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Manuscript title: Diagnostic study of geomagnetic storm-induced ionospheric changes in mid-latitude D-region using VLF signal propagation characteristics

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Iteration: Major Revision

Dear Editor,

Thank you very much for handling our manuscript and for organising the effort that is taking it through the review and subsequent revision process. We are also thankful to the reviewers for their time and helpful comments and suggestions. We have now revised our manuscript based on suggestions and/or comments in yours and the reviewers' report. Please find below the point-by-point response to the review reports:

EDITOR'S COMMENTS

Dear Dr. Nwankwo,

Thank you for submitting your revised manuscript to Annales Geophysicae. I have now received two reviews of your manuscript, which are attached for your reference. Based on the review comments, I find that your manuscript still needs some revisions before final acceptance.

One reviewer provides only a few comments. However, the other reviewer would like you compare your VLF observations with those from ionosondes. In addition, both the reviewers recommend the authors to properly evaluate the current results with reference to the previous studies in the Discussion part.

The feedback provided in the reviewer assessments of your manuscript is important and should be taken into account as you complete your revision.

I look forward to receiving your revised manuscript.

Sincerely,

Keisuke Hosokawa
Topical Editor
Annales Geophysicae

Authors Response

We have now revised our manuscript based on your suggestions and the reviewer comments. In this revised manuscript we presented a profound literature review in the introduction section against a properly referenced background of the body of work done in the subject area. We clearly defined the goal of this present work that seek to augment the limited body of research related to the impact of geomagnetic storms on VLF propagation along the transmitter-receiver great circle paths (TRGCPs) within the Earth-Ionosphere waveguide. The ionosonde observation enabled us to study the state of the local ionosphere to be able to assess our findings within the context of a coupled magnetosphere-ionosphere system. As suggested, our revised manuscript compared the VLF observations with those from ionosondes. We also evaluated our current results with reference to the previous studies in the Discussion part.

We, therefore, present to you our revised manuscript.

COMMENTS BY REFEREE#1

The preprint of the article seems to me interesting and quite worthy for its publication.

The authors continued their studies of the effects of geomagnetic storms in the mid-latitude D region, begun in their previous works, for example, in [Nwankwo V. U. J., Chakrabarti S. K. and Ogunmodimu O. Probing geomagnetic storm-driven magnetosphere-ionosphere dynamics in D-region via propagation characteristics of very low frequency radio signals, J. Atmos. Sol-Terr. Phys., 145, 154-169, 2016]. They used VLF data from mid-latitude paths obtained during storms of different intensities and obtained detailed and interesting statistics on the occurrence of VLF signal amplitude anomalies along these paths.

This information itself is very valuable and complements the results of studies of VLF propagation during periods of magnetic storms and substorms carried out over the past decades.

In my opinion, at the end of the article, the authors should say at least a few words about what, in their opinion, are the reasons for the occurrence (or absence) of these anomalies. If these reasons are the precipitation of energetic magnetospheric electrons during and after storms, then in the future, satellite data on such precipitations could be drawn into the data obtained by the authors, of course, if such data are available. In addition, for the periods of storms considered by the authors, it would be possible to analyze the data of riometric measurements, as well as VLF observations on other paths.

P.S. I noticed one typo in the text of the preprint. In line 60, instead of "Kleimenov et al ..." you need "Kleimenova et al ..."

Authors Response

Thank you very much for your detailed review and helpful comments

We have now added what in our opinion are the reasons for the occurrence (or absence) of the observed anomalies. Please see lines 428-437, 445-448 and 550-557.

We also supported our findings with results based on extended investigation such as TEC analysis and the ancillary data/information of the timing, classification and location of associated solar flares, coronal mass ejections (CMEs), solar particle events (SPEs), and the timings for the sudden storm commencements (SSCs). Please lines 523-540

The typo in "Kleimenov et al ..." have been corrected as "Kleimenova et al ..."

COMMENTS BY REFEREE#2

Diagnostic study of geomagnetic storm-induced ionospheric changes over VLF signal propagation paths in mid-latitude D-region by Nwankwo et al.

This paper presents VLF signal analysis over two propagation paths associated with 15-20 geomagnetic storms in the mid-latitude region from September 2011 to October 2012. The authors characterized VLF signal disturbances according to the five metrics/parameters defined at different times in the diurnal variation. Based on analysis they found dipping in five VLF parameters (ranging from 25% to 80% of the analyzed cases) during the storms compared to the respective pre-storm values. Further, the authors added virtual heights and critical frequencies of the E- and F-regions from ionosonde stations nearby the VLF transmitters.

The paper is interesting, however, based on my observation, I recommend major revision with the following modifications.

1) The propagation disturbances of the VLF/LF waves have been extensively studied for several decades showing that the signals are strongly affected by the geomagnetic storms at high and mid-latitudes. However, the previous studies are not properly referred to in the text

and so the results presented by the authors are not properly evaluated with reference to the previous studies. The authors are recommended to state clearly what results are newly added to our knowledge about the VLF propagation disturbances and D-region ionosphere.

2) Authors are advised to mention the significance of the five metrics or how they are connected to the ionospheric variation/properties. What do these five metrics tell us about the D-region ionosphere? This has to be discussed clearly.

3) Authors combined VLF observations of D-region ionosphere with ionosonde observations of E and F regions ionosphere. It will be meaningful to compare the D-region parameters (like electron density, or D-region reference height) deduced from VLF observations with the ionosonde parameters. This is the major concern for the paper.

4) Statistical results should be summarised effectively with one/two figures. Repetition of the same kind of figures confuses the goal of the paper.

5) "The MDP signal appears to be more responsive (about 68% for combined analysis shown in figs 7 and 9) to geomagnetic perturbations than other signal metrics"

A more detailed discussion is needed. For example, how does geomagnetic storm dominates over daytime solar ionization in determining VLF amplitudes?

6) "A rise in SRT and SST amplitude under geomagnetic storm conditions"; what does this mean in connection to ionosphere during the geomagnetic storms? An explanation is needed.

7) What could be the physical reason for "strong storm responses" on DHO path compared to the responses on GQD path, though both the GQD and DHO are almost at the same latitude (GQD is slightly higher). Ionosonde results may also be checked with satellite electron precipitation data in this regard.

8) Figure 2: Mention the name of the transmitters in Caption.

Authors Response

Thank you very much for your detailed review and helpful comments

1) This manuscript has now been revised to present a profound literature review in the introduction section against a properly referenced background of the body of work done in the subject area. Previous studies have now been properly referred to in the text and referenced or cited accordingly (please see the revised "Introduction"). The results presented here are now properly evaluated with reference to the previous studies. However, we clarify that this work is built on our previous effort (e.g., Nwankwo et al. 2016) in which we cited many other supporting works. We present our findings based on the combine diagnostics of the D, E and F region during storm disturbances in the D region. So far, we are not aware of any similar effort and therefore consider our results to be new and addition to knowledge.

2) We have now mentioned and/or discussed the significance of the five metrics and how they connect to ionospheric variations and what they reveal about the D region ionosphere. In addition to the profound literature review, please also see lines 150-173 and 295-315.

3) We are not sure of how best to meet the expectation of the Reviewer on this. However, I believe that lines 428-437, 439-453, 512-527, 529-540 (and the revised conclusion) should be able to address this concern.

4) We retain the responses made here during the Angeo-discussion. There is an important observation/finding associated with the statistical analysis done here. We have statistically analyzed the metrics for (i) 1-day (mean value) before, during and after the storms (figure 7) and (ii) 2-day (mean value) before, during and after the storms (figure 9). Interestingly, the percentage dip of the MBSR and MASS increased significantly in the 2-day mean signals before the events (when compared with the 1-day mean value). It will be challenging to

summarize the statistics in one/two figures because of the need to show results of the two propagation paths (GQD-A118 and DHO-A118). Also, the plots need be large enough for readers to see and compare.

5) We have enumerated what in our opinion are the reasons for the responsiveness of the MDP to geomagnetic storms. In addition to the profound background provided in the introduction section, please also see lines 428-437, 534-540, 550-552.

6) More details about the SRT and SST has been provided in the text. Please see lines 301-311, 446-448

7) Please see lines 501-540. In future work we will also check with satellite electron precipitation data and perhaps perform Ovation-Prime auroral model runs for the intervals of interest – see https://www.ngdc.noaa.gov/stp/ovation_prime/data/

8) The name of the transmitters has been mentioned in the caption as suggested.

We believe that in its current state, our revised manuscript is now suitable for further consideration by your journal, and sincerely hope that the paper will now be accepted for publication.

Thank you very much.

Victor U. J. Nwankwo