

# Response of lightning energy and total electron content with sprites over Antarctic Peninsula

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**Abstract.** This paper investigates the response of the lightning energy with the total electron content (TEC) derived from GPS over Antarctic Peninsula during St Patrick's geomagnetic storm. During this event, sprite as one of the mesospheric transient luminous events (TLEs) associated with positive cloud-to-ground (+CG) lightning discharges can be generated. In this work, GPS and lightning data for the period from 14 to 20 March 2015 is analyzed. Geomagnetic activity and electric field data are also processed to relate the geomagnetic storm and lightning. Results show that during St Patrick's geomagnetic storm, the lightning energy was produced up to ~257 kJ. The ionospheric TEC was obtained 60 TECU, 38 TECU and 78 TECU between 18:00 and 21:00 UT for OHI3, PALV and ROTH stations, respectively. The peak of lightning energy was observed 14 hours after peaked of TEC. Sprite possibly generated through the electrical coupling process between the top cloud, middle and upper atmosphere with the DC electric field found to be ~10 mV m<sup>-1</sup> which leading to the sprite generation after the return strokes on 18 March 2015.

## 1. Introduction

In the electromagnetic coupling, an electromagnetic energy source and how it was transmitted from one region to the other region must be fully understood. This transmission depends on the electrical behaviour of the medium which is regulated by the existence of charged particles and its dynamics through electrical conductivity. The lightning discharges are the major source of electromagnetic energy in the lower atmosphere which radiating electromagnetic waves in a frequency range. Normally, convective clouds accumulate a negative charge in the lower and a positive charge at the top regions. The electric breakdown happens when the electric field strength passes 400 kV m<sup>-1</sup>. At this time, it will occur as lightning. Lightning reacts as a source of electromagnetic radiation which stimulates the alternating current in the global circuit [1].

Some researchers indicate that the return current from the ground does not end in the clouds during lightning discharge [2]. It keeps moving upwards and ends in the lower ionosphere. This transient current is related with optical emissions such as sprites, elves, blue jets and blue starters in the space between the top of the cloud and the lower ionosphere [2]. Sprite is the members of a family of transient luminous events (TLEs) that illuminate the stratosphere and mesosphere above thunderstorms between 20 and 95 kilometres in altitude. Sprites are the results of the excitation and



ionization of air molecules due to collisions with electrons accelerated by quasi-electrostatic (QE) field in the upper atmosphere established by cloud to ground (CG) and its current probably going to persist. Sprite propagating streamer upward may appear up to 90 km, downward initiated at 70–85 km and ends at about 40–50 km altitude [3].

Sprites and other mesospheric TLEs related with CG lightning discharges has been studied by many numbers of researchers. Worldwide sprites and halos over the thunderstorms in the mesosphere are due to large CG flashes almost exclusively with positive polarity. Roughly 5 to 10% of worldwide lightning activity is referable to the positive (+CG) lightning, which transfers the positive charge to ground mentioned by [4]. Sprite drove by the sustained mesospheric quasi-static electric field generated by lightning. Referring to the Maxwell equations; the potential energy is relative to the charged moment change in the lightning discharge that generates the sprite caused of the linearity [5]. A parameter related with lightning intensity is the charge moment which the product of a charge took away from the thundercloud and the length of a lightning channel.

In this work, we studied the response of lightning discharges associated sprite during the St. Patrick day storm on 17 March 2015. St. Patrick day storm was the first storm of solar cycle 24 which reached a level of “Severe” on the NOAA geomagnetic storm scale [6]. Two different types of data have been analyzed to ascertain the influence of lightning on the ionosphere over the Antarctic Peninsula through the observation of total electron content (TEC). TEC is an indicator of ionospheric variability derived from GPS signals. While lightning data from worldwide lightning location network (WWLLN) and was used as a proxy to identify regions of intense thunderstorms since GPS signals cannot be directly used to track the actual occurrence of lightning events due to different in frequency domains.

## 2. Data and methods

### 2.1. Data

WWLLN data was used to study the variation of lightning energy during the geomagnetic storms which locates lightning using time of group arrival (TOGA) at VLF: 3-30 kHz from lightning stroke. WWLLN data was collected from 14 March to 20 March 2015 for this study. The WWLLN data files are in ASCII which including the date and time in UTC, Latitude and Longitude in Fractional Degrees and Energy in Joules of the lightning stroke detected, and residual fit error always  $\leq 30$  microseconds and are considered as a good data. Nsta is the number of WWLLN stations which observed the stroke in the range from 1000 to 8000 km distant. The WWLLN Network confirms that lightning has occurred when 5 or more stations have recorded to produce a good observation. RMS is the energy uncertainty in Joules. This network evenly capable of detecting CG and intra cloud (IC) flashes likewise detection efficiency (DE) [7]. In the area of Antarctic Peninsula, only one WWLLN sensor was installed in Rothera. The location of WWLLN sensors to the GPS stations is about 666.9 km from OHI3 to ROTH and 360.2 km from PALV to ROTH, respectively.

The geomagnetic index called planetary 3-hour-range index ( $K_p$ ) and disturbance storm time (Dst) index was used to indicate the level of the geomagnetic disturbance.  $K_p$  is an excellent indicator of disturbances in the Earth's magnetic field and Dst is a measure of geomagnetic activity used to assess the severity of magnetic storms. The  $K_p$  index is obtained from the Space Weather Prediction Center (SWPC) at <http://www.sec.noaa.gov> and Dst index from the Kyoto data service (<http://swdcwww.kugi.kyoto-u.ac.jp>). Magnetic field data represented by interplanetary magnetic field B in z-component (IMF  $B_z$ ) was obtained from NASA (<http://omniweb.gsfc.nasa.gov/>). GPS data used in this study were taken from Scripps Orbit Permanent Array Center (SOPAC). Data from three GPS stations of O'Higgins (OHI3: 63.32°S, 57.90°W), Palmer (PALV: 64.78°S, 64.05°W) and Rothera

(ROTH: 67.57°S, 68.13°W) was taken to observe the TEC fluctuation over the Antarctic Peninsula. The variation of TEC was discussed before and after the major geomagnetic storm on 17 March 2015.

## 2.2. Data processing

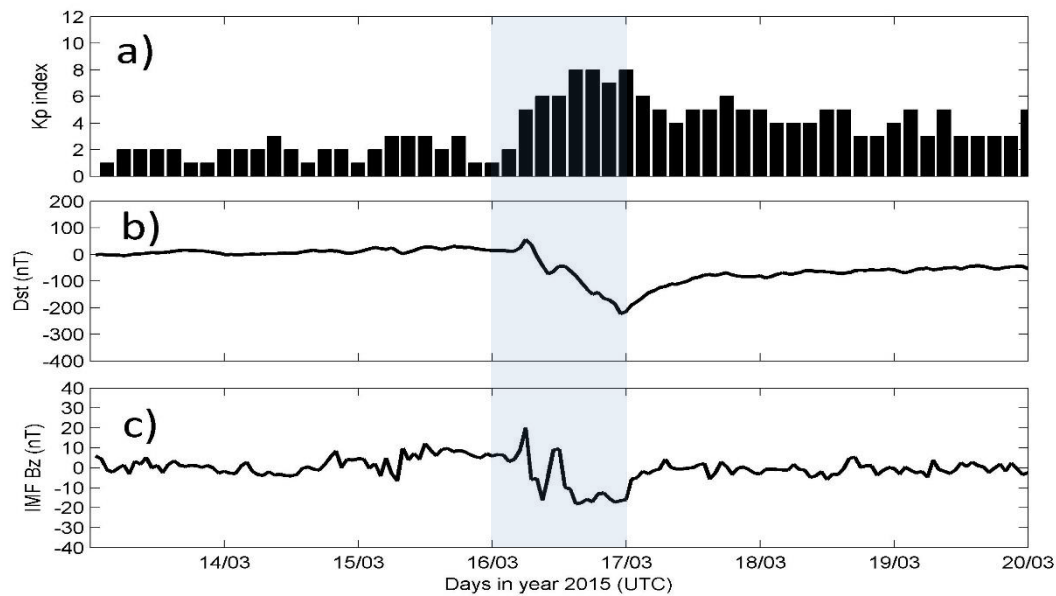
In this study, lightning energy and variation of GPS TEC were analyzed to investigate the existence of sprites during the geomagnetic storm event. In order to process the GPS data, code in MATLAB program was used to compute TEC. Prior the processing, it need to be cleaned first using Translate Edit Quality Check (TEQC) routine prepared by UNAVCO (<http://www.unavco.org>). The data average were performed in 30 seconds interval in order to shorten the processing time but was later changed into three hours interval. The GPS TEC algorithm calculates TEC with an elevation angle  $< 30^\circ$  and applies satellite and receiver bias corrections. The software takes RINEX observation files utilize the Hatanaka (d-file compression) with at least C1 (course/acquisition code transmitted on the F1), L1, L2, P2 observables as inputs. The differential code bias (DCB), satellite (P1-C1) biases and the (P1-P2) DCB biases files provided by the AIUB Data Centre of University Switzerland are used to correct the instrumental bias. The vertical TEC (VTEC) is calculated based on the MATLAB code developed by Suparta et al. [8].

## 3. Result and discussion

### 3.1. The variation of lightning energy and TEC during the geomagnetic storm

The St. Patrick's Day storm of the low solar cycle 24 was occurred due to a magnetic filament erupted in concert with a slow C9-class solar flare from sunspot AR2297 [9]. During this event, the speed of solar wind had increment from 400 to 650  $\text{kms}^{-1}$  on 17 March 2015, and follow by the next days, the speed of solar wind was fluctuated within 500–650  $\text{kms}^{-1}$ . This storm is categorized as severe geomagnetic storm arises from two consecutive moderate storms forced by two consecutive southward IMF structures [10].

Fig. 1 shows the indication of severe geomagnetic storm represented by variations of Kp, Dst index and interplanetary magnetic field in z-component (IMF  $B_z$ ) between 14 March and 20 March 2015 including the 3 days before and after the geomagnetic storm event. The gray background shows the starting and ending of the geomagnetic storms. During this event, Kp reached maximum value of 8 and it was started with a positive Dst around 06:00 UT and a minimum Dst equal to -223 nT at 23:00 UT. After the shock arrival, the northward IMF  $B_z$  component was strongly reached the value of  $\sim +20$  nT at 05:00 UT due to the coronal mass ejection (CME) hits the earth on 17 March before turning southward to the first minimum peak value of about  $\sim -16$  nT at 08:00 UT. Then it aggressively turned northwards and varied drastically between south and north around 11:00 UT. After 14:00 UT, the IMF  $B_z$  turned southward again with the second lowest value of  $\sim -18$  nT and move northward before it keep fluctuated violently between north and south directions at 05:00 UT on the next day until the end of 21 March.

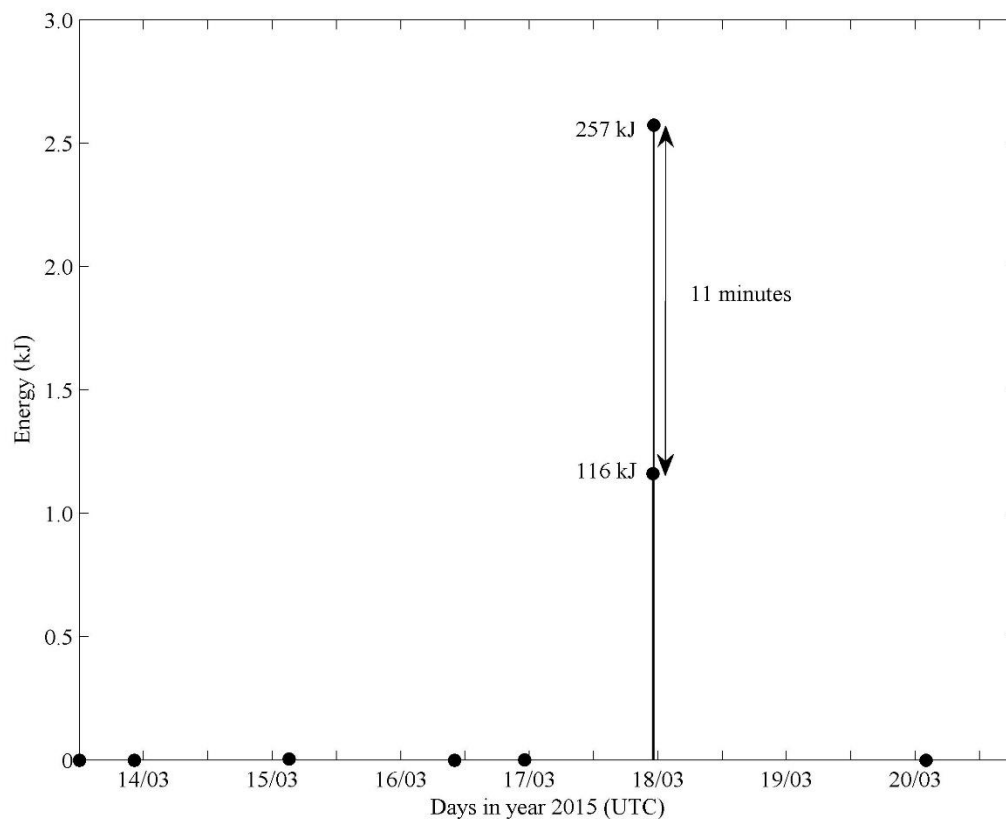


**Figure 1.** The variation of (a) Kp from NOAA/SEC, (b) Dst from World Data Center-C2 for geomagnetism, Kyoto and (c) IMF  $B_z$  from OMNIWeb between 14 and 20 March 2015

To relate the occurrence of geomagnetic storm with lightning, we analyzed the WWLLN data from 14 March to 20 March 2015 and found a total of 7 times of lightning occur in this study. The occurrences of lightning over Antarctic Peninsula are tabulated in Table 1. As show in the table, two days having twice lightning was detected occur on 14 & 18 March 2015. Lightning energy was in the range from  $\sim 13$  J up to  $\sim 257$  kJ throughout the observation. The highest energy recorded is  $\sim 257$  kJ on 18 March 2015 at 11:19 UT. There was zero energy produced for a few days during the lightning activity. The gap time between first and second occurrences of lightning is 11 minutes on 18 March 2015 as shown in Fig. 2.

**Table 1.** The occurrences of lightning in March 2015

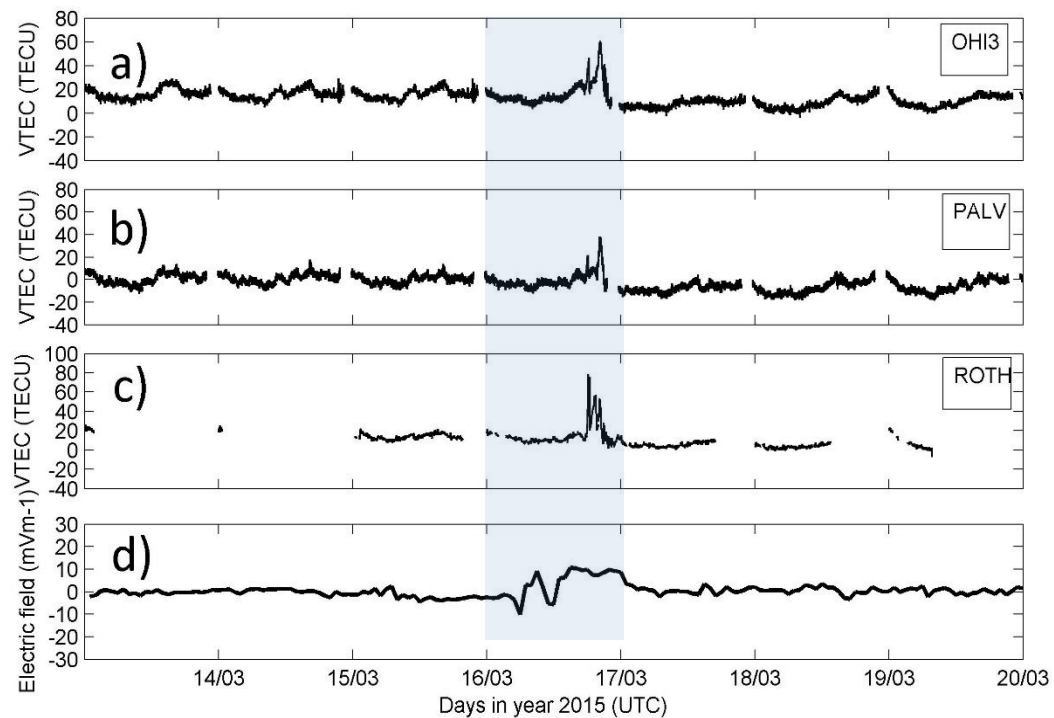
Date	Time (UTC)	Latitude (Deg S)	Longitude (Deg W)	Residual Error	Nsta	Energy (J)
2015/03/14	00:44:13.6598	-65.5968	-62.422	27.9	5	0
2015/03/14	10:28:06.9148	-74.3485	-53.1605	10.1	5	0
2015/03/15	15:16:34.3455	-64.7031	-70.6191	25.2	6	398.40
2015/03/17	11:12:22.2773	-63.5902	-70.755	24.6	5	13.44
2015/03/18	11:08:01.8062	-59.025	-72.6091	25.9	13	116074.01
2015/03/18	11:19:55.4806	-59.0645	-72.5936	17.3	7	257396.03
2015/03/20	14:01:21.1022	-61.1733	-79.3165	20.7	5	0



**Figure 2.** Variation of lightning energy based on WWLLN data over Antarctic Peninsula

To look the response of lower to upper atmosphere, the variations of vertical TEC derived from GPS data and electric field for selected station in Antarctic Peninsula between 14 and 20 March 2015 are demonstrated as in Fig. 3. The gray background refers to the response between TEC fluctuation and electric field during the severe geomagnetic storm. The TEC demonstrate almost similar patterns and the intensity of the fluctuations increase dramatically for three stations during the storm. It was noticed that highest TEC value was obtained for three stations is 60 TECU, 38 TECU and 78 TECU between 18:00 and 21:00 UT for OHI3, PALV, and ROTH, respectively. The magnetic storm event demonstrates the rate of TEC was maximal on most disturbed days of 17 March 2015. The electric field was observed  $\sim 10 \text{ mVm}^{-1}$  during the lightning discharge, which is similar to the TEC response. The typically enhancements of TEC occur some distance from the region where the lightning activity is the largest.

As shown in Fig. 3, the night on 17 March have significant relation between lightning and geomagnetic storm that corresponds well in time and space to localized regions of enhanced TEC fluctuation at OHI3, PALV and ROTH. The structure of the phase fluctuations is increased caused by the presence of irregularities in the ionosphere including the coupling process of electric discharge between upper-lower altitudes. The most important that how possible sprites are generated from the response between TEC and lightning, which would be discussed in the next section.



**Figure 3.** TEC and electric field variations for selected three stations in Antarctic Peninsula

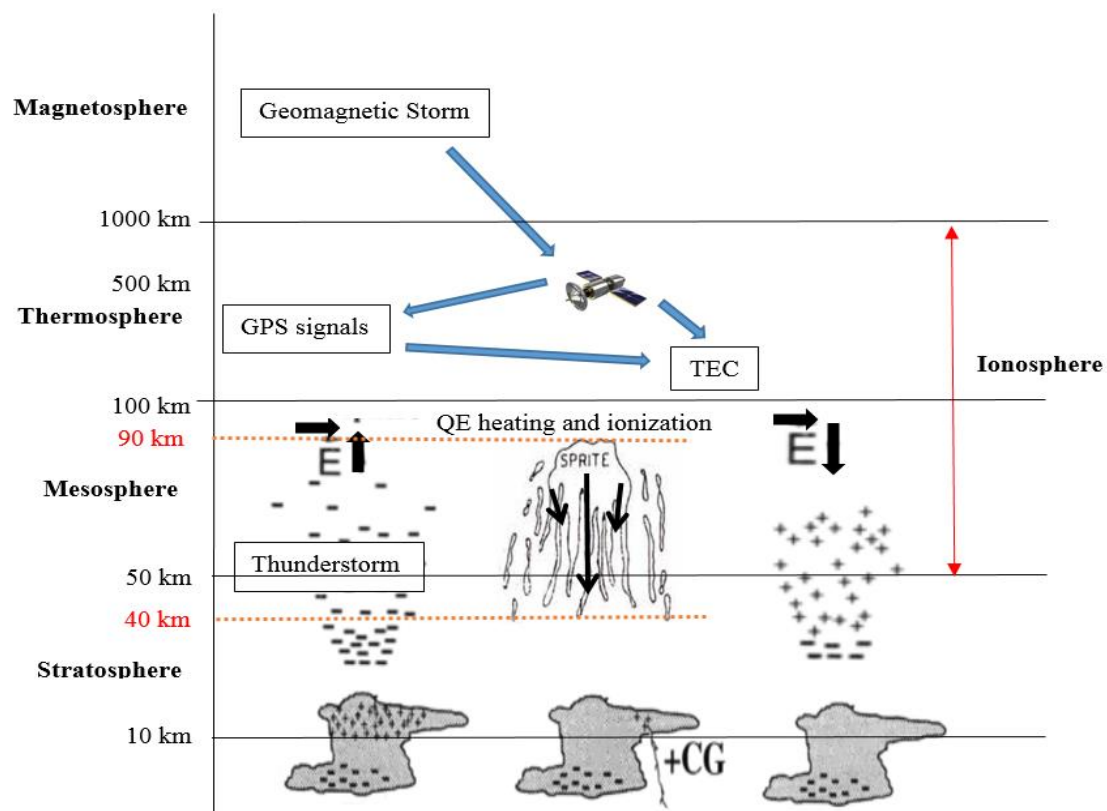
### 3.2. Possibility sprites generated by the geomagnetic storm

Referring to Fig. 2, high-energy particles penetrating between upper-lower altitudes and increases the electrical conductivity of the upper-lower atmosphere during the lightning discharges. We suggest that the maximum energy produced is proportional to the charge moment changes (CMC), which possibly generate sprites. As reported by Takahashi et al. [11], absolute optical energies emitted from sprites were estimated for 14 streamer-type sprites for the first time and the averages of the time integrated optical energies are 176 kJ and 119 kJ for the N2 1PG and N2 2PG bands, respectively. On the other hand, sprites may occur during this time with the energy obtained reached up to 257 kJ which is much highest than the streamer sprites obtained by [11]. The important of sprite mechanism during geomagnetic storms will improve our understanding of all processes in the upper-lower atmosphere that lightning will also take part in this process.

From the perspective of the upper atmosphere, the good response between the TEC fluctuation and the electric field probably generates sprites after the events on 18 March. This assumption following Fullekrug and Rycroft which calculated the DC electric field from single sprite with a CMC of 500 C.km and transferring a charge of 20 C over a vertical distance of 25 km to be  $4.4 \text{ mVm}^{-1}$  [12]. This support that the sprites may be produced since the electric field in this event was observed to be  $\sim 10 \text{ mVm}^{-1}$  and phase of TEC was maximum on 17 March 2015. The electric field is necessary for the production of sprites which is sensitive to the time scale of the thundercloud field due to the significant reduction of electrons. On the other hand, the schematic diagram of electrical processes between the cloud top, middle, and upper atmosphere is illustrated in Fig. 4. The figure shows the



significant relation with sprites during lightning discharge and geomagnetic storm event. In the upper atmosphere, the GPS signals through TEC fluctuation will perturb the electric environment and in different ways coupled to the atmosphere. In addition, the upper atmosphere producing the ionosphere with high electrical conductivity and energetic charged particles from the Sun through the ionization process from solar X-ray and UV radiation. Furthermore, thunderstorm also plays a crucial role for transporting energy and constituting electrical coupling between atmosphere and ionosphere through the global electric circuit (GEC) [13]. Redistribution of charges in the thunderstorm resulted upward propagating QE field which is initiated from the upper charger-layer of a thunderstorm. The current in a lightning stroke can radiate the electromagnetic field of  $\sim 20$  GW peak power [14] which affect the ionospheric disturbances due to the heating and acceleration of electrons, production of ionization and optical emissions.



**Figure 4.** Schematic diagram in emergence of sprites between lower and upper atmosphere

Below the upper ionosphere layer (see Fig. 4), the interactions between electric fields and particles cause electrical breakdown at 80 km and 70 km altitude with 35 kA and 350 C km and 45 kA and 360 C km respectively [15] which leading in the production of sprites. Sprite is a type of optical emission occurs in the mesosphere layer. Their dynamics are governed by streamer discharges. Sprites are typically initiated at 70–85 km altitudes with downward propagating streamers which come to the end at about 40–50 km altitudes [4]. Upward propagating streamers may appear later and can reach about 90 km altitude as shown in Fig. 4. In other part, sprites are related with stratiform regions of mesoscale convective systems (MCS) adjoining to the stronger convective cores. They tend to occur during the mature to decomposing stages of thunderstorm development. Triggered by the sudden establishment

of a strong QE field above thunderclouds due to intense +CGs lightning strokes which lower positive charges from a cloud to the ground.

#### 4. Conclusion

Throughout the analysis, the response of lightning discharges and TEC associated sprite during the St. Patrick day storm on 17 March 2015 was overlooked. We observed the good response with almost similar patterns between TEC fluctuation and interplanetary electric field which the TEC value was highest for all the selected stations of OHI3, PALV, and ROTH in Antarctic Peninsula. TEC and geomagnetic activity are strongly correlated with the production of sprites. We also observed that high lightning energy was produced  $\sim 257$  kJ with the DC electric field to be  $\sim 10$  mVm<sup>-1</sup>. With these values, ionospheric storm leading to the sprite generation after the return strokes on 18 March 2015. However, studies of sprites generated during high lightning energy are still in their infancy. Since sprites could change electrical properties of the atmosphere and influence the processes related to weather and climate, intense research activity in this area is required to more accurately predict the coupling between upper and the lower of the atmosphere.

#### Acknowledgments

This research is funded by the Ministry of Science, Technology and Innovation Malaysia (MOSTI) through the Flagship Program under ZF-2014-016 grant. The second author is PhD candidate supported by Universiti Teknikal Malaysia Melaka and the Ministry of Higher Education. The authors would like to thank the Space Weather Prediction Center (SWPC) for daily of Kp data; the World Data Center-C2, Kyoto, Japan, for hourly final of Dst data; NASA for providing the magnetic field and GPS data for Rothera station. We would also like to thank the Scripps Orbit Permanent Array Center (SOPAC) for archiving GPS data at O'Higgins and Palmer stations; the Astronomisches Institut University of Bern (AIUB) Data Centre of University Switzerland for CODE data.

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