$Q_t$ot" → Q_{tot}

Response: *This has been corrected (**L437**).*

A52: L401: "$L_t$ot" → L_{tot}

Response: *Corrected* ***(L442).***

A53: L411-412: "(i.e., the Joule heating that is directly deposited to the neutrals…" → See point 1 of the Report.

Response: *See responses to comments A26 and A28 above; this has been changed in the text as:*

"(i.e., the Joule heating that is promptly deposited to the neutrals…" ***(L453).***

A54: L421: "that goes directly to the neutrals…" → Same as above, L411-412. Also L222 and 215.

Response: *See responses to comments A26, A28 and A53 above; this has been changed in the text as:*

"that goes promptly to the neutrals…" ***(L462).***

A55: Equation 11→ Explain ? For m_n = 0 (much smaller than m_i), it follows that nothing goes 'directly' to the ions, while the opposite holds if m_i=0 - everything goes directly to the ions. This suggests that the fractions that go 'directly' to the ions and neutrals are related to some temporal scales, for 'prompt' energy transfer ion->neutrals versus 'delayed' energy transfer (while eventually all the energy is transferred to the neutrals).

Response: *We completely agree with the reviewers' comments on this equation, and we have addressed this throughout the text, as discussed above in response to comments **A26**, **A28**, **A53** and **A54**, as well as other comments below. (**L466-478**).*

A56: L429: 'where Q^{Ti}_{J} is the part of the Joule heating directly deposited to the ions," → See point 1 of the Report.

Response: *We agree that this is not clearly stated, and have removed this sentence; also the whole section 3.2.2 was revised (**L466-478**).*

A57: L433: "negligible" → negligibly

Response: *Corrected (**L476**).*

A58: Equation 13 → Are the signs of the heating and cooling terms correct ? => apparently opposite to Eq. (10).

Response: *A reference to the TIEGCM manual (where this equation is from) has been added. It is noted that Equation 10 refers to the neutral thermodynamic equation, whereas Equation 13 is the thermodynamic equation of the electrons.*

A59: L451: "The later time is…" → The latter time is…

Response: *Corrected (**L495**).*

A60: L463: "Energy flow according to the neutrals" → Energy flow (for ? to / from ?) Neutrals

Response: *"According to" has been added here to emphasize that different heating and cooling mechanisms or channels are associated with each species, and hence the energy budget should be looked at separately for each species; we would thus prefer to maintain this term.*

The following sentence has been added in the abstract to emphasize this point:

L11-12: "The energy budget is investigated individually for neutrals, ions and electrons, as different heating and cooling mechanisms are associated with each species."

A61: L465-466: "by Joule heating due to the differential velocity between the neutral winds

and the ions under the effects of electric fields…" → Does this mean the u_n \times B term of Eq. (5)? (see also point 1 of the Report)

Response: *As also discussed above in response to point #1 of the report, this is not related to u_n \times B term of Eq. (5); instead, the Joule heating arises from the frictional dissipation of ion motion driven by the electric field, where collisions with neutrals convert this kinetic energy into thermal energy. A substantial portion of this energy is deposited into the neutral gas, with additional energy initially increasing ion temperature and then being transferred to the neutrals via collisional coupling.*

A62: L473-474: Supplementary Material S1 → I was not able to find S1, but I could access the zenodo data / movies at https://zenodo.org/records/16993755.

Response: *Indeed, this can be found through the above zenodo link, and not through supplementary material; references to S1, S2 and S3 have been removed from the manuscript, and have been replaced by the corresponding zenodo references.*

A63: L478: "1with" → 1 with

Response: *Corrected (**L522**).*

A64: L481: "the part of the Joule heating directly deposited to the neutrals…" → See point 1 of the Report.

Response: *See responses to comments A26, A28, A53, A54 above; this has been changed in the text as:*

"the part of the Joule heating promptly deposited to the neutrals…" *(**L525**).*

A65: L482-483: "half of the total Joule heating is directly deposited to the neutrals.." → See point 1 of the Report.

Response: *See responses to comments A26, A28, A53, A54, A64 above; this has been changed in the text as:*

"half of the total Joule heating is promptly deposited to the neutrals…" *(**L527**).*

A66: L:488: "…during…" → at

Response: *Corrected (**L532**).*

A67: L490: "Joule heating directly deposited to the neutrals…" → See point 1 of the Report.

Response: *See responses to comments A26, A28, A53, A54, A64, A65 above; this has been changed in the text as:*

"Joule heating promptly deposited to the neutrals… ***(L534)***.

A68: L491: "$q\Delta_T in$" → $q\Delta_{Tin}$

Response: *Corrected (**L535**).*

A69: L492-493: "This, as discussed below, is attributed to the inclusion of smaller scales in the AMIE model, enabled by the long-term assimilation of multiple datasets" → Also actual vs. average / statistical boundary conditions ? See point 2 of the Report.

Response: *Indeed, as discussed in point 2 above, this is also due to the actual vs. average / statistical boundary conditions. This sentence has been changed as follows in the revised manuscript:*

L542-544: "This, as discussed below, is attributed to the inclusion of smaller scales in the AMIE model, and also due to the fact that the AMIE model incorporates time-dependent observations and thus better reflects the state of the system."

A70: L463: "Energy flow according to the ions" → Energy flow (for ? to / from ?) ions

Response: *See response to comment A60*

A71: L508: Supplementary Material S2 → I was not able to find S2, but I could access the zenodo data / movies at https://zenodo.org/records/16993755.

Response: *See also response to comment A62 above; references to S1, S2 and S3 have been removed from the manuscript, and have been replaced by the corresponding zenodo references.*

A72: L509: "..before the peak of the storm…" → delete "the peak of"

Response: *Corrected (**L559**).*

A73: L510: "..is a small fraction of the joule heating" → about 10%

Response: *This has been added as follows:*

"..is a small fraction (~10%) of the joule heating" ***(L560)***.

A74: L512 : "..during the peak…" → at the peak

Response: *Corrected (**L562**).*

A75: L514: "Energy flow according to the electrons" → Energy flow (for ? to / from ?) electrons

***Response:** See response to comment A60*

A76: L508: Supplementary Material S3 → I was not able to find S3, but I could access the zenodo data / movies at https://zenodo.org/records/16993755.

***Response:** See also response to comment A62 above; references to S1, S2 and S3 have been removed from the manuscript, and have been replaced by the corresponding zenodo references.*

A77: L531: "…collisions become large…"→ Instead of large larger ?

The numbers are still quite small compared to ions and neutrals.

***Response:** Corrected (**L581**).*

A78: L531: "during…" → at

***Response:** Corrected (**L581**).*

A79: L532: "..infer that during the peak…" → infer that at the peak…

***Response:** Corrected (**L582**).*

A80: L533: "…due to enchanced EPP…" → Figure 5 (middle and right) shows EUV and EPP together => split ?

***Response:** We agree that it would be better to split these inputs, however it is noted that this is an output parameter of TIEGCM, and a significant change in the TIEGCM source code would be needed in order to output them separately, which unfortunately was not possible for this paper.*

A80-85: Figure 5:

- " Terms in red…" → Terms with red…
- "..to heating of the ions.." → heating of the electrons
- "..terms in blue…" → terms with blue
- "..of the ions." → of the electrons
- "Three electric potential…. → Two electric potential
- "Heelis" → delete Heelis

***Response:** All corrected (Caption of Figure 5)*

A86: L537: "…processes processes…" → delete duplicate

***Response:** Corrected (**L587**).*

A87: L551: “...a revisit to the joule heating…” → ..a revisit of the joule heating

***Response:** Corrected (**L601**).*

A88: L552: “… even basic principles…” → even basic assumptions =

***Response:** Changed according to the reviewer’s comment (**L602**).*

A89: L553: “… AE dataset…” → AE-C and AE-E ? Just AE is a bit confusing with Aurroal Electrojet, used as well in the paper.

***Response:** This has been changed to*

“Atmosphere Explorer C, D and E datasets” *(**L603-604**).*

A90: L554: “..has shown..” → have shown

***Response:** Corrected (**L604**).*

A91: L554: “..are times where…” → are times when

***Response:** Corrected (**L604**).*

A92: L560: “During the peak…” → At the peak…

***Response:** Corrected (**L610**).*

A93: L563: “ the peak of storm..” → the peak of the storm….

***Response:** Corrected (**L613**).*

A94: L567: “…~1…” → ~1 h

***Response:** Corrected (**L617**).*

A95: L576-578: “Moreover, the use of higher resolution electric fields from assimilative techniques

instead of empirical models, compensates part of the small-scale variability but nevertheless, residual underestimation persists (i.e. scales below 1o)” → Small scale variability is just part of the explanation. The use of boundary conditions better tuned to the actual data is another part - see point 2 of the Report.

***Response:** This has been added in the Summary and Conclusions section, according to the response to the reviewer’s comment A1.*

A96: L583: "..in the altitudes…" → near the altitudes

Response: *Changed according to the reviewer's comment (**L640**).*

A97: L584: "profiles with sufficient statistical" → ... profiles down to a couple of atmospheric scale heights under the spacecraft. This is essential for an LTI missions and would enable sufficient... (?)

The key point of Vogt et al. (2023) is the extrapolation under the spacecraft, at altitudes difficult to reach (because of thermal stress), but essential for the Joule heating - those altitudes where the ionospheric current and the Joule heating maximize.

Response: *Indeed, we agree; this has been added, and the text now reads as follows:*

L639-644: "As demonstrated by Vogt et al. (2023), a twin-spacecraft mission with altitudinal separation and with comprehensive instrumentation that performs measurements near the altitudes of interest would be able to provide the altitude profiles down to a couple of atmospheric scale heights under the spacecraft. This is essential for an LTI mission and would enable measurements with sufficient statistical significance, so as to derive the climatological characterization of Joule heating as a function of altitude, while also resolving the open question of the significance of Joule heating at small scales."

A98: L592-593: "CO2, are also significantly different for the two runs" → Presumably because of the same reason, actual conditions versus statistical / average - see also above, L576-578, and point 2 of the Report.

Response: *Indeed, we agree with the reviewer; the following sentence has been added:*

L651-652: "…, due to the different external drivers and the resulting different neutral temperatures of the LTI regions."

A99: L596: "but are not included in the presented analysis." → Because they are small / negligible ?

Response: *Indeed, their contribution is small/negligible with respect to the other terms.*

A100: L608: "from the viewpoint of the neutrals" → Because of the impact on density, I suppose, with further effect on drag, orbits / debris, etc - as pointed out below, L618.

Response: *Indeed, that is possibly the reason.*

A101: L613: "as higher fields will give higher Joule heating; " → And AMIE is indeed expected to provide higher electric fields - tuned to actual conditions - as compared to Weimer 2005 or other statistical models, which can only capture 'average' values.

Response: *Indeed, the AMIE model provides higher electric fields. Also in response to the second reviewer's comment, the following text has been added, together with the new **Figure 6**:*

L631-636: "To investigate the effect of the average electric field on the observed discrepancies in the modeled Joule heating, in Figure 6 we plot the high-latitude electric potential for the two models and for the two time-steps used in this study. In the left-hand side of this figure the Weimer-2005 model results are given, whereas in the right-hand side figure the results of the AMIE model are given. As it can be seen from these panels, the Weimer-2005 model gives higher potential at the pre-storm baseline timestep, while the AMIE model gives higher potential at the peak of the storm. At the baseline timestep, the potential patterns of the two models are spatially different, while at the peak of the storm both models capture the two-cell structures quite similarly."

A102: L638-639 "Acknowledgements. The authors acknowledge the use of data obtained from [SuperDARN (http://vt.superdarn.org/tiki-index.php), Super-

MAG (https://supermag.jhuapl.edu), and AMPERE (http://ampere.jhuapl.edu)] for the period of 15-21 March 2015." → Are these data used in the paper ?

Response: *These were used for test-runs with other models, which ended up not being used, and have been removed.*

We thank the reviewer for the constructive comments and the evaluation of the manuscript. We have addressed all comments in detail, and in response to these comments the revised manuscript now also includes a new figure (Figure 6). In the following, our responses to the reviewers' comments are marked in blue italics, whereas the additions to the manuscript are marked in blue.

Reviewer #2 Evaluations:

General Comments

This study analyzes the energy budget in the high-latitude lower thermosphere-ionosphere during the 17 March 2015 storm. The authors compared the energy budget derived from TIE-GCM simulations with two electric potential drivers. Before I can suggest acceptance, several concerns should be addressed.

Major comments:

1. Joule heating estimate:

- The JH powers shown in Figure 2 seem to be different from the values shown in the authors' another study by Tourgaidis 2025a, which used the same model and drivers to show the global Joule heating during the same storm.
- Equation 11 is not correct for the partition of JH to the ions. See https://egusphere.copernicus.org/preprints/2025/egusphere-2025-2679/egusphere-2025-2679.pdf and https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2021EA001925

2. Particle precipitation power:

- JH is multpled by a factor of 1.5. Similarly, other terms, especially the particle precipitation power, may also be underestimated in the model.
- It's unclear what drivers for the particle precipitation were used in this study. The EPP powers are only 1/10 of the JH power. This seems a tiny percentage compared with the previous studies.

Please see the detailed comments in the attached PDF. In addition, the text shown in the figures is too small. It's tough to read if the manuscript is printed on A4 paper.

Annotated Comments on Manuscript

B1: L7: "version 2.0 (TIE-GCM 2.0)" : The latest version is 3.0. An assessment of the differences between the two version may be addressed in the discussion.

Response: *Indeed, we agree that an investigation of the differences between the two versions of TIEGCM is an important study. A detailed comparison of TIEGCM 2.0 and TIEGCM 3.0 was not possible in the timeframe of the writing of this manuscript (TIEGCM 3.0 was released after the submission of the manuscript); however it is an interesting study that will be the target of a follow-up investigation. In response to this comment, the following text has been added in the Summary and Conclusions section:*

L678: "The recently release TIEGCM 3.0 offers higher spatial resolution compared to TIEGCM 2.0 that was used in this study, and subsequent investigations need to investigate the effects of smaller-scale sub-grid variability on the resulting Joule heating"

B2. L11-12: "Discrepancies between the model runs are discussed and the way forward to close the gaps in present knowledge is highlighted." : Please demonstrate explicitly what is highlighted and what is the novelty in this study. It's not surprising to see the differences between the two runs because of two drivers.

Response: *The main highlights and novelty of this study include the calculation of the energy budget and the corresponding partitioning of energy between species. In particular, the quantification of the various energy terms, their variability, and the discrepancies between models, highlights the need for the accurate quantification of Joule heating, as the single-most term with the highest variability, both during the evolution of the storm-time event that was simulated, and also when the two model runs are inter-compared. Another highlight is the investigation of the energy budget individually for neutrals, ions and electrons, as different heating and cooling mechanisms are associated with each species; this is a novel approach compared to other studies that focus on the energy budget from the perspective of the neutrals. These have been highlighted in the abstract and the Summary and Conclusions section, as follows:*

L665-668: "We then quantified the variability of the main energy flow estimates from three different perspectives: that of the neutrals, of the ions and of the electrons, as different heating and cooling mechanisms are associated with each species. It is noted that, whereas in most studies the state of the LTI is presented from the viewpoint of the neutrals, herein a view of the main energy transfer terms is presented separately according to each species."

and further down in the "Summary and Conclusions" section:

L689-695: "The quantification of the various energy terms, their variability, and the discrepancies between models, highlights the need for the accurate quantification of Joule heating, as the single most important term with the highest magnitude and highest variability, both during the evolution of the storm-time event that was simulated, but also when different model runs are inter-compared. This has significant implications for our knowledge and understanding of the storm-time response of the LTI to the external forcing. Through the model runs it is concluded that obtaining new, systematic measurements of all required parameters for the calculation of Joule heating is required to improve our understanding of the energy balance and energy transfer processes"

B3: L20: "O3, O2, O and CO2": What is the role of N2 and NO?

Response: *Indeed, these were missing; N2 and NO have been added. A comment has been added that N2 absorbs radiation <100 nm at altitudes between 100-200 km. Also a reference to Brasseur and Solomon (2005) has been added. NO and CO2 are discussed further down in the manuscript. (**L21**).*

B4: L24: "…which can greatly exceed the energy input from solar EUV radiation." : Reference? Do you compare the two quantities in power (GW) or total energy (J) during a given period?

Response: *Even though Joule heating in not known quantitatively, and even though there are large discrepancies between models, the fact that during geomagnetic storms Joule heating can exceed the largest energy source for the system, which is the solar EUV radiation, has been reported in past studies (e.g., Knipp et al. 2005, Verkhoglyadova et al 2016). This can also be observed in Figure 3, where in the left-hand side plot EUV is the largest heating term, whereas in the right-hand side Joule heating is much larger. The comparisons in this figure and the above references are done in terms of power (GW). A relative comment and the above references have been added in the text.*

B5: L29: "..dissipating energy…": "…dissipating **electromagnetic** energy.."

Response: *electromagnetic energy has been added. (**L31**).*

B6: L32-34: "However, the exact quantification of Joule heating is largely unknown, primarily due to a lack of systematic measurements of all relevant terms contributing to Joule heating (see, e.g., Sarris

(2019); Palmroth et al. (2021); Tourgaidis et al. (2025a)), leading to large discrepancies between models…" : As stated here, can you assess the accuracy of the Joule heating estimate and other terms in this study. What is the ground base that can be used for a comparison?

Response: *Based on the detailed comparisons between the models, the assessment is that Joule heating is the single most important energy source with the largest discrepancies between different models and the largest variability during a storm. It is concluded that detailed measurements are needed to resolve this energy term quantitatively. With respect to the accuracy of Joule heating, it is believed that the AMIE model run is more accurate. The following text has been been added in the Summary and Conclusions section:*

L669-680: "It was found that the largest differences in the energy flow for the different processes is observed primarily in the Joule heating rates, and in the associated heating from the ions to the neutrals. Specifically, it was found that the AMIE model run gives more than twice as large Joule heating and ion-to-neutral heating than the Weimer 2005 model. These discrepancies are attributed to the average electric field that is estimated by each of the model drivers, as higher fields will give higher Joule heating. The discrepancies are also due to the different temporal variability in the electric field and also due to the differences in the small spatial scales of the electric field that can be resolved by each of the models, as higher spatial and temporal variability will result in higher Joule heating. This sub-grid variability of the electric fields is a key unknown factor in LTI electrodynamics and energetics, and has significant implications for the quantification and prediction of the effects of energy inputs such as Joule heating for density enhancements in the LTI and the resulting drag effects on Low Earth Orbit satellites. The recently released TIEGCM 3.0 (HAO, 2025) offers higher spatial resolution compared to TIEGCM 2.0 that was used in this study, and subsequent investigations are needed to investigate the effects of smaller-scale sub-grid variability on the resulting Joule heating.

L681-688: "Together with the above issues related to spatial resolution of the models, the discrepancies are also related to the fundamental differences of the forcing models: whereas the Weimer (2005) model represents a statistical, climatological average response to given solar wind and IMF conditions, the AMIE model incorporates time-dependent observations and thus better reflects the actual, event-specific electrodynamic state of the system. During the storm maximum, when the magnetosphere–ionosphere system departs significantly from an average behavior, deviations from climatological patterns become substantial. Under such highly disturbed conditions, the use of boundary conditions that closely represent the instantaneous electrodynamics becomes particularly critical. The enhanced Joule heating in the AMIE-driven simulation therefore likely reflects a more realistic representation of the storm-time energy input."

L689-692: "The quantification of the various energy terms, their variability, and the discrepancies between models, highlights the need for the accurate quantification of Joule heating, as the single most important term with the highest magnitude and highest variability, both during the evolution of the storm-time event that was simulated, but also when different model runs are inter-compared."

B7: L34-35: "It can thus be stated that Joule heating is among the least known and least quantified processes in the LTI, …." : I think it is overstated. Although Joule heating is the major energy dissipation in the system. All other processes are not fully understood.

Response: *We agree that other processes are also not fully understood, and this is captured here by stating that Joule heating is among the least known and least quantified processes. The end results of the simulations presented herein reinforce this statement, as the variability of Joule heating between the two model runs exceeds the variability that is observed in other heating sources.*

B8: **Figure 1 legend: "..**Joule heating estimates (Empirical, TIE-GCMWeimer, TIE-GCM Amie)…" : The peak values of TIEGCM Weimer and TIE-GCM Amie seem to be smaller than in your study of "Globally-and Hemispherically-Integrated Joule heating rates during the 17 March 2015 geomagnetic storm, according to Physics-based and Empirical Models." https://egusphere.copernicus.org/preprints/2025/egusphere-2025-2679/egusphere-2025-2679.pdf

Response: *We thank the reviewer for a very thorough review of the manuscript. The reason for the observed differences that the reviewer refers to is the different latitude ranges used for the integrations. In Tourgaidis et al. (2025a) we discussed the hemispherically integrated Joule heating, and thus the latitude range that was used for the integration of Joule heating are from 0 degrees up to 88.5 degrees (the maximum latitude of TIEGCM). In this study we focused on the high latitude region of the northern hemisphere and thus the integration was performed between 56.3 degrees up to 88.5 degrees. Nevertheless, the reviewer is correct because there is a wrong statement in the current study. We say in Lines 153-155:*

"Calculations of the various energy terms were performed at every grid point of TIE-GCM; subsequently, energy terms were integrated across all latitudes and longitudes, as well as across all altitudes. Integrations were performed separately for the Northern and Southern hemispheres."

We changed this to:

L156-157: "Calculations of the various energy terms were performed at every grid point of TIE-GCM; as the focus of the study is the high latitude LTI, energy terms were integrated from 56 degrees latitude up to the pole, and across all longitudes and altitudes."

*Also, although we indeed performed calculations for both hemispheres during the simulation runs, we did not include south hemisphere results, thus the phrase "Integrations were performed separately for the Northern and Southern hemispheres" was removed. (**L156-157**)*

B9: L133-135: See my comment for Figure 1

Response: *See our response to comment B8 above*

B10: L157: "2.3 External drivers of TIE-GCM - Electric Potential Models" : In addition to electric potential, what drivers do you used for precipitating particles and how the electric potential models can be compatible with the precipitating particle models?

Response: *We thank the reviewer for this comment; indeed a description of the drivers used for precipitating particles and a discussion on the compatibility between the electric potential models and the precipitating particle models was missing. In response to that, section 2.3 was renamed as:*

"2.3 External drivers of TIE-GCM - Electric Potential and Particle Precipitation Models" (**L160**).

and the following text has been added in the same section:

L178-185: "It is noted that in the AMIE-driven simulation, both the high-latitude electric potential and the auroral precipitation are derived from the AMIE solution, ensuring internal consistency between the electrodynamics and particle energy input. In contrast, in the Weimer-driven simulation, the electric potential is specified using the statistical Weimer (2005) model, while auroral precipitation is prescribed using an empirical parameterization based on the IMF Bz and By, and the solar wind velocity (see TIEGCM 2.0). Thus, the convection and precipitation forcing in the Weimer-driven simulation are not derived from a single electrodynamic solution but represent independent statistical descriptions. This difference in forcing consistency may contribute to differences in the simulated energy deposition and thermospheric response, particularly during the peak of the storm."

B11: L197: "owever" → However

Response: *Corrected (**L219**).*

B12: L214: "Tourgaidis et al. (2025a)" → The Joule heating power values are different in the two studies, how could it be if the runs are the same.

Response: *See response to comment B8*

B13: L257-258: "…a factor of 1.5.." → If the Joule heating is underestimated, other associated energy transfer may be also underestimated/overestimated, such as precipitating heating. If so, your results may over-hightlight the Joule heating effect.

Response: *This factor is introduced by the TIEGCM developers to account for the discrepancies in neutral temperature between TIEGCM and empirical models. We agree with the reviewer that similar factors might indeed need to be included in other terms as well, and this can only be investigated by in situ measurements of all the parameters needed to assess all heating terms.*

B14: L250 : "typically caused by a variety of wave-particle interaction mechanisms.." → In addtion to diffuse aurora due to wave particle interaction, monoenergetic electron precipitation is also important. Do you include the monoenergetic precipitation in your simulation? If not, how can you assess the energy budget when other mechanisms are absent.

Response: *TIEGCM includes monoenergetic particle precipitation*

B15: L253: "Tourgaidis and Sarris (2022)" : It's unclear that in this study you use the TS package as input for the precipitating electrons to the models or you just use the internal module in the model.

Response: *References to WPIT have been removed, as this paper is not entirely relevant to the results presented herein.*

B16: L254: "effects of Energetic Precipitating Electrons" → Give the equation here although it appears in Figure 2

Response: *The following equation has been added in the manuscript:*

$$q_{EPP} = \pi \int_{E_{min}}^{E_{max}} J(E)dE$$

B17: L280 : "the proton precipitation" → As shown in Figure 2, proton precipitation is marked with dashed outline and not estimated. This should be mentioned here.

Response: *Indeed, this has not been discussed in great length; the following text has been added in the revised manuscript:*

L305-308: "Solar proton precipitation inside the polar cap is included in TIEGCM, with a characteristic energy in the default model configuration that is assumed to be 10 keV and an energy flux that is set to a very low default value (1.E-20). A realistic and time-variable proton precipitation is an improvement that needs to be incorporated in future model runs."

B18: L292-294: "UV radiation is the strongest heating source in a global scale. By measuring the ratio of Te/Tn, which is driven by EPP and UV radiation, it is possible to estimate the fraction of UV radiation that is deposited to the electrons and neutrals." → Can you give the equation used to calculate the solar radiation heating? And which solar EUV model is used as input to the simulation?

Response: *In response to this comment, we added the following text in the manuscript:*

L329-335: "More specifically, solar extreme ultraviolet (EUV) irradiance in TIE-GCM is specified using the EUVAC model (Richards et al., 1994) in the range 5-105nm. EUVAC is based on the F74113 reference spectrum, measured during low solar activity, with adjustments applied in specific wavelength ranges (e.g., fluxes between 15–25 nm doubled and fluxes below 15 nm increased by a factor of three). Solar variability is parameterized using the F10.7 index (daily and 81-day average values). For wavelengths <5 nm, GOES X-ray measurements are used to establish reference irradiance and variability. The 1.8–5 nm range follows the Hinteregger model (Hinteregger, 1981) based on the SC21REFW spectrum, while the 105–175 nm range is specified using the Woods and Rottman model (Woods and Rottman, 2002) derived from UARS/SOLSTICE observations."

Richards, P. G., Fennelly, J. A., & Torr, D. G. (1994), EUVAC: A solar EUV flux model for aeronomic calculations, Journal of Geophysical Research, 99(A5), 8981–8992.

Hinteregger, H. E. (1981), Representations of solar EUV flux for aeronomical applications, Advances in Space Research, 1(12), 39–52.

Woods, T. N., & Rottman, G. J. (1990), Solar ultraviolet variability over time periods of aeronomic interest, Journal of Geophysical Research, 95(A5), 6227–6236.

B19: L342-343: "however in the results presented below only the two main radiative cooling terms, NO and CO2, are included and are presented below." → Please give the equations and parameters used to calculate the coolings.

Response: *The corresponding equations have been added in the manuscript, in* ***L377-384.***

B20: L372-373: "The relevant formulas as used in TIE-GCM can be found in Schunk and Nagy (2009)." → It would be good to show the set of equations used in the calculation instead of references.

Response: *It is noted that the related formulas that are used in TIE-GCM are numerous (more than 12 equations), and we believe that repeating them here would make the paper difficult to read; it is also beyond the scope of the manuscript. Thus the reader is directed to the relevant literature for the exact equations.*

B21: Equation 11: → m_i? See https://egusphere.copernicus.org/preprints/2025/egusphere-2025-2679/egusphere-2025-2679.pdf and https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2021EA001925

Response: *We thank the reviewer for this comment that allows us to clarify this point. In response to the reviewer's comment, the following derivation and equations have been added in the text, including a reference to the approach followed by Lomidze et al. (2021) and its association with the approach that is followed in TIEGCM:* ***L466-483:***

According to (Tourgaidis et al., 2025a), the total Joule heating is given as:

$$Q_J = \sum_n \nu_{in} m_i n_i (\boldsymbol{u}_i - \boldsymbol{u}_n)^2 \tag{14}$$

Furthermore, Lomidze et al. (2021) define the ion thermodynamic equation as:

$$Q_{ie} + F_{in} = L_{in} \tag{15}$$

where

$$F_{in} = \sum_n \frac{n_i m_i}{m_i + m_n} \nu_{in} m_n (\boldsymbol{u}_i - \boldsymbol{u}_n)^2 \tag{16}$$

From Eq. 14 and Eq. 16:

$$F_{in} = \frac{m_n}{m_n + m_i} Q_J \tag{17}$$

"Eq. 17 is the one used in TIE-GCM (TIEGCM Model Description, 2018). Thus, from the point of view of the ions, the heating rates include a fraction of the Joule heating and heating due to elastic collisions with electrons. On the other hand, ions are cooled due to ion-neutral collisions. In general, the contributions of the ion-electron collisions Qie are negligibly small, thus the part of the Joule heating deposited to the ions F_{in} , goes eventually to the neutrals through ion-neutral interactions (L_{in})."

B22: L432: Lin → Is this equivalent to the integration of Equation 6?

Response*: Indeed, this is the case. It is the same parameter used in Lomidze et al. (2021), which represents the ion cooling rates due to collisions between ions and neutrals.*

B23: L613: "the average electric field that is estimated by each of the model drivers, …" → This may be true, however, it was not presented in the manuscript. Can you show how different the electric fields or cross polar cap potential are from the two drivers?

Response: *We added Figure 6 with the polar plots of the high-latitude electric potential for each case. We also added the following text:*

L631-636: "To investigate the effect of the average electric field on the observed discrepancies in the modeled Joule heating, in Figure 6 we plot the high-latitude electric potential for the two models and for the two time-steps used in this study. In the left-hand side of this figure the Weimer-2005 model results are given, whereas in the right-hand side figure the results of the AMIE model are given. As it can be seen from these panels, the Weimer-2005 model gives higher potential at the pre-storm baseline timestep, while the AMIE model gives higher potential at the peak of the storm. At the baseline timestep, the potential patterns of the two models are spatially different, while at the peak of the storm both models capture the two-cell structures quite similarly."
