Reply to Referee Report 1

Title: Observations of traveling ionospheric disturbances driven by gravity waves from sources in the upper and lower atmosphere.

Overview of Manuscript

This work investigates the sources of ionospheric disturbances due to atmospheric gravity waves due to high latitude space weather and low latitude tropospheric dynamics. They used multiple observational techniques to detect traveling ionospheric disturbances (TIDs) with large and medium scale characteristics, and atmospheric gravity waves (AGWs). Using observations and reanalysis data, they investigated the upper atmospheric dynamics that possibly excited the large and medium scale TIDs originating from the troposphere. The manuscript has the potential to contribute significantly to literature; however, there are some issues that need to be addressed.

It is concerning that no relationship between the observed wave and the source has been made in the current state of the manuscript. Instead, only what appeared to be a literature review of the previous works was done in conjunction with the results presented. Additionally, the presentation of the work from abstract to the conclusion is not in any chronological order, thus making it very difficult to comprehend the work and make the necessary relationship between any observed phenomenon and the other. For instance, the author mentioned the observed AGWs that induced MSTIDs. No comparison was made in order to prove that the AGWs indeed induced the observed MSTIDs. Also, they mentioned that the observed AGWs were excited though space weather event or tropospheric activity without arguing with evidence whether the said source is really the source or not. They provided some evidence and in some cases links to the evidence. Most of the links are not working.

Considering this lack of details, and the other comments listed below, I suggest the manuscript be subjected to a major revision. If these issues can be addressed, and the techniques more properly explained, the manuscript will contribute significantly to literature.

Major Comments

- **Abstract:**
  1. The abstract did not capture the necessary aspects of the work to give the reader a complete idea about the work. The work was not introduced, and the order of presentation makes it difficult follow. Kindly revise the abstract.

Reply. *We have rewritten the abstract to better capture the aspects of this work, highlighting the multi-instrument techniques of TIDs observations and physical mechanisms that are sources of atmospheric gravity waves driving the TIDs.*

- **Introduction:**
  1. The introduction of the work is too precise and lacks a chronological presentation. There is no detailed presentation in this section. I encourage the authors to revise the introduction.

Reply. *The introduction has now been rewritten and reorganized. In addition to a literature review that is impossible to be made chronological, considering the multifaceted aspects of TID research, the content of the manuscript is introduced. The purpose of this work to show that gravity waves driving equatorward propagating TIDs at high latitudes are generated by solar wind – MIT coupling on the dayside, even during low geomagnetic activity. The eastward propagating TIDs waves are attributed to sources of gravity waves generated in the troposphere by geostrophic adjustment processes and shear instability. This physical mechanism has not been previously considered as a source of TIDs.*

2. No in-depth and related literature review has been made.

Reply. *In the introduction, the referencing of the published papers is now organised in paragraphs, each dedicated to specific aspects of the previous work (i.e., theory of GWs and their relation to aurorally generated TIDs, lower atmospheric sources of GWs/TIDs (including polar vortex that has been recently, in our opinion, overemphasized), and TIDs detection techniques.*

- **Data sources and methods**

1. The data sources and methods are not detailed enough to understand the step by step process to analyze the data. They are possibly assuming the readers are familiar with the subject. They need to expand and give more information on the methodology.

Reply. *Descriptions of the techniques and methodologies are now expanded and reorganized into subsections of Section 2.*

2. Kindly provide a map showing the location where each data was collected. The comprehension as to the location where the authors are referring to in the manuscript is confusing, it would be better for the reader to know the locations of data collection.

Reply. *A map of instruments used in this study is now shown in the new Figure 1.*

3. The authors gave shallow descriptions of the methods used in retrieving the parameters. I suggest they restructure this section into subsections for each instruments and give a detail description of each instrument as well as the methodology employed in retrieving the parameters. The section can be structured as follows:

2. Data sources and methods

2.1. Advanced Modular Incoherent Scatter Radar (AMISR)

Description of the instrument and the methodology/ data analysis

2.2. Multi-point and multi-frequency continuous HF Doppler sounding system

Description of the instrument and the methodology/ data analysis

2.3. SuperDARN

Description of the instrument and the methodology/ data analysis

2.4. Global Navigation Satellite System (GNSS)

1. Description of the instrument and the methodology/ data analysis

Reply. *Thank you for the suggestion to structure this section. Descriptions of the specific techniques and methodologies are now discussed in more detail, and the section is reorganized.*

- **Result**

The presentation of the result is quite confusing. This section also needs further revision.

Reply. *We have now revised/reorganized and expanded Sections 3 and 4 discussing the specific results in more detail.*

- **AGWs/TIDs originating from sources in the troposphere**

This section needs total revision with more graphical evidence.

Reply. *Section 4 has now been rewritten/restructured and additional data are presented to show more graphical evidence that is now discussed in more detail.*

- **Discussion**

1. The discussion and conclusion are too shallow and fail to mention the main scientific contribution of the work to literature.

Reply. *We have now more clearly stated the main contribution of this work (i.e., solar wind – MIT coupling on the dayside generating TIDs, even during low geomagnetic activity; sources of gravity waves generated in the troposphere by geostrophic adjustment processes driving TIDs). The results are now presented in more detail in Sections 3 and 4.*

- **Summary and conclusions**

1. The conclusion does not reflect the results presented and discussed. The authors intend to investigate the source of the AGWs induced MSTIDs. However, this has not been demonstrated in the current state of the manuscript.

Reply. *We do not have any means to observe AGWs in the upper neutral atmosphere, but Nykiel et al. (2024) (now referenced in Introduction) showed that Joule heating is a primary energy source for the night-time TIDs triggered in the auroral region, while the daytime TIDs can be also driven by precipitating particles in the polar cusp. PIFs are known to be associated with poleward moving auroral forms (precipitation), a source of AGWs/TIDs. All TID cases presented in Section 3.1 and 3.2 are shown to have sources at high latitudes. Fig. 3 discussed in Section 3.1 shows PIFs poleward of Alaska, which are the sources of AGWs/TIDs. Figs. 6 and 7 (in the European sector), and Fig. 8 (in the North American sector) show EICs, indicating the sources of TIDs. We believe this is now adequately summarized in Section 6.*

Minor Comments

- **Abstract:**
  1. For instance, Between **Lines 21-24**: The work was not introduced properly, rather information about the instruments were given.

Reply. *Abstract has been revised to introduce this work (see, our reply above).*

3. **Line 27-29:** they mention the aim of the work, however, the preceding and succeeding sentences are not compatible, making the flow in the write-up interruptive. Kindly revise.

Reply. *The abstract has been revised and the sentences rewritten.*

- **Introduction:**

1. **Line 47-48:** *TIDs generated by AGWs originating in the lower atmosphere come from a variety of sources… .*
   a. The authors need to be mindful of the choice of words. AGWs capable of propagating to the ionosphere and modulating TEC are considered TIDs or perturbation generated in the ionosphere. It will be better to say TIDs are GWs modulated TEC or better still to say TIDs are driven by GWs. This is the case when considering TIDs mostly originating from the lower atmosphere.
   b. This sentence is too long. I suggest you break it into two parts:
      i. sources at the lower latitude and equatorial regions.
      ii. sources at high latitude.

Reply. *The introduction has now been rewritten considering the referee's suggestions. Thank you.*

2. **Line 59-62:** *The Joule heating due to the ionospheric currents of in the lower thermosphere is a source of equatorward propagating AGWs … .*
    a. It should rather be "*The Joule heating due to the ionospheric currents in the lower thermosphere is a source of equatorward propagating AGWs …. .* [remove the "**of**"]

Reply. *Corrected.*

- **Data sources and methods**

1. **Line 83-84:** *To retrieve TIDs, background densities are removed by applying Savitzky-Golay filter (Press and Teukolsky, 1990).*

    a. How was the data preprocessed before the application of the Savitzky-Golay filter? Why is this filtering method chosen over the other methods?

Reply. *This is now discussed in more detail in the expanded Section 2.1.*

2. **Line 86-98:** The authors just cited the works done by others and possibly assumed the readers are familiar with the method. It is important to state and discuss the specific methods used, even if the readers are familiar.

Reply. *This is now discussed in more detail in the revised Section 2.*

3. **Lines 100-114:** a brief but yet no detailed description of the SuperDARN is given. However, similar to the other instruments, basically no information on the methodology used to first preprocess the data, followed by the data analyzing to retrieve the necessary background information or wave parameters. Kindly provide this information.

Reply. *To address this, we have modified the text in lines 100-114 to provide a more thorough description of the SuperDARN data, specifically clarifying that we utilized the fitacf2.5 dataset. We have also included a citation for the software toolkit that produces this dataset, allowing readers to access detailed information on the data processing procedures and underlying assumptions. Furthermore, we have included a brief description with relevant citations on how SuperDARN datasets can be used to extract Medium-Scale Traveling Ionospheric Disturbances (MSTIDs) parameters. By incorporating these changes, we aim to give readers a clear understanding of the data processing and analytical steps involved in our study.*

4. **Line 116:** What is SECS inversion technique? Why have you chosen this approach over the others? Details are needed to enhance the understanding of the reader.

Reply. *This is now discussed in more detail in the revised Section 2.*

5. **Line 123-136:** Similar to other comments on the previous instruments.

6. **Line 134-135:** The authors need to give enough details on this procedure instead of citing reference.

Reply. *More details are provided.*

7. **Line 138-142:** This section is not supposed to be here. It should be in the acknowledgement.

Reply. *While this looks like Acknowledgement, it is one important data source used in this study. Revised and included as subsection 2.6. Solar wind data*

- **Result**

  - **AGWs/TIDs originating from lower thermosphere at high latitudes**

1. **Line 146-167:** This section needs to be in the introduction.

Reply. *Moved to the introduction.*

- **Event of January 8/9, 2013** The presentation

of this section:

2. the presentation is not arrange such that the reader can easily understand.

Reply. *Yes, the introduction to this section confounded by too many references may have been confusing. This is now clarified, the section content revised, and we believe better understandable to the reader*.

3. the presentation of the corresponding Figures is not in sequential order. For instance, in some part of the text, results presented in Figure 9 are presented before Figure 8.

Reply. *Figures have several panels, some of which are referred to later in the text, but we have rearranged the text and reference the figures in sequential order.*

4. some undefined abbreviations are found within this section.

Reply. *We make sure that the abbreviations have been explained.*

- **Events of November 1 and 4-5, 2014**

5. What are the parameters of the observed waves? How do you know they are large-scale characteristics? This section needs to be revised. Either a table or a plot needs to be provided with the wave parameters. Putting some of them in the texts is not enough.

Reply. *The ground-scatter range mapping (Bristow, Greenwald and Samson, 1994; Frissell et al., 2014) is now applied to estimate the characteristics of the observed waves. In Section 3.1, Figure 3d have been revised, and similarly in Section 3.2 the estimated wave characteristics are discussed, and figures are provided in the Supplement.*

1. **Line 301-302:** *Atlantic are sources of the GWs, which supports previously published results referenced above and points to winter jet stream as a likely source of GWs*.

    a. Please cite some references.

Reply. *A reference is now cited in the introduction of Section 4.*

Events of November 1-8, 2014

2. **Line 376-378: …** *were likely sources of MSTIDs propagating eastward to southeastward, as observed in the detrended vTEC maps (indicated by arrows in Figs. 13a,b) on November 1 and 8, 2014*.

    a. It has been mentioned that the propagation of the MSTIDs are indicated by arrows in Figure 13a.b. However, no arrows have been plotted. Only ">>" were used. Kindly use real arrows.

Reply. *The arrows have been edited.*

3. **Line 388-390:** *As described in more detail by Chum and Podolská (2018) and Chum et al. (2021), the use of well correlated signals at two or three different frequencies makes it possible to determine a 3-D phase velocity vector.*

    a. How will the reader know the details in Chum and Podolská (2018) and Chum et al. (2021) with respect to the obtained result? Kindly mention here the exact point of these references.

Reply. *The description of the HF Doppler sounder technique along with these references are now part of Section 2.2. Section 4 has been significantly revised and a new, more recent event, with better GNSS coverage is added.*

Physical mechanism of GW generation in the troposphere

4. **Line 439:** *Using the ERA5 reanalysis, similar to Figs. 15e,f, north-eastward propagating GWs in the ….*

    a. This is a bit confusing. There is no Figs. 15e,f. Kindly check and correct.

Reply. *This is now corrected in Section 4.4 discussing Fig. 17.*

• **Discussion**

1. **Line 454-455:** "*In Section 3.1, we have shown evidence that even during a geomagnetically very quiet period the TIDs that were observed by PFISR in Alaska can be attributed to sources at high latitudes*".

    a. This aspect of the manuscript in Section 3.1, appear more of literature review and presentation of result. I would like to encourage the authors to really show (with diagrams) other evidence that the high latitude sources were really the possible sources of the detected TIDs.

Reply. *As we have already explained in a reply above, all TID cases presented in Section 3.1 and 3.2 are shown to have sources at high latitudes. The Joule heating is a primary energy source for the night-time TIDs triggered in the auroral region, while the daytime TIDs can be also driven by precipitating particles in the polar cusp. PIFs are known to be associated with poleward moving auroral forms (precipitation), a source of AGWs/TIDs.*

Reply to Referee Report 2

Title: Observations of traveling ionospheric disturbances driven by gravity waves from sources in the upper and lower atmosphere.

Overview of Manuscript

This work presents Observations of traveling ionospheric disturbances driven by gravity waves from sources in the upper and lower atmosphere. They use a multi-instrument approach with the aim of attributing observed TIDs to atmospheric gravity waves generated in the lower thermosphere at midlatitudes. The work has the potential to contribute to existing literature if revised and some issues fixed.

I therefore recommend the manuscript be accepted after revision.

Comments

1. The authors did not capture the important aspects of the work done. Please rewrite the abstract so it captures the attention of the reader and gives a clear overview of the work.

   Reply 1. *We have rewritten the abstract to better capture the aspects of this work, highlighting the multi-instrument techniques of TIDs observations and physical mechanisms that are sources of atmospheric gravity waves driving the TIDs.*

2. The introduction is not very clear. It is very confusing to read and is more of a literature review than an introduction of the subject matter. Please rewrite it.

   Reply 2. *The introduction has now been rewritten and reorganized. In addition to a literature review that is mandatory, the content of the manuscript is introduced. The purpose of this work to show that gravity waves driving equatorward propagating TIDs at high latitudes are generated by solar wind – MIT coupling on the dayside, even during low geomagnetic activity. The eastward propagating TIDs waves are attributed to sources of gravity waves generated in the troposphere by geostrophic adjustment processes and shear instability. This physical mechanism has not been previously considered as a source of TIDs.*

3. The authors keep citing and referring the reader to works done without stating exactly in the text what they want the reader to know. Please cite and state the point you want to let the readers know in the text.

   Reply 3. *In the introduction, the referencing of the published papers is now organised in paragraphs, each dedicated to specific aspects of the previous work (i.e., theory of GWs and their*

relation to aurorally generated TIDs, lower atmospheric sources of GWs/TIDs (including polar vortex that has been recently, in our opinion, overemphasized), and TIDs detection techniques.

4. Please elaborate on the SECS inversion technique and it´s advantage over other techniques.

   Reply 4. *Descriptions of the techniques, including the SECS inversion technique, are now expanded and reorganized into subsections of Section 2.*

5. Please can the authors represent the instruments used and also the location of the studies in a table or map? This will help the reader.

   Reply 5. *A map of instruments used in this study is now shown in Figure 1.*

6. The methods used to arrive at the results are very shallow and would be difficult for replication by the reader. The authors should please give detailed and step-by-step writeup of the methodology employed.

   Reply 6. *In addition to rewritten and expanded Section 2, Sections 3 and 4 have been significantly revised discussing specific results in more detail.*

7. Please the authors should state clearly in the text the contribution (the new findings) of this work to already existing literature.

Reply 7. *We have now more clearly stated the contribution of this work in Sections 1, 5 and 6 (i.e., solar wind – MIT coupling on the dayside generating TIDs, even during low geomagnetic activity; sources of gravity waves generated in the troposphere by geostrophic adjustment processes driving TID*