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Atmospheric Chemistry and Physics
Discussions

Interactive comment on "Modeling of the Very Low Frequency (VLF) radio wave signal profile due to solar flares using the GEANT4 Monte Carlo simulation coupled with ionospheric chemistry" *by* S. Palit et al.

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We earnestly thank reviewers for their minute scrutiny of the manuscript. We believe that their noble and scholarly suggestions will be helpful for further improvements of it's quality and credibility. We have tried our best to follow their suggestions and make necessary modifications in the manuscript.

Journal Name: Atmospheric Chemistry and Physics

Title: "Modeling of the Very Low Frequency (VLF) radio wave signal profile due to solar flares using the GEANT4 Monte Carlo simulation coupled with ionospheric chemistry" by S. Palit, T. Basak, S. K. Mondal, S. Pal, and S. K. Chakrabarti, submitted for publication in ACP.

(A) Comments Reviewer 1:

First an apology note: I apologize to the authors for delaying my review. It was not intentional and happened because of a misunderstanding.

The paper deals with modeling the observed amplitude perturbations of VLF (very low frequency) transmissions propagating in the earth-ionosphere waveguide, which are caused by solar flare X ray ionization effects in the daytime D region ionosphere. The authors combine computational codes and models, which are openly available, to produce quantitative estimates of VLF amplitude perturbations which are then compared with the observations.

The methods and models they use include: 1) A high energy physics Monte Carlo simulation code to derive the electron density production rates as a function of altitude caused by X-ray solar flare energy fluxes as measured by satellites (GOES, RHESSI). 2) The estimates of (1) are inputted in a simplified D region ion-chemistry model, used before to model lightning induced radiation belt electron precipitation (LEP) events and early fast VLF events in the D region; it consists of 4 types of ion species and the main production and loss processes (there are 4 coupled continuity equations) and is used here to obtain elevated electron density profiles in the D region during the solar X-ray event. 3) The electron density profiles from (2) are inputted in (the publicly available) long wave propagation capability (LWPC) code which can estimate the amplitude and phase of a given VLF transmission that is received at a given location (here only amplitudes are computed). Finally, the amplitude estimates are compared with the measured VLF amplitude changes during the solar flares by simple superposition in time.

The methodology is applied in two cases of an M and an X type flares and the agreement between the model results and the measurements is indeed very good. Apparently, this implies that the applied methodology, which, to my knowledge was never used before, is working well meaning that the paper deserves to be published (after some minor corrections and improvements; particularly the authors need to clarify/detail their methodology procedures better). Overall, I think this is a nice piece of work. Minor suggestions:

1). Since the authors deal with the lower ionosphere below 90 km, that is, the D-region, they should be specific throughout their text and refer to the "D-region ionosphere", instead of "ionosphere".

Ans. Most of the "ionosphere" is replaced with "D-region ionosphere", Only in some places the term "lower ionosphere" is kept to avoid repetitions.

2). Also better replace the term "ion production" to "electron-ion" production throughout the text, especially since all your computations refer to electron density.

Ans. all the terms "ion production" is replaced with "electron-ion production".

3). VLF receivers measure amplitude and phase. Explain why here you simulate only amplitudes while LWPC predicts phases as well.

Ans. We calculated the amplitude and phase simultaneously. We have worked with the phase also, though we think there are scopes of further improvements in our modeling of the observed phase. In follow up work, we will include both the phase and amplitude simultaneously.

4). Line 29. Note that the work of Haldoupis et al. 2009 using the GPI model did not apply to LEPs but on early/fast VLF perturbations caused by direct lightning effects on the overlying D region during sprite occurrences (e.g., see Haldoupis et al., JGR, vol 109, A10303, 2004).

Ans. We have corrected the line

"The model has also been adopted successfully by Haldoupis (Haldoupis et al., 2009) for his work on the lightning induced electron precipitations or LEPs."

to

"The model has also been adopted successfully by Haldoupis (Haldoupis et al., 2009) for his work on the early VLF perturbations associated with transient luminous events."

5). Lines 50 to 54. Please remove the paragraph symbol §and replace it with the word "section".

Ans. All the §is replaced with "Section"

6). Page 3, section 2. I suggest you add a bit more of description in "Observations". Please comment on the diurnal variation of the VLF signal and describe the reason for this pattern. It always helps a reader who is not familiar with VLF to understand better things. Also I suggest you replace the figure (a) that is for Feb, 18, 2011 with that of either day Feb. 15, or Feb. 24 in which you get the M or X type flares used in the present analysis.

Ans. We added the the following paragraph in explaining the observations.

" The diurnal variation on normal day is characterized by the presence of two signal minima around the local ground sunrise and sunset time of the receiver. The minimum around the sunrise is called the sunrise terminator time (SRT) and the minimum around the sunset is called the sunset terminator time (SST). The appearance of the sunrise terminator time (SRT) in the diurnal behaviour actually signifies the formation of the D-region, while the sunset terminator time represents the start of disappearance of the D-region [Sasmal et al., 2009]. During the day time between the SRT and SST, the signals reflect from the D-region and vary with the solar zenith angle with the maximum amplitude around the noon when the electron production rate in the ionosphere reached its maximum level. The D-region disappears at night and also the E-region becomes weak with less uniform electron density.

The fluctuations in the night time VLF signal amplitude are attributed to the fact that the VLF signal reflects randomly from the upper E-or lower F-region with no non-deviated attenuation at the lower D-region. Also, the atmospheric convections and oscillations may result in such fluctuations. "

In Figure 1(a), we used the VLF data of 18th February, 2011 because on that day there are many solar flares detected. This is an example of solar active day where many solar flares have been detected by the ground based VLF receiver.

7) If I am not mistaken, you are the first to be using the GEANT4 toolkit for this kind of work in the earth's ionosphere. Since it has been developed for high energy physics, I suggest you provide a few more details about it, its advantages and disadvantages/limitations. Is it easy this toolkit to be used and is it openly available so that it can be acquired by other ionospheric researchers (e.g. provide an internet site where it can be downloaded)?

Ans. More details of the GEANT4 toolkit, its applicability to ionospheric simulations, its advantage, disadvantage and availability have been included in the text.

The modified text is

" GEANT4 is a well known object-oriented detector simulation program (Agostinelli et al., 2003), which includes all the required physics for the production of electron ion pair in the atmosphere by energetic photon interactions. Most of the ionization occur due to the collision of molecules with secondary electrons produced by initial photo ionization. The earth's ionosphere is a giant detector and as such, the software used to analyse detectors in high energy physics could be used here as well. Furthermore GEANT4 (GEANT is the abbreviation of Geometry and Tracking) is a openly available and widely tested toolkit and can be downloaded from the website http://geant4.cern.ch/. The Monte Carlo processes deal with the transport and interaction of particle with matter in a defined geometry and store all the information of track, nature and number of secondaries efficiently. With this application we can find accurately the ionization processes

and tracks without any prior knowledge and assumption of chemical or physical model of the region. The included electromagnetic processes related with X-ray incidence are well developed and suitable for application in the context of Ionosphere. For simulation with UV the application at this stage is not quite desirable, but with some development in the toolkit area it is possible to use it for Monte Carlo simulation with UV and EUV incidence in the ionosphere. We simulated only the rate of ionization at different altitudes due to solar X-ray photons during flares using this GEANT4. For the chemistry part related to the interaction of the produced electron and ions in the D-region ionosphere we adopt a different chemical model. "

8). Lines 81 to 98. Try to improve this part of the paper so that its more intelligible for the reader. Give more details on the X-ray spectra and how they are obtained and used in the GEANT4. You mention RESSI x-ray spectra and OSPEX software in the Figure2 caption briefly but not in the text. I believe you need to discuss how you obtain the energy spectra and provide more details as how these are used.

Ans. Required clarifications are made.

The modified text is

" Initially, the Monte Carlo process is triggered by primary particle generation class of GEANT4 with photons of energy ranging from 1-100 keV. We are not interested in higher energy gamma ray photons as their energy deposition height is much lower than that of the D-region Ionosphere. First a uniform spectrum (equal number of photons per keV bin) is chosen for input in primary generation class, such that the incident photons in a specific bin have random energies within the range of the bin. This gives a distribution of electron-ion production rate in a matrix form, the ij^{th} element of which gives the electron production rate ($cm^{-3}sec^{-1}$) in i^{th} km due to the incident photons in the j^{th} keV bin. We produce such altitude distributions by simulation with different incident angles of the photons. The real altitude distributions of electron-ion production rate during a flare are obtained by multiplication of altitude distributions matrix of corresponding time (hence angle of incidence) with the actual flux spectrum at that height. For this we collect the back-ground subtracted solar spectra during the flares from Rhessi satellite data (http://hesperia.gsfc.nasa.gov/rhessi2/). This method helps us saving a significant amount of computation time. "

9). In Figure 3, x-axis is Ne production rate, that means dNe/dt, but the units in the label are cmˆ-3. Be accurate with the terms here and in the text. In Figure 4, the axis label should be "electron production rate" and not "electron produced".

Ans. The corrections are made. Modified figures are attached herewith.

10). Page 7, top paragraph. Yes, the GPI model is for nighttime. Can you justify better why this is sufficient for daytime? For example electron detachment is much slower during the night. Negative ions live much longer during the night than during the day when detachment is driven by sunlight photons.

Ans. We think that any differences in result with the application of GPI model from night to day time only manifest through the value of the coefficient (like detachment coefficient gamma) chosen at different times. Later we simulated with normal day diurnal variation of ion density (mainly due to ionization by Lymann-alpha) with this model and found good agreement with the model like IRI model etc. We plan to include this results in details in the next publications. For this time we assume that during X-ray flares this model can be applied.

11). Lines 137-139. Explain what is the gamma coefficient in Eq. 2 (detachment coefficient) and provide a reference as to what is its most likely value during the day. Since it is a very uncertain quantity can its value affect seriously the present calculations of the GPI model and how this depends on altitude?

Ans. Few lines in the paragraph are added with new references. Values of the possible photo-detachment coefficient and those from our calculation are also mentioned. The time evolution of the negative ion density (closely related to the gamma coefficient) is

also shown in figure 8 in the corrected version along with the picture of electron density in Figure 7.

12). Page 8 upper part. You talk about Ix and N(t) as perturbed parts relative to the ambient parts. Obviously these are the contributions of the ongoing X ray flux impacting on the lower ionosphere. The term "perturbed" and "perturbation component" refers usually to a small change away from a mean/steady state, which here is not true since the X-ray contribution alters D region ionization significantly (1 to 3 orders of magnitude). It is better to use here a more proper term or simply use X-ray distribution.

Ans. The term "perturbation" is changed to "modulation" and the term "unperturbed" is changed to "ambient" throughout the manuscript.

13). Lines 210-211. This sentence does not read well, please improve it.

Ans. The line

"Furthermore, for the X-class flare as the abundance of higher energy photon is greater than that in the M-class flare, the dominance of the ambient electron density in determining the VLF amplitude starts somewhat later."

is changed to

"Furthermore, since the M-class flare spectrum is relatively softer than that of the X-class one, the ambient electron density starts to dominate the VLF amplitude a bit earlier during decay of the M-class flare. We can see that the deviation of the modelled slope from the observed one starts earlier for M-class flare than the other."

14). Line 215. Correct to "occurrence" from "occurrance".

Ans. The term "occurrance" has been changed to "occurrence".

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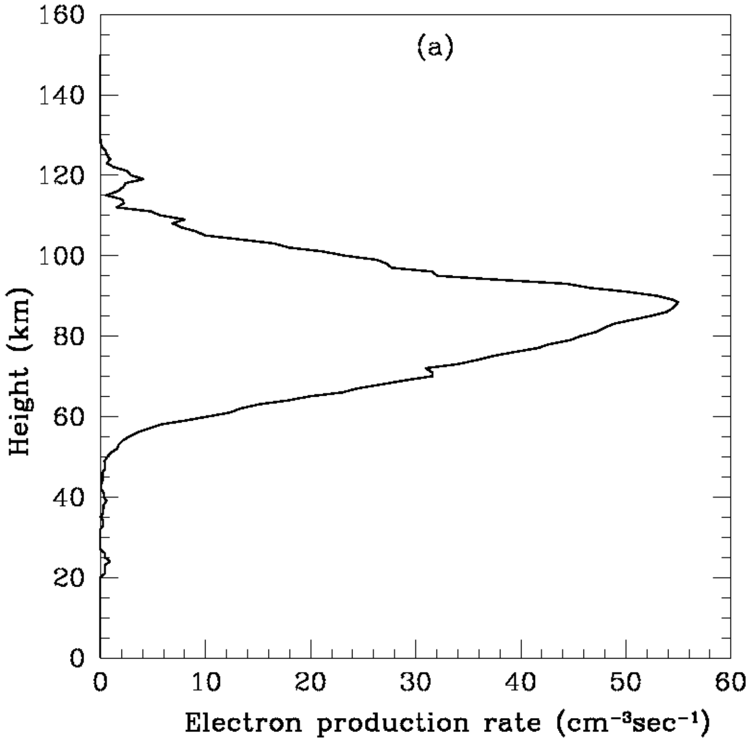
(a)
Height (km)
Electron production rate (cm⁻³sec⁻¹)
0
20
40
60
80
100
120
140
160
0
10
20
30
40
50
60

Fig. 1.

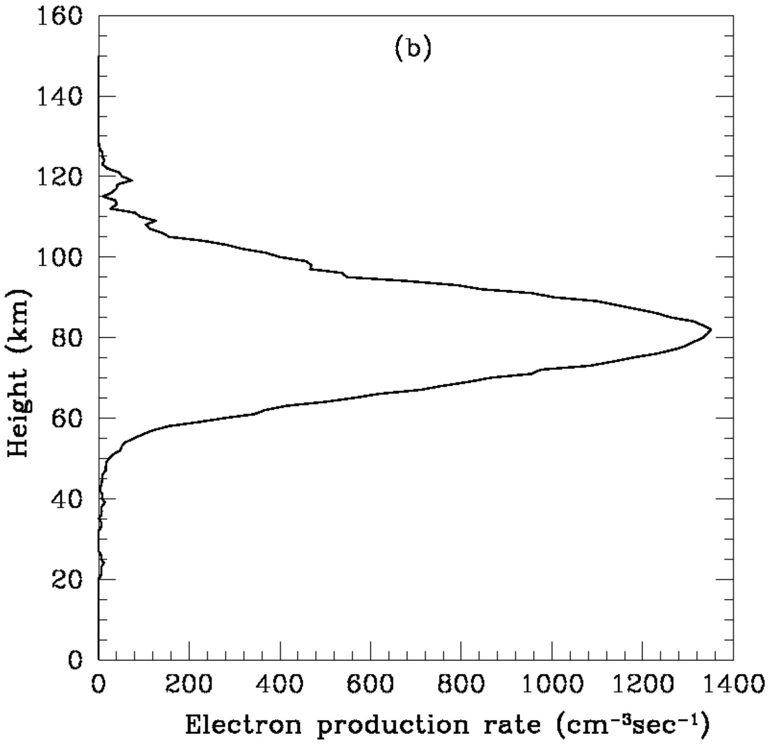
(b)
Height (km)
Electron production rate (cm⁻³sec⁻¹)
0
20
40
60
80
100
120
140
160
0
200
400
600
800
1000
1200
1400

Fig. 2.

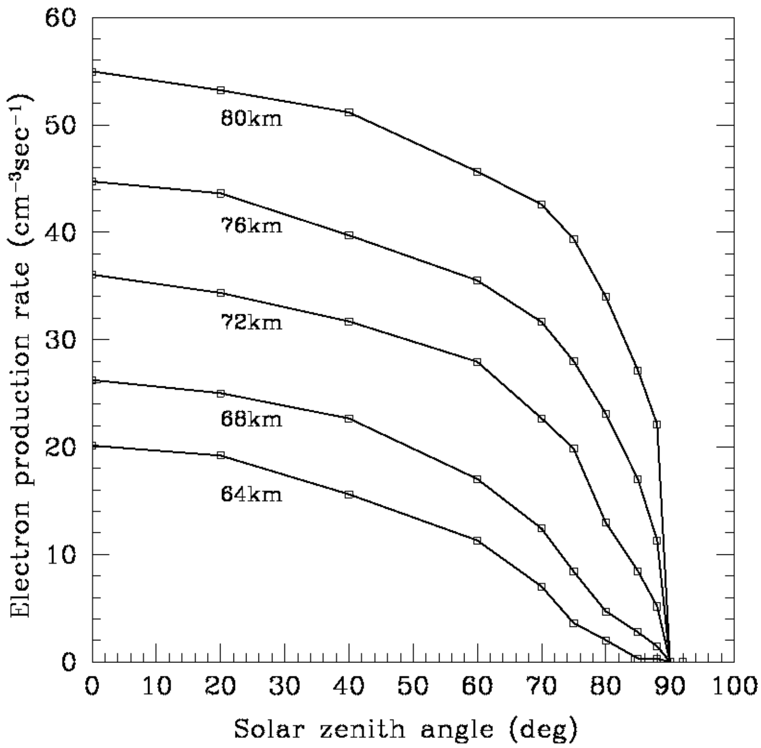
60
50
40
30
20
10
0
Electron production rate (cm⁻³sec⁻¹)
80km
76km
72km
68km
64km
0 10 20 30 40 50 60 70 80 90 100
Solar zenith angle (deg)

Fig. 3.