Influence of lightning on total electron content in the ionosphere using WWLLN lightning data and GPS data

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Abstract

Lightning data from World-Wide Lightning Location Network (WWLLN) and the total electron content (TEC) data estimated from Global Positioning System (GPS) measurements obtained from Trignet have been analyzed to ascertain the influence of lightning on the ionosphere over southern Africa. In this study, data from six dual frequency GPS reference stations in regions with different lightning activity levels within South Africa have been used. The analysis reveal periods of TEC variations of $\sim$ 1 TECU on geomagnetic "quiet" days which correspond to periods of intense lightning activity in the regions. One of the hypotheses for this link between atmospheric weather and ionospheric activity is that the enhancement of TEC is caused by the infiltration of energy dissipated by lightning discharges in the troposphere into the thermosphere.

Key words: *GPS, Lightning and Ionosphere*

1. INTRODUCTION

Over the past few decades considerable attention has been given to the effects of thunderstorms and the lightning they produce on the middle and upper atmosphere. Studies (e.g. Collier et al., 2006; Lay et al., 2007) have shown that the most active regions of thunderstorms are over the Africa, Americas and South-East Asia, with the major proportion of lightning discharge occurring over land. A series of lightning discharges during a long-lasting thunderstorm can lead to appreciable modifications of the conductivity in the regions above, which in some cases caused electron density variations in the middle ionosphere (Vellinov et al., 1992) and red sprites (e.g. Pasko et al.). Statistical studies (Davis and Johnson, 2005; Johnson and Davis, 2006; Davis and Lo, 2008) have shown that the peak and background electron concentration in the E layer were significantly enhanced due to lightning discharges.

Recent study (Lay et al., 2013) has found anomalous total electron concentration (TEC) variations of $\sim$ 1.4 TEC unit (TECU) in the nighttime TEC associated with large thunderstorms in the U.S region.

This work is motivated by the desire to explore more the potential links between thunderstorms and the ionosphere within South Africa regions through the background TEC. TEC is an indicator of ionospheric variability derived from the modified GPS signal through free electrons. It is also the parameter of the ionosphere that produces most of the effects on GPS signals. Lightning data from WWLLN was used as a proxy to identify regions of intense thunderstorms and the observations through the ionosphere was conducted by analyzing TEC measurements from ground-based dual frequency GPS recievers in regions with different thunerstorm activity levels within South Africa.

2. Data and Method of Analysis

The lightning measurements presented are from WWLLN. WWLLN exploits the VLF (3-30 kHz) band term as "sferics" emitted by lightning during the return stroke and employs the Time of Group Arrival (TOGA) described by Dowden et al. (2002) to determine the location of each stroke. Each lightning stroke location requires the TOGA from at least four stations with time residual of less than 30 microseconds (Rodger et al., 2004; Rodger and R. L. Dowden, 2005). WWLLN currently has over 50 sensors distributed across the globe and provides real-time lightning locations globally (Rodger et al., 2009) with less than 10 km and 10 microseconds location and timing errors respectively (Abarca et al.).

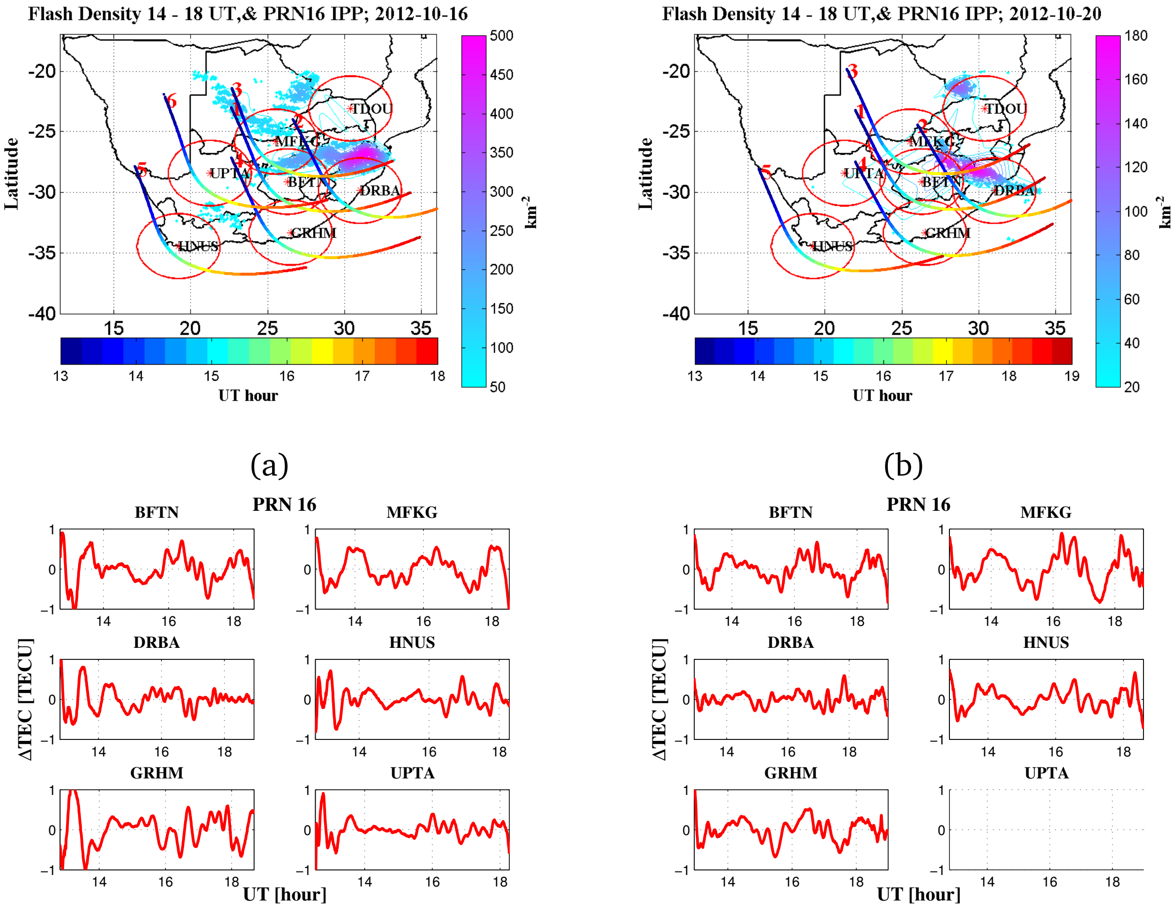
The RINEX observation files obtained from the Trignet (`http://www.trignet.co.za/`) were processed using the "GPS_TEC" analysis application software, developed at Boston College (Seemala and Valladares). The software calculates STEC from the observation data and the STEC values are converted to vertical TEC (VTEC) values by dividing them using a suitable mapping function given by Eq. (1) below, The existence of these biases is due to the fact that the two GPS frequencies undergo different propagation delays inside the receiver and satellite hardware. The mapping function S(E) is given by

$$\mathrm{S(E)} = \left\{1 - \left(\frac{\mathrm{R_E} \times \cos(\varepsilon)}{\mathrm{R_E} + \mathrm{h_E}}\right)^2\right\}^{-0.5} \tag{1}$$

where R_E is the Earth radius, ε is the elevation angle in radians, and h_E is the altitude of the thin layer above the surface of the Earth (taken as 350 km). An elevation cutoff of 20° was used to minimize the multipath effects on GPS data. In the method adopted here, the control curves or "undisturbed" conditions ($\mathrm{TEC_{fit}}$) used are modeled by fitting a 6th order polynomial to the STEC measurements by a GPS pseudo-random number (PRN) from each station, similar to the method described in (Lay et al., 2013). The degree of fluctuations in the STEC was estimated by subtracting the $\mathrm{TEC_{fit}}$ values from the STEC. The removal of the $\mathrm{TEC_{fit}}$ tends to filter out lower-frequency variations, this method is only sensitive to higherfrequency variation. Geomagnetic activity was evaluated using global geomagnetic index Kp.

3. Results

These normalized global lightning data from the WWLLN are used to map intense thunderstorm regions over Southern Africa with high time and spatial resolution. The lightning data was recorded in universal time (UT) system per event which is equivalent to South Africa standard time (SAST) (UT + 2 hours). GPS data from six reference GPS receiver stations on between 13 to 19 UT on 5, 8, 16 and 20 October, 2012 has been selected, processed and analyzed and the results to be presented in Figures 1 and 2 below.



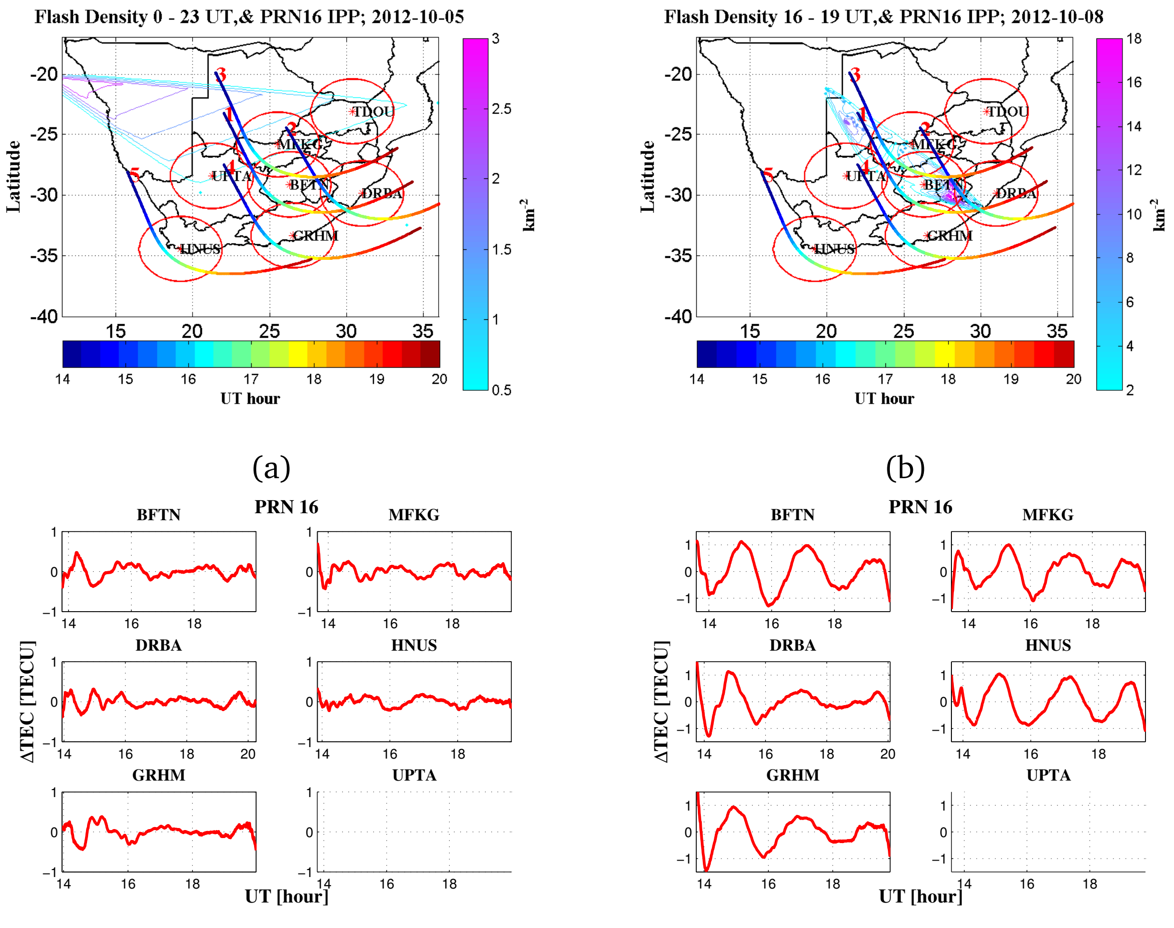
(a)

(b)

(c)

(d)

Figure 1: Top row: corresponding TEC measurement paths (IPP at 350 km) from PRN 16 between 13-19 UT visible at individual refrence receiver stations for high lightning activity and geomagnetically quiet days (a) 16 October,2012 (Kp= 2.3) and (b) 20 October, 2012 (Kp=0.7). The color of the paths is the corresponding time in UT as shown in the colorbar below the figure. The distribution of flash density is also presented in color scale (from light blue to violet):The light blue color indicates regions of relative low flash density and the violet color indicates regions of relative high flash density. Bottom rows: STEC deviations for PRN 16 from the control curves (TEC_{fit}), (c) on 16 October,2012 and (d) on 20 October, 2012



(a) (b)

(c) (d)

Figure 2: To rows:corresponding TEC measurement paths (IPP at 350 km) from PRN 16 between 13-19 UT on (a) 5 October, 2012 (Kp = 2.3) and (b) 8 October, 2012 (Kp = 6.3) Bottom row: STEC devation for PRN 16 from the control curves (TEC_{fit}).

4. Discussions and conclusions

Our analysis show clear evidence of lightning related enhancements in ionospheric TEC in the range of 1 to 1.2 TECU on selected days when there was high lightning activity and low geomagnetic activity. The TEC enhancements typically occur some distance from the region where the lightning activity is the largest, which confirms the hypothesis that the TEC enhancements is likely due to gravity waves caused by the lightning. Distribution of thunderstorms within Southern Africa is not uniform. The warm Agulhas current which flows towards the east coast of Africa from $\sim 27°$ to 40°S and high pressure systems in the Indian Ocean provides favourable conditions for thunderstorm formation in the region. Therefore a relatively significant level of lightning activity is concentrated predominantly off the east coast of South Africa. The low lightning activity are usually observed off the west coast of Southern Africa. This is due to the cold Benguela current which prevails at the area and hence inhibits convective activity (Collier et al., 2006). In our analysis two of large thunderstorm systems located off the east coast of South Africa are observd between the time 13 and 19 UT on 16 October,2012 and 20 October, 2012 as shown in Figures 1(a) and 1(b) respectively. On the 16 October, 2012 the lightning activity has spread to other regions, a considerable level of persistent lightning activity with flash density of 500 km^{-2} was observed off the east coast of South Africa between 14 and 18 UT. The TEC measurements from PRN 16 for

each station were significantly disturbed between the time frame 14 to 18 UT as they move towards the the region of the large thunderstorms. Figure 2c shows that the TEC fluctuations on 5 October geomagnetically quiet and low lightning activity day are very small in amplitude are mainly uniform among all the stations over the entire region, indicating that there are no source localized fluctuations originating within South Africa. Similarly Figure 2d shows TEC fluctuations and 8 October geomagnetically active and low lighting activity day and TEC variation was relatively smooth compared to 16 October and 20 October. Evidence of influnece of lighting on te electron content in the ionosphere has been demonstrated. Future studies needs to be done on quantifying the amount of energy involved.
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