Irregularities of ionospheric VTEC during lightning activity over Antarctic Peninsula

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Abstract. This paper investigates the irregularities of vertical total electron content (VTEC) during lightning activity and geomagnetic quiet days over Antarctic Peninsula in year 2014. During the lightning event, the ionosphere may be disturbed which may cause disruption in the radio signal. Thus, it is important to understand the influence of lightning on VTEC in the study of upper-lower interaction. The lightning data is obtained from World Wide Lightning Location Network (WWLLN) and the VTEC data has analyzed from Global Positioning System (GPS) for O’Higgins (OHI3), Palmer (PALV), and Rothera (ROTH). The results demonstrate the VTEC variation of ~0.2 TECU during low lightning activity which could be caused by energy dissipation through lightning discharges from troposphere into the thermosphere.

1. Introduction

The performance of precise navigation system is essential to ensure smooth communication between satellite transmitter and ground based station receiver. However, variation in the ionosphere can lead to disruption of the signal and significant error through solar events [1], geomagnetic activity [2], atmospheric gravity waves (AGW) [3, 4], lightning [5, 6], and plasma bubble [7]. Other authors have studied the effect of lightning activity on ionospheric irregularities in America [8], Europe [5] and South Africa [6] for a mid-latitude region. This paper explores the vertical total electron content (VTEC) disturbance with lightning activity in Antarctic Peninsula. The objective of the study is to investigate the VTEC irregularities during lightning activity with a low geomagnetic storm. Whether with the low geomagnetic activity, the lightning will somehow affect radio signals through the VTEC variation. Lightning is an electrical discharge between positive and negative regions of a thunderstorm. The cloud interacts with ice particle and begins separating smaller particles. The separation of net positive and negatively charged cloud forms huge electrical potential between cloud and cloud (CC) and between cloud and ground (CG) [9]. As the lightning is discharged, it couples energy through quasi electrostatic (QE) and electromagnetic pulsed (EMP) field and travels to mesosphere and lower ionosphere [6]. The EMP caused an increased ionization by heating the atmosphere which changes the atmospheric conductivity. It may have an indirect impact on the lower atmosphere or even interact with an electron that can diffuse from mesosphere to upper atmosphere.
The ionosphere can be measured using Incoherent Scatter Radar (ISR), ground and space based insonde, Low Earth Orbit (LEO) satellite and Global Navigation Satellite System (GNSS). In this case, Global Positioning System (GPS) is used as it offers global availability of signal and accurate performance. GPS is used to measure vertical TEC (VTEC) enhancement which shows scintillation in F region.

2. Methodology
The lightning data is collected for Antarctic Peninsula throughout the year 2014 which is obtained from World Wide Lightning Location Network (WWLLN). The data contain information on lightning energy in Joules (J), latitude and longitude in Fractional Degrees, date and time of lightning occurrence in UTC and number of station participate in the observation. Root Mean Square (rms) is the uncertainty energy in Joules. The sensor installed in Antarctic Peninsula is located in Rothera (ROTH) which is 360 km away from Palmer station (PALV) and 666 km away from O’Higgins station (OHI3).

The GPS data is collected from Scripps Orbit Permanent Array Centre (SOPAC). Three GPS station is selected which are O’Higgins (OHI3: 63.32°S, 57.90°W) at UTC – 4 hour, Palmer (PALV: 64.77°S, 64.05°W) at UTC – 4 hour and Rothera (ROTH: 67.57°S, 68.12°W) at UTC – 3 hour. The GPS data is processed using Translation Editing Quality Check (TEQC), a toolkit provided by UNAVCO to translate binary format data and extract variables in GPS data. The VTEC is calculated based on Suparta et al. [10] with a 30 seconds interval. The data is then smoothed and averaged at 150 seconds to remove noise. Additionally, Astronomisches Institut University of Bern (AIUB) provides Differential Code Bias (DCB) to rectify the instrumental bias caused by ionospheric pierce point.

Several studies [11, 12] have shown that high geomagnetic index has significant impact on VTEC. In order to investigate the impact of VTEC on lightning event, it is important to ensure that the study is isolated from geomagnetic storm. There is several methods such as using Kp index however, we have used Ap indices from Geophysical Institute Gottingen University to provide a daily average level of geomagnetic activity. Ap less than or equal to 5 nT is selected to identify low geomagnetic activity in order to focus on the lightning event and investigate the VTEC irregularities. Figure 1 shows the method of analysis for this study.

The data is plotted in 3 consecutive days together with VTEC irregularities, lightning energy and geomagnetic indices. The data is plotted at Universal Time (UT). The duration of lightning is taken between 0 to 75 minutes before and after the lightning occurrence. The distance between the GPS base station and the location of lightning data is measured using Haversine formula which is determined based on their latitude and longitude. The delta VTEC (ΔVTEC) is calculated to determine the enhancement of VTEC. The formula for slant TEC (STEC) and ΔVTEC are as in equation (1) and (2).

\[ VTEC = STEC(\cos z)^{-1} \]  
\[ \Delta VTEC = |VTEC_i - VTEC_{15n}| \]  

where STEC is the slant TEC in TECU and $z$ is the angle between STEC and VTEC in radian [13], $i$ is the time of VTEC during lightning occurrence in minute and $n$ is the time of enhancement of VTEC before or after lightning occurrence in minute.

3. Results and Discussion
3.1. Ionospheric VTEC irregularities and lightning activity during a low geomagnetic storm
From a total of 72 numbers of lightning occurrence detected in Antarctic Peninsula in 2014, 29 numbers of lightning activity are found to occur during the low geomagnetic event with $Ap$ index less than or equal to 5 nT. However, only 22 numbers of lightning shows a sufficient result to analyze the VTEC irregularities before or after the lightning occurrence as the remainder has missing VTEC data.

As the data is plotted in three consecutive days, the data is combined to produce 14 cases. Figure 2 demonstrates the VTEC response and lightning activity during geomagnetic quiet days. Typical VTEC response can be observed as it progressively increases from 20:00 to 10:00 hour UT as the sun is rising and decreases gradually from 10:00 to 20:00 hour UT as the sun is setting. As the sun is rising, the atmosphere is heated up which causes VTEC to gradually increase from 10 TECU to peak of 40 TECU at Palmer station. The number of lightning appeared in a day is one only in Case 1 to 10, 13 and 14, 2 numbers in Case 12, and the highest is 6 numbers in Case 11.

**Figure 2.** VTEC irregularities and lightning energy in line graph and $Ap$ indices in bar graph. From top to bottom is a) Case 1 to 3 and b) Case 4 to 6

The relationship between $Ap$ index and VTEC can be clearly observed in Figure 2(a) in Case 1. It shows the lightning event that occurs on 10th January 2014 with $Ap$ equal to 4 nT. The impact of geomagnetic activity can be observed on the 9th January at $Ap$ equal to 8 nT which shows VTEC peak
for PALV at 34 TECU as compared with a peak of 31 TECU on the 10th January 2014. A similar observation is also demonstrated for Case 4 in figure 2(b) and Case 14 in figure 3(b). The VTEC irregularities are further examined by concentrating on the specific duration of lightning discharge.

![Figure 3. VTEC irregularities and lightning energy in line graph and Ap indices in bar graph. From top to bottom is a) Case 7 to 10 and b) Case 11 to 14](image_url)
3.1.1. Ionospheric VTEC irregularities and lightning event. The VTEC result is further analyzed to identify its response before and after the lightning events. The lightning discharge is plotted in 0 minute (Min) while the VTEC is plotted 75 minutes before and after the event. Figure 4 and 5 show the compilation of VTEC irregularities and lightning energy. There are two typical trends which are a positive and a negative gradient of VTEC. The positive gradient occurs as the sun is rising and vice versa for the negative gradient. The positive gradient is shown in figure 4 and 5 for lightning numbers 1, 4, 6, 8, 10, 12, 13, 17, 25 and 26. Meanwhile, the negative gradient of VTEC is depicted for lightning numbers 3, 7, 9, 11, 19 to 24 and 27 to 29. Other lightning numbers such as 2, 5, 14 to 16 and 18 show a missing VTEC result.

Figure 4. VTEC irregularities and lightning energy. From top to bottom shows lightning a) No. 1 to 5, b) No. 6 to 10, and c) No. 11 to 15

Figure 4(a)(1) shows the positive gradient of VTEC for Case 1 which is highlighted in the rectangular dashed line that overlapped with lightning energy and VTEC of OHI3, PALV and ROTH. During lightning strike, PALV shows VTEC of 14 TECU at 22:59 UTC. Similarly in figure 4(b)(6),
there is a positive gradient of VTEC as shown by OHI3 and PALV which gradually increasing from 28 to 29 TECU and 20 to 21 TECU respectively. However, figure 4(c)(11) shows a negative gradient of VTEC. During lightning event, the VTEC is at 7 TECU and progressively decrease to 6 TECU within 15 minutes.

It can be observed that 35% of the results show lightning strikes with positive gradient and 41% of the events occur with negative gradient. Typically, only one lightning is recorded within 150 minutes of VTEC as depicted in figure 5. However, figure 5(b)(19 to 24) shows both positive and negative gradient of VTEC with six (6) lightning discharges within 39 minutes ranging from 1.6 kJ to 56.2 kJ. The sudden increase in lightning number could be due to intense negatively charge cloud or due to seasonal transition from spring to summer. The VTEC enhancement that occurs after lightning strikes may be due to ionosphere is heated up.

Figure 5(c)(28) shows VTEC enhancement before lightning strikes. This is because a tremendous amount of charge has to build up first. Other factors that can contribute to lightning development are ice, hail, semi frozen water drops or graupel [14]. Precipitation could also potentially be responsible for lightning development. Data collected from www.wunderground.com shows a positive precipitation in lightning event number 12, 28 and 29. This means that 10% of the total lightning events may be caused by precipitation.

![Figure 5. VTEC irregularities and lightning energy. From top to bottom shows lightning a) No. 16 to 18, b) No. 19 to 26, and c) No. 27 to 29](image)

Table I summarized the result of ΔVTEC before and after the lightning occurrence of the twenty-nine (29) number of lightning detected during a low geomagnetic event. The VTEC differential value is calculated and the result is tabulated. The average distance is calculated for the three GPS stations is between 296 km and 1396 km. Approximately 83% of the total lightning event is located within 1000 km average distance from GPS station. It can be noted that there are some unavailable VTEC data from ROTH.
The average ΔVTEC before the lightning event is 0.32, 0.28 and 0.29 TECU for OHI3, PALV and ROTH respectively. Meanwhile, after a lightning strike the average ΔVTEC is 0.17, 0.15 and 0.16 TECU respectively. It is clear that the average irregularities of VTEC during lightning activity are 0.23 TECU in Antarctic Peninsula.

Table I. The ΔVTEC irregularities for lightning event during low geomagnetic activity in 2014

| No | Case | Date       | Average distance (km) | ΔVTEC (TECU) before lightning event | ΔVTEC (TECU) after lightning event | Positive (P) or Negative (N) gradient |
|----|------|------------|-----------------------|------------------------------------|----------------------------------|-------------------------------------|
|    |      |            |                       | OHI3  | PALV | ROTH | OHI3 | PALV | ROTH |         |
| 1  | 1    | 9-11 Jan   | 1051                  | 0.20  | 0.32 | -    | 0.13 | 0.26 | -    | P      |
| 2  | 2    | 15-17 Jan  | 677                   | -     | -    | -    | -    | -    | -    |        |
| 3  |      |            | 537                   | 0.38  | 0.30 | -    | 0.25 | 0.27 | -    | N      |
| 4  | 3    | 26-28 Jan  | 906                   | -     | 0.35 | -    | -    | 0.31 | -    | P      |
| 5  |      |            | 327                   | -     | -    | -    | -    | -    | -    |        |
| 6  | 4    | 16-18 Feb  | 418                   | 0.40  | 0.21 | -    | 0.42 | 0.25 | -    | P      |
| 7  | 5    | 17-19 May  | 1033                  | -     | 0.02 | -    | -    | 0.07 | -    |        |
| 8  |      |            | 1221                  | 0.41  | 0.01 | 0.01 | 0.15 | 0.11 | 0.13 | P      |
| 9  | 6    | 25-27 May  | 1025                  | -     | 0.04 | -    | -    | 0.05 | -    | N      |
| 10 |      |            | 853                   | 0.54  | 0.45 | 0.69 | 0.26 | 0.10 | 0.32 | P      |
| 11 | 7    | 23-25 Jun  | 817                   | -     | 0.45 | -    | -    | 0.37 | -    | N      |
| 12 |      |            | 1396                  | 0.22  | 0.24 | 0.21 | 0.00 | 0.04 | 0.01 | P      |
| 13 | 8    | 2-4 Jul    | 936                   | 0.42  | 0.24 | -    | 0.19 | 0.08 | -    | P      |
| 14 |      |            | 1283                  | -     | -    | -    | -    | -    | -    |        |
| 15 | 9    | 21-23 Jul  | 498                   | -     | -    | -    | -    | -    | -    |        |
| 16 | 10   | 27-29 Jul  | 607                   | -     | -    | -    | -    | -    | -    |        |
| 17 |      |            | 707                   | -     | 0.57 | 0.24 | -    | 0.17 | 0.19 | P      |
| 18 | 11   | 13-15 Sep  | 764                   | -     | -    | -    | -    | -    | -    |        |
| 19 |      |            | 794                   | -     | 0.07 | -    | -    | 0.08 | -    | N      |
| 20 |      |            | 787                   | -     | 0.19 | -    | -    | 0.13 | -    | N      |
| 21 |      |            | 764                   | -     | 0.17 | -    | -    | 0.07 | -    | N      |
| 22 |      |            | 780                   | -     | 0.15 | -    | -    | 0.15 | -    | N      |
| 23 |      |            | 741                   | -     | 0.03 | -    | -    | 0.01 | -    | N      |
| 24 |      |            | 731                   | -     | 0.01 | -    | -    | 0.02 | -    | N      |
| 25 | 12   | 29-31 Oct  | 319                   | -     | 0.15 | -    | -    | 0.05 | -    | P      |
| 26 |      |            | 439                   | 0.01  | 0.45 | -    | 0.07 | 0.15 | -    | P      |
| 27 |      |            | 581                   | 0.34  | 0.71 | -    | 0.04 | 0.27 | -    | N      |
| 28 | 13   | 2-4 Nov    | 296                   | -     | 0.75 | -    | -    | 0.22 | -    | N      |
| 29 | 14   | 10-12 Dec  | 317                   | -     | 0.61 | -    | -    | 0.10 | -    | N      |

Average VTEC (TECU) 0.32 0.28 0.29 0.17 0.15 0.16

Figure 6 reveals the scatter plot of ΔVTEC results obtained from Table I. The ΔVTEC distribution is mainly observed at ~0.2 TECU. The maximum ΔVTEC is 0.75 TECU and the minimum is 0.01 TECU. Other authors have found that the VTEC enhancement during intense lightning activity is between 1.2 and 1.4 TECU [6] in South Africa that has high number of the lightning activity. These results could possibly be due to low number of lightning detected and the distance between location of lightning and GPS station is more than 300 km. Hence, the dissipation of energy through lightning discharge caused a very low energy infiltration in the ionosphere.

Figure 7 also shows boxplot of VTEC on each GPS station which corresponds to the median VTEC of less than ~0.2 TECU after lightning strikes. The maximum shown by PALV before lightning...
strikes could indicate the ΔVTEC irregularities can reach up to 0.75 TECU which is significantly higher due to the distance of lightning strikes is nearer to PALV than OHI3 or ROTH.

![Graph](image)

**Figure 6.** ΔVTEC irregularities distribution against lightning number from 1 to 29. The dot and ‘x’ marks ΔVTEC before after lightning strikes respectively for OHI3, PALV and ROTH.

![Boxplot](image)

**Figure 7.** Boxplot of ΔVTEC irregularities before and after lightning strikes

3.2. **Lightning distance from GPS station**

Several authors [5, 6] have investigated the lightning activity and used 300 km as a distance limitation. In this case, using similar approach would only restrict the study to only one case which is insufficient for statistical analysis. Figure 8 reveals the majority location of lightning strike occurs over the ocean during autumn, spring and summer. The red dot shows the GPS station of OHI3, PALV and ROTH,
the ‘x’ marks the lightning location and the number represents lightning numbering sequence. The distance between PALV and dashed small circle is 500 km and big circle is 1000 km. The lightning location outside the dashed circle is less than 1500 km.

Figure 8. Lightning map in Antarctica Peninsula

The ionosphere over land when GPS measurement is taken could be disturbed due to the infiltration of lightning energy into the upper atmosphere during winter which increases the ionospheric irregularities occurrence [6]. Additionally, the absolute ΔVTEC decreases with distance which indicates that VTEC enhancement reduces the further away lightning occurrence is from GPS station. This is because gravity waves launched by lightning have very small vertical component and would need to propagate hundreds of kilometres horizontally to reach ionospheric altitude.

4. Conclusion
It can be concluded that the VTEC response conducted on quiet days of geomagnetic activity during lightning strikes can be observed approximately 0.2 TECU for overall stations. The distance between 300 and 1000 km of the location of a lightning strike from GPS station could also give an impact on the VTEC enhancement as the lightning detected within that range is found have higher VTEC variation. Nonetheless, causes of VTEC irregularities isolated from lightning activity needs much investigation as it could be due to solar activity, atmospheric gravity waves, plasma bubble, lower atmosphere condition and/or any of the combination of the above. A statistical analysis needs to be performed in future work based on long-term data to clarify whether during a low geomagnetic it will produce the lightning strike.

Acknowledgements
We would like to extend our gratitude to Ministry of Science, Technology and Innovation Malaysia (MOSTI) that funded the research through the Flagship Program under ZF-2014-016 grant. The authors would like to thank Scripps Orbit Permanent Array Centre (SOPAC) for providing important GPS data at O’Higgins, Palmer and Rothera station. We also appreciate the essential CODE data given
by Astronomisches Institut University of Bern (AIUB) Data Centre of University Switzerland and lightning data from World Wide Lightning Location Network (WWLLN). We also sincerely acknowledge the World Data Center-C2, Kyoto, Japan, for archiving geomagnetic data.

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