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Impacts of ionospheric electric fields on the GPS tropospheric delays during geomagnetic storms in Antarctica

W Suparta

Space Science Centre (ANGKASA), Institute of Climate Change, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor Darul Ehsan, Malaysia.

*Email: wayan@ukm.edu.my

Abstract. This paper aimed to overview the interaction of the thunderstorm with the ionospheric electric fields during major geomagnetic storms in Antarctica through the GPS tropospheric delays. For the purpose of study, geomagnetic activity and electric fields data for the period from 13 to 21 March 2015 representing the St. Patrick's Day storm is analyzed. To strengthen the analysis, data for the period of 27 October to 1st November 2003 representing for the Halloween storm is also compared. Our analysis showed that both geomagnetic storms were severe ($Ap \geq 100$ nT), where the intensity of Halloween storm is double compared to St. Patrick's Day storm. For the ionospheric electric field, the peaks were dropped to -1.63 mV/m and -2.564 mV/m for St. Patrick and Halloween storms, respectively. At this time, the interplanetary magnetic field Bz component was significantly dropped to -17.31 nT with $Ap >$ 150 nT (17 March 2015 at 19:20 UT) and -26.51 nT with $Ap = 300$ nT (29 October 2003 at 19:40 UT). For both geomagnetic storms, the electric field was correlated well with the ionospheric activity where tropospheric delays show a different characteristic.

Keywords: Ionospheric electric fields, Tropospheric delays, Geomagnetic storms, Antarctica

1. Introduction

Characterization the cause-effect mechanisms driving the formation and evolution of middle and the coupling between the upper and the lower levels of the atmosphere is challenging task. The physical mechanism on how the ionospheric activities interact directly or indirectly to troposphere is still not clear. It is well known theoretically that the high latitude ionosphere-troposphere contains the footprints of processes that have their origin in the planetary space. Many different techniques are now available for probing the ionosphere-troposphere, from radar measurements to the analysis of radio propagation noise. Among them the use of Global Navigation Satellite System (GNSS) measurements allows to describe the 3D plus time evolution of the ionospheric plasma and water vapor over restricted regions [1,2]. Mathematical techniques combined with experimental observations provide the ability to study the ionosphere from high in the F-region to the lower atmosphere. Thus the coupling processes between the magnetosphere and the neutral atmosphere can be approximated. Therefore, the possible linkages between solar phenomena, solar-induced interplanetary disturbances, the magnetospheric state and the chemistry of the middle and lower terrestrial atmosphere have been explored over the years with intent to separate natural variations from the anthropogenic forcing [3]. However, a solar influence on water vapor over Antarctica during the intense magnetospheric disturbance [2] found that the coupling between the upper and lower levels of the atmosphere is less sensitive enough to sense the coupling process. In fact, there are many phenomena occurs from the ionosphere to the lower atmosphere such as precipitation events, including water vapor distribution, formation of clouds and aerosols and the chemistry of the lower atmosphere [3], formation of polar stratospheric clouds, lightning and atmospheric electricity [4], and a long-lived trace gas in the mesosphere provides a possibility atmospheric motion and drags as well as hazard material detection during active weather. In this sense, global electric circuit is identified as a possible physical mechanism for the coupling process.

Lightning and thunderstorm activity, as related to global electric circuit plays an important role in the coupling between Earth's lower atmosphere and the ionosphere [5]. Thunderstorm activity has an effect on the E-sporadic layer and the global electric circuits are shown to be organized by lightning phenomena over the geomagnetic equator. Global thunderstorm charge ionosphere and current returns

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to ground through fair weather conduction. The effects thunderstorms on atmospheric circulation and their role in the lower atmosphere are very important to forecast weather and ultimately find out how the climate is changing. Measurement of lightning is usually conducted by Very Low Frequency (VLF) band (2~200 KHz) and thus lightning will release a large amount of energy into that propagates for long distances. However, the exact role of lightning and other variables in the frequency band still not well understood. In this study, an electric field which may drive the ionospheric phenomena is employed as a media or wire to transfer solar energy from space to Earth's surface for the coupling process. To realize the investigation, the geomagnetic activity during St. Patrick's Day storm (17 March 2015) and the Halloween storm (29 October 2003) is analyzed.
Therefore, the study of ionospheric effects of geomagnetic storms and their connection to the lower atmosphere remains one of the most important scientific tasks. Measurements of an electric field for determining atmospheric parameters will act as a better basis for understanding the electrical coupling between the ionosphere and the atmosphere. The most importance is how electric field from space interacts through ionosphere and affect thunderstorms in the upper troposphere.

2. Data and Methods

To study the response of electric field connecting by space weather, data for the period of 15~20 March 2015 during St. Patrick's geomagnetic storm is compared with Halloween storm that has occurred between 27 October and 1 November 2003. The geomagnetic index called planetary index (*Ap*) and interplanetary magnetic field in the southward (z) component (IMF Bz) in Geocentric Solar Magnetospheric (GSM) rather than Geocentric Solar Earth (GSE) were used to indicate the level of the geomagnetic disturbance. Data for *Ap* index and IMF Bz are obtained from the OmniWeb website (http://omniweb.gsfc.nasa.gov) of the NASA Goddard Space Flight Center (GSFC). Both parameters are in units of Nanotesla (nT) and the data was averaged from 1-min to 1-hour.

To analyze the response of the ionospheric phenomena on the Global Positioning System (GPS) propagation at the lower atmosphere, the zenith path delay (ZPD) data at Bernardo O'Higgins (OHI3: 50°S, 74°W and ellipsoidal height 32.15 m) and Palmer station (PALM: 64.77°S, 64.05°W and ellipsoidal height 31.0427 m) was used. The observations are focused in the Antarctic Peninsula where the region is expected to have experienced global warming. The ZPD for St. Patrick's storm was taken at a five-minute interval from the Crustal Dynamics Data Information System (CDDIS) NASA (ftp://cddis.gsfc.nasa.gov/pub/gps/products/troposphere/zpd/). However, for the Halloween storm, the ZPD data was obtained with an interval of 2 hours. Since no ZPD data for PALM during the Halloween storm, the ZPD is estimated using adaptive neural-fuzzy interference system (ANFIS), which using surface pressure, temperature, and relative humidity as inputs. The meteorology data is obtained at the respective station that was managed by British Antarctic Survey (BAS) website (https://legacy.bas.ac.uk/met/metlog/). The estimation approach is called the ANFIS ZTD. More in-depth about the ANFIS ZTD concept and the implementation can be found in Suparta and Alhasa [6].

Then, to link the ionospheric phenomena to the case of lower atmosphere such as thunderstorm, interplanetary electric field (IEF) obtained from OmniWeb of the NASA GSFC is employed. Since the IEF data at certain days was missing (or no data recorded), the equatorial ionospheric eastward electric field (EEF) from Cooperative Institute for Research in Environmental Sciences (CIRES) of University of Colorado (https://geomag.colorado.edu/) is employed. The real-time variation of EEF data was calculated with transfer function model from solar wind data and a climatological model to account for the quiet day variations of EEF [7]. In the equatorial ionosphere of the Earth, the wind-driven currents coupled with the Earth's primarily horizontal magnetic field produce the EEF. On the other hand, EEF is a result of solar wind electric fields penetrating from high latitudes to the equator. Based on this concept, EEF is predicted on a real-time basis using the solar wind data from the Advanced Composition Explorer (ACE) satellite. Detail of the model can be referred to Manoj et al. [8].

3. Results and Discussion

Figure 1 shows the indication of severe geomagnetic storms as represented by *Ap* index and IMF Bz in hourly basis. As shown in Figure 1(a), the severe geomagnetic storm was occurred with $Ap > 100$ nT on 17 March 2015 which so-called the St. Patrick's day storm. The 2015 St. Patrick's Day storm was the first storm of solar cycle 24 with the G4 level based on the NOAA scale. The sudden

storm commencement (SSC) was registered at ~04:45 UT on 17 March 2015 and then there was a quick drop of the IMF Bz to the value of −18.1 nT, observed at ~16:00 UT. This commencement caused by a coronal mass ejection (CME) at 02:00-02:30 UT on 15 March 2015. This geomagnetic storm was first reported by Kamide and Kusano [9]. As seen in the figure, prior to severe level, the event was initiated with a minor storm in the early morning of 17 March 2015 and then the IMF Bz component sharply turned southward and reached the minimum of -16.1 nT at 08:20 UT with $Ap < 75$ nT, but became positive (northward) at 11:50 UT with IMF Bz ~10 nT. After that the IMF Bz is largely southward to -18.10 nT for ~30 min of time at ~14:32 UT when the $Ap > 150$ nT (severe level). About 3 hours later, it has northward direction to -11 nT when the $Ap = 150$ nT and three hours later reached IMF Bz of -17.3 nT at 19:20 UT when the *Ap* reached more than 150 nT. Finally, it became positive (northward) at 24:00 UT on 17 March 2015 and subsided in the noon on 18 March 2015 (with the minor storm due to the effect of CME on 15 March 2015) and the IMF Bz still maintained in the northward direction. During the severe geomagnetic storm (~6 hours), the observed periods with largely negative IMF Bz led to the interconnection between the IMF and the Earth's magnetic field lines. This makes the storm of the 2015 St. Patrick's Day storm of 17–18 March 2015 is the first largest in the solar cycle 24 [10].

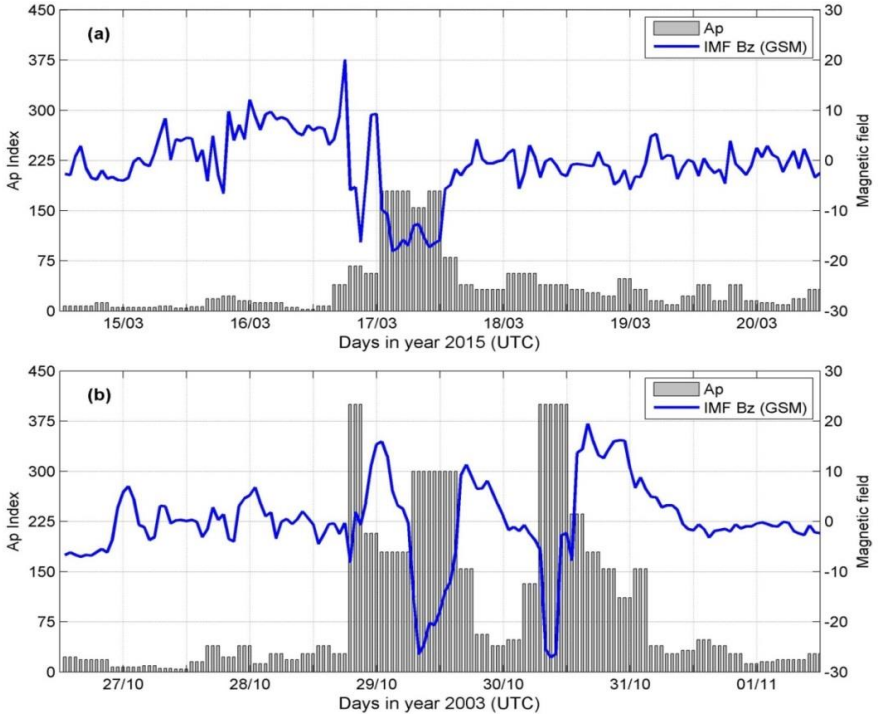

Figure 1. Variation of geomagnetic activity as indicated by *Ap* index and IMF Bz (GSM) for (a) St. Patrick's storm and (b) Halloween storm. The date in the middle of graph shows the noon UT time.

Figure 1(b) shows the super geomagnetic storm which was well known as the Halloween storm for comparison with the St. Patrick's Day storm. These storms reached $Ap > 375$ on 29 and 30 October 2003. The most significant impact was to have four negative peaks with two the largest of IMF Bz with -26.5 nT ($Ap = 300$ nT) at 19:40 UT and -27.1 nT at 20:36 UT, respectively. However, prior to the first largest negative peak, it has IMF Bz of -8.2 nT where $Ap > 375$ at 06:27 UT and the last one after 2.5 hours is -8 nT in the morning of 31 October 2003. The Halloween storm shows a double strength in the intensity of geomagnetic activity as compared with the St. Patrick's storm. However, the pattern of both storms is almost similar with a W shape. Details character of this storm has been published in many scientific journals by several authors [e.g., 2, 11, 12]. The difference between the two storms are the occurrence of flare activity, where Halloween storm recorded X17.2/4B and St. Patrick's storm was recorded more only in C and M classes (or no major solar flares). Although the G4 storm possibly will not affecting the astronauts, it could affect the communication system (GNSS

and radio signals on Earth). More than that how it propagates and finally, how it affects the weather on the ground (Earth surface) or lower atmosphere phenomena like a thunderstorm are still a challenging task to be answered.

The idea behind the use of ZPD to connect it to the upper atmosphere during geomagnetic storms is a possible cause of GPS disturbances at high latitudes. Patches with containing small-scale plasma structures is one of the phenomena which related to the distribution of scintillations at high latitudes and clearly disturbed the GPS signals [e.g., 13,14]. Jacobsen and Andalsvik [15] have studied the impact of the disturbances on the network RTK and Precise Point Positioning (PPP) techniques and found that the positioning errors is increased rapidly for both techniques. In other word, with the same GPS signals, ionospheric TEC is strongly influenced by geomagnetic storms. Figure 2 shows the variation of zenith tropospheric delay (ZTD) or zenith path delay (ZPD) from CDDIS NASA derived from GPS measurements over the Antarctic Peninsula during (a) St. Patrick's storm and (b) Halloween storm, respectively. As shown in Fig. 2a, the GPS signals more experienced with an irregular variation on 16 March 2015 after the CME was subsided. It takes approximately 8 hours after CME subsided and reach the lower atmosphere with ZPD is 2.30 m (PALM) and 2.34 m (OHI3) where PALM leads ~3 hours compared to OHI3. Both ZPD shows a similar variation and the ZPD peak different a few hours which is expected due to the geographical variations between the stations. Looking at the St. Patrick's storm on 17 March 2015, the ZPD was decreased to ~2.25 m which is 0.74% lower compared to their average value. The ZPD will increase again ~1.2% at midnight of 18 March 2015. Comparing to Fig. 1a, during a major storm occurs (St. Patrick's Day), it can be said there is no direct response to the lower atmosphere. This indicates that the effects of the St. Patrick's storm for the selected GPS station in Antarctic Peninsula are somewhat less pronounced. Looking at the time difference in upper atmosphere and on the ground (travel ~8-10 hours), the positive response of ZPD is after the CME shocked on 15 March 2015. The response by increasing peak of ZPD is on 16 March 2015 at ~06:00 - 14:00 UT with an increase of 5.7% compared to their mean average. However, the response of ZPD with duration time at post the CME event and to make a firm suggestion regarding this needs further investigation.

When looked at the Halloween storm in Fig. 2b and compared with Fig. 1b, it can be seen that two stations (OHI3 and MARA) shown a positive response of Halloween storm to lower atmosphere. Noted in Fig. 2 that since meteorological data is only available daily at PALM and two days were no ZPD data at OHI3, then ZPD estimated using ANFIS ZTD for Rothera (ROTH: 67°33'57.1"S, 68°07'43.5"W) and Base Marambio (MARA: 64°14'41"S, 56°39'25"W) is plotted for the comparison. Selection of these stations is only based on the data available for both storms and in the scope of Antarctic Peninsula. From Fig. 2b, PALM and ROTH showed a drop peak on 29 October 2003 as compared to other two stations. ROTH station is located at Rothera point, Adelaide Island with the crushed rock surface. The geographical distance between ROTH and MARA is about 640 km where ROTH is on the west side of OHI3. The high response of lower atmosphere during this Halloween storm is possibly due to the enormous of solar flares compared to St. Patrick's storm. The solar flare was correlated well with the occurrence of the ionospheric storm and the GPS signals were strongly delayed through the irregular variation of total electron content (TEC) in the upper atmosphere [10]. By comparing the ZPD average between both geomagnetic storms, the ZPD during St. Patrick's Day is 2.6% higher compared to Halloween storm. However, the high of ZPD observed possibly due to a different in the meteorological season is still needs to be investigated further. In addition, whether solar flares have a connection to the lower atmosphere is still a big challenge to prove. The ZPD response from two effects of geomagnetic storms disturbances on the GPS receiver on the ground demonstrated very dynamically. Their impact on tropospheric delays changing very fast and seems to be random. Propagation signals from the upper atmosphere seems never reach the troposphere, it has been diminished or disappeared due to the attenuation and a possible occurrence of convection and absorption of waves. On the other hand, the shielding of the earthward region is very strong to break by the electric field current from the magnetosphere. This is in contrast with the upper atmosphere that patches associated with scintillation can be clearly observed at high latitudes due to precipitation of energetic particles.

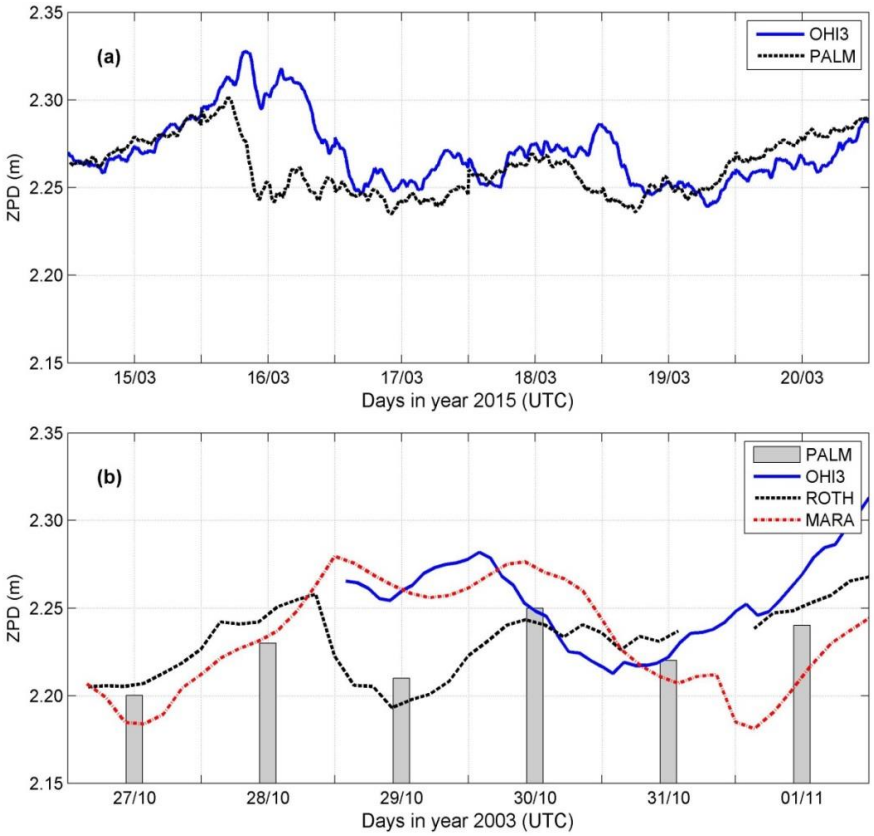

Figure 2. Variation of zenith tropospheric delay from GPS signals during (a) St. Patrick's storm and (b) Halloween storm, respectively

Another way to study the connection between the upper atmosphere and the lower levels of the atmosphere is analyzing the penetration of electric field as presented in Fig. 3. The magnitude of penetration electric field drive by the solar wind/IMF and supported by the strength of the magnetospheric convection will possibly bring the electric field current to the Earth's surface. As introduced in Section 2, EEF is predicted on a real-time basis using the solar wind data from ACE satellite. As shown in Fig. 3a, Ey observed from NASA representing the east-west component of the electric field was plotted due to its induced on the ground by geomagnetic activity. The use of Ey assuming that the solar wind is due to the ExB drift of the interplanetary magnetic and electric fields, IEF Ey is calculated based on the Ey = Vx × Bz, where Ey be the dawn-dusk component of the IMF, Vx be the solar wind velocity, and Bz be the vertical component of the interplanetary magnetic field. The vectors are relative to the geocentric solar magnetospheric coordinate system [8]. On the other hand, the x-axis is along the Sun-Earth line with the origin of the Earth, and is negative toward the Earth. The y-axis is the cross product of the Earth's dipole axis and is positive toward dusk. The z-axis is perpendicular to the xy plane and is positive to the Earth's magnetic north. Figure 3a shows the IEF variation during quiet day times from CIRES. It shows two peaks every day at around 14:00 and 22:00 UT which possibly due to the action of the atmospheric dynamo. Penetration of electric field is conducted by solar wind in the inner edge of the ring current in the shield region of equatorward. This electric field penetrating the ionospheric region with produces a net dusk-to-dawn electric field during geomagnetic storms. This can be depicted from the figure that the strongest disturbance for the quiet + penetration of EEF variation was a quick drop to a -1.46 mV/m at ~04:50 UT. This peaked drop was confirmed by IEF to a -1.0 mV/m (red color) with led about one-hour. On the other hand, the irregular variation of both EEF and IEF confirmed that it was strongly influenced by the St. Patrick's Day storm. This means that the IEF was successfully penetrated to the middle- and low-latitude ionosphere.

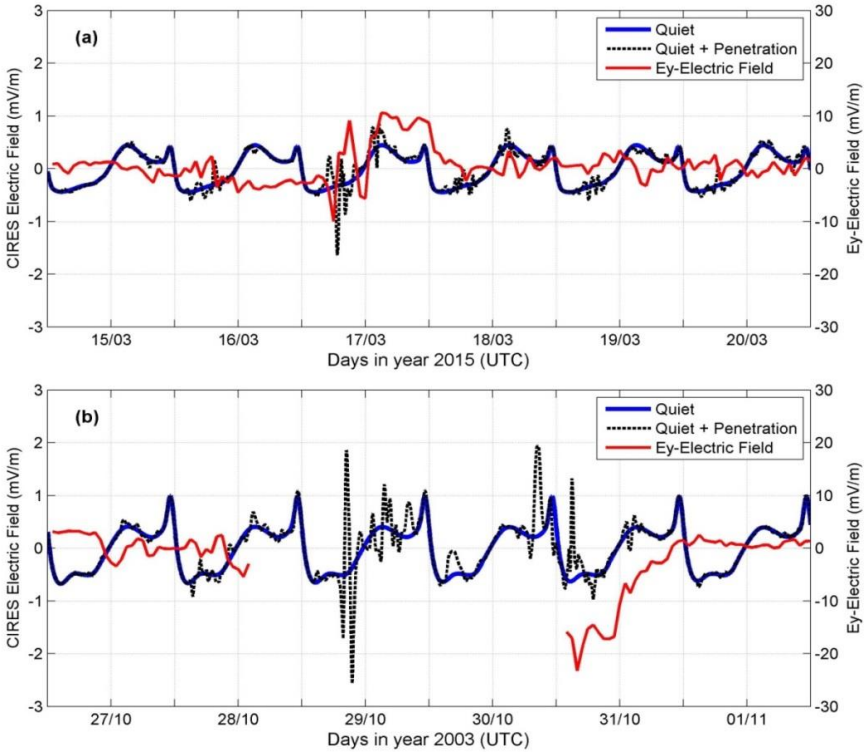

Figure 3. Variation of Equatorial Electric Field (EEF) to indicate ionospheric electric field disturbance for (a) St. Patrick's storm and (b) Halloween storm, respectively

For Fig. 3b, the CIRES data (EEF) initially first drop to a -1.7 mV/m at 18:00 UT on 29 October 2003 and two hours later become a positive at 20:00 UT to a 1.8 mV/m. The significant drop of EEF was observed at 22:00 UT with a -2.6 mV/m and fluctuated between -0.25 and 1.4 mV/m. The high positive of EEF was observed at 20:00 UT on 30 October 2003 with a value of 1.9 mV/m and reduced to 1.4 mV/m at 05:00 UT on 31 October 2003. Unfortunately, during the super intense of a geomagnetic storm, it was no observation data for the Ey-electric field from late afternoon 28 until 30 October 2003. The negative peak of Ey has recorded ~-24 mV/m at 04:00 UT on 31 October 2003. Thus the high fluctuation during 29 to 30 October 2003 indicated that the geomagnetic activity was strongly influenced by space weather as well as the satellite facilities. No data during this period indicates that there has been a power outage (blackout) in which super geomagnetic storms causes damage to electric transmission lines.

4. Proposed a connection between the upper and the lower level of the atmosphere

Based on the response of GPS tropospheric delays on the geomagnetic storms, the different in intensity of the geomagnetic storm will affirm to have a different characteristic of ZPD. Looking at the onset of geomagnetic storms, the Halloween storm is more pronounced as compared to the St. Patrick's storm. The delay of GPS signals represented by ZPD is increased during the major storms. In contrast, the ZPD during St. Patrick's Day has been reduced, or the energy from space can be said to have been lost before reaching the neutral atmosphere. The interaction of upper-lower atmosphere from space perspective can be illustrated in Fig. 4. In general, solar activity has clearly direct influence to the upper atmosphere, so-called the space weather. ZPD derived from GPS signals from the neutral atmosphere is very important for weather forecasts, numerical weather prediction as well as climate when the ZPD value is transformed into the precipitable water vapor (PWV). PWV is an indicator of climate change which can be useful for synoptic use, prediction of thunderstorms, etc.

If the connection between the upper-lower atmospheres happening, some physical mechanisms of how solar activity influences terrestrial weather/climate changes can be explained. For example in Fig. 4a, the occurrence of thunderstorms will generate lightning. A lightning discharge will create large earth currents in the atmosphere and this initial charge separation will create an electric

field through the global electric circuit (GEC). Thunderstorm is the major source of DC electric field. Rycroft [16] reviewed that thunderstorm can connecting to the magnetosphere through electromagnetic radiations generated from lightning discharges. These effects look like from below that the ionospheric equipotential surface above the thundercloud is lowered when the energetic electrons is precipitated. Now, this work is to propose how the space weather has a direct or indirect connection to earth's climate and climatic changes with lightning activity as illustrated in Fig. 4b.

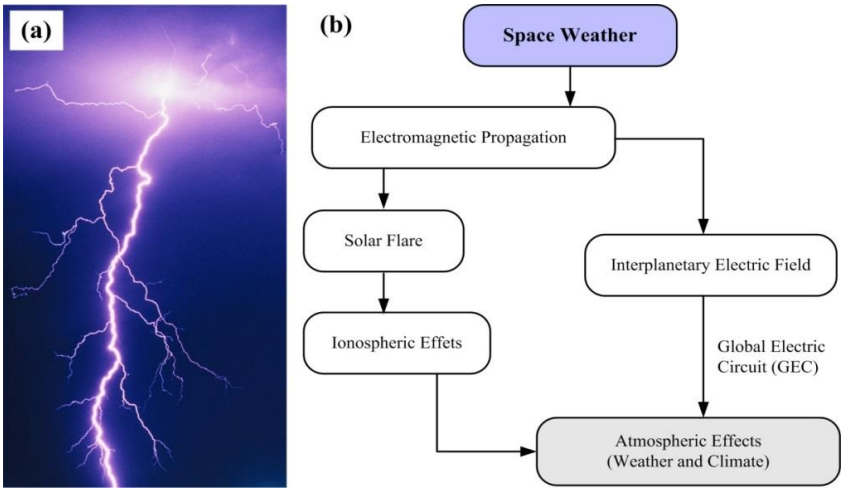

Figure 4. (a) The occurrence of thunderstorm with generates an electric field and (b) proposed a simple mechanism between the upper and the lower levels of the atmosphere

As shown in the Fig. 4b, the space weather clearly affecting the upper atmosphere by the disturbance of radio signals. The propagation delays of this signals can be indicated by TEC fluctuation and the strong effects of space environment is also characterized by how big the occurrence of solar flare. The direct effect of ionosphere to the lower atmosphere in the current research during short-term study is still difficult to prove. The effect maybe indirectly to GPS water vapor variability. The ionosphere is most contained of electron content, while the Earth's surface (ground) can be assumed as chassis or negative charge. In DC role, the current should be flow from positive to negative charges (or, ground to negative charge). This connection will be from below and form a GEC. Another way from right side of Fig. 4, the interaction from space to the ground can be thought thundercloud that can also form a GEC. GEC plays an important role in the coupling between the ionosphere and the Earth's lower atmosphere. The global atmospheric electric field acts as a medium to transfer energy from the Sun to Earth's surface. This situation can be measured through IEF/EEF. IEF/EEF will affect the atmosphere through the interaction between solar wind and thunderstorm, where more active of thunderstorm in the upper level of the troposphere the lightning activity will more generate current. Despite of thunderstorm, the variations in the galactic cosmic ray intensity, modulated by solar activity, are also manifest in changes the atmospheric ionization; however there is some uncertainty that these have significant potential to affect the lower atmosphere [17]. These mechanisms suggest that the temporal distribution and strength of solar activity as indicated by geomagnetic disturbances are important inputs for GPS tropospheric delays.

5. Conclusion

The use of interplanetary electric field (IEF) to connecting the upper and the lower levels of the atmosphere during a major geomagnetic storm based on GPS propagation were successfully proposed. GPS signals were clearly disturbed during the major geomagnetic storm. The electric field variation was also correlated well with the ionospheric activity. It is noted that the tropospheric delays during St. Patrick's Day are slightly affected by the electric field as compared to the Halloween storm. A small to moderate solar flare that occurred during St. Patrick's Day may hard to affect the region of the lower atmosphere. The energetic particle from electromagnetic emission is insufficient to ionize the atmosphere. Finally, the response of the lower atmosphere to the space weather can be said very

small, or delayed in few hours. In contrast, the Halloween storm shows more energy transferred to the lower atmosphere as indicated by the blackout of electric transmission lines during the high event.

The coupling process proposed is an increase in the electric field of the upper atmosphere indicates substantial disturbances to the GEC through an increase in the incident density of energetic particles in the atmosphere. This increase is from magnetosphere by dynamo activity. In addition, the major change in the conductivity from the ionospheric E-region (mesosphere) to the lower atmosphere with changes of cloud structure and cloud base temperature is possibly by cosmic ray modulation (accompanied by a change in downward longwave radiation). Thus, GEC may constitute a variable physical mechanism linking space weather and the earth's weather and climate. Since the ZPD to have different response on the level of geomagnetic storms as well electric field, each of GPS satellite needs to be investigated in future work. The links of the ionospheric electric field to the lower atmosphere through lightning activity also needs to be validated, especially for the Antarctic Peninsula whether they have a direct or indirect response to weather and climate.

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