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Research paper

Effects of the intense geomagnetic storm of September–October 2012 on the equatorial, low- and mid-latitude F region in the American and African sector during the unusual 24th solar cycle

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ABSTRACT

The main purpose of this paper is to investigate the response of the ionospheric F layer in the American and African sectors during the intense geomagnetic storm which occurred on 30 September–01 October 2012. In this work, we used observations from a chain of 20 GPS stations in the equatorial, low- and mid-latitude regions in the American and African sectors. Also, in this study ionospheric sounding data obtained during 29th September to 2nd October, 2012 at Jicamarca (JIC), Peru, São Luis (SL), Fortaleza (FZ), Brazil, and Port Stanley (PST), are presented. On the night of 30 September–01 October, in the main and recovery phase, the h´F variations showed an unusual uplifting of the F region at equatorial (JIC, SL and FZ) and mid- (PST) latitude stations related with the propagations of traveling ionospheric disturbances (TIDs) generated by Joule heating at auroral regions. On 30 September, the VTEC variations and foF2 observations at mid-latitude stations (American sector) showed a long-duration positive ionospheric storm (over 6 h of enhancement) associated with large-scale wind circulations and equatorward neutral winds. Also, on 01 October, a long-duration positive ionospheric storm was observed at equatorial, low- and mid- latitude stations in the African sector, related with the large-scale wind circulations and equatorward neutral winds. On 01 and 02 October, positive ionospheric storms were observed at equatorial, low- and mid-latitude stations in the American sector, possibly associated with the TIDs and an equatorward neutral wind. Also, on 01 October negative ionospheric storms were observed at equatorial, low- and mid-latitude regions in the American sector, probably associated with the changes in the O/N_2 ratio. On the night of 30 September–01 October, ionospheric plasma bubbles were observed at equatorial, low- and mid- latitude stations in the South American sector, possibly associated with the occurrence of geomagnetic storm.

1. Introduction

A geomagnetic storm is the result of the energy transfer from the solar wind to the magnetosphere (Gonzalez and Tsurutani, 1987; Tsurutani et al., 1997). There is a strong relationship between the occurrence of geomagnetic storms and ionospheric disturbances. The responses of ionosphere–thermosphere system in the mid-latitude region during geomagnetic storms have been extensively documented, during solar cycles 21, 22 and 23 (e.g., Prolss and Jung, 1978; Yeh et al., 1991; Pavlov, 1994; Richards and Wilkinson, 1998; Foster and Rich, 1998; Huang et al., 2003; Keskinen et al., 2004; Foster and Rideout, 2005; Basu et al., 2005; Annakuliev et al., 2005; Foster et al., 2007; Basu et al., 2008; Borries et al., 2009; Heelis et al., 2009 and references therein). Other investigators have studied the ionospheric response of equatorial and low- latitude F region during geomagnetic storms in solar cycles 21, 22 and 23 (e. g., Batista et al., 1991; Fejer and Scherliess, 1997; Abdu, 1997; Sobral et al., 1997; Abdu et al., 1998; Reddy and Mayr, 1998; Sobral et al., 2001; Batista et al., 2006; de

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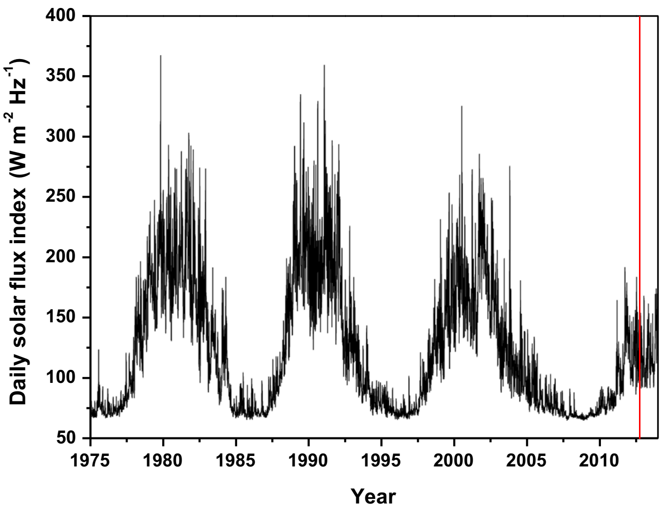

Fig. 1. The 10.7 cm solar flux index variations during 1975–2013. The vertical red line represents the days of September 30 and October 1, 2012 (period in which an intense geomagnetic storm occurred). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Abreu et al., 2010a; Sahai et al., 2011; Klimenko et al., 2011; Batista et al., 2012; de Jesus et al. 2012). However, the morphology of the equatorial, low- and mid- latitude due to the intense geomagnetic storms have not been well covered during solar cycle 24, particularly in the American and African sectors. The effects of the intense geomagnetic storms on the equatorial, low- and mid- latitude ionosphere are important space weather issues. The interest in these investigations is associated with the current lack of understanding and our inability to predict the response of the upper atmosphere due to geomagnetic storms.

It should be mentioned that the solar cycle 24 shows entirely distinct characteristics as compared to earlier solar cycles (see Fig. 1). The solar activity levels can be represented by the decimetric solar flux index expressed in F10.7 flux units (Wm^{-2} Hz^{-1}). Fig. 1 shows the F10.7 variations from January 1975 to December 2013. The vertical red line in Fig. 1 represents the days 30 September and 1 October 2012 (geomagnetic disturbed period investigated). Fig. 1 shows that in solar cycle 24 the period of low solar activity was longer than those in other solar cycles. Fig. 1 also shows clearly that the values of F 10.7 are smaller in solar cycle 24 than those in previous solar cycles, especially during the period of high solar activity. The maximum values of F10.7 in solar cycle 21, 22 and 23 are 367, 359.2 and 325.1, respectively. The 191.6 was the maximum (value of F10.7) in cycle 24 up through 2012. The geomagnetic storm analyzed in this investigation occurred during the period of high solar activity in solar cycle 24, with the F10.7 flux values ranging from 128 to 136.

During the recent past, several investigators (e.g., Danilov and Morozova, 1985; Schunk and Sojka, 1996; Abdu, 1997; Buonsanto, 1999; Danilov, 2013) have reviewed the effects of geomagnetic storms at low-, mid- and high- latitude regions. During the periods of intense geomagnetic disturbances, a large amount of energy is dissipated in the polar region, which leads to profound changes in the global winds circulation via Joule heating (Schunk and Sojka, 1996). According to Buonsanto (1999), if the heating imposed over the high latitudes due to the solar wind via the magnetosphere are impulsive, the equatorward winds will take the form of equatorward surges or traveling atmospheric disturbances (TADs). It should be mentioned that TADs can manifest themselves in the ionosphere as traveling ionospheric disturbances (TIDs) (Hunsucker, 1982; Hocke and Schlegel, 1996; Buonsanto, 1999).

Geomagnetic disturbances could initiate positive ionospheric storms (positive phase), which is characterized by the electron density greater than normal (average of the quiet days) values (Prolss, 1993; Buonsanto, 1999; Sahai et al., 2005; de Abreu et al., 2010a, 2011). Also, the geomagnetic storms could initiate negative ionospheric storm (negative phase). This case is when the electron density value is significantly reduced compared to the normal pre-event value when no stormy condition is in place (quiet period) (Schunk and Sojka, 1996; Mansilla and Zossi, 2012). It is generally accepted that the negative ionospheric storms are due to composition (O/N_2 density ratio) changes (Prolss, 1980; Buonsanto, 1999; Sahai et al., 2009a, 2009b). However, for the positive ionospheric storms different mechanisms are proposed. Prolss (1995) has pointed out that positive ionospheric storms are due to an enhancement in the equatorward neutral winds arising from the auroral latitude energy injection.

In this paper, we carried out investigations to understand the response of the equatorial, low- and mid- latitude ionospheric F region in the American and African sectors during the intense geomagnetic storm which occurred between 30 September and 01 October 2012 (a period of high solar activity during the unusual 24th solar cycle). We used observations from 20 GPS stations and 4 digital ionosonde stations. The prime objectives of the present study are to investigate the generation or suppression of the equatorial ionospheric irregularities and dynamics of the ionosphere in the American and African sectors during this intense geomagnetic storm.

2. Observations

In this study, we present and discuss the simultaneous ionospheric sounding observations (minimum F-region virtual height, h´F, and F-region critical frequency, foF2) from Jicamarca (every 30 min; equatorial station and hereafter referred as JIC), Peru, São Luis (every 10 min; equatorial station and hereafter referred as SL), Fortaleza (every 10 min; a near equatorial station and hereafter referred as FZ), Brazil, and Port Stanley (every 30 min; a mid-latitude station and hereafter referred as PST), during the period from 29 September to 02 October 2012. Also, vertical total electron content (VTEC) from 20 Global Positioning System (GPS) receivers in the American and African sectors (see Table 1 and Fig. 2), during the period from 29 September–02 October 2012, are presented. The GPS observations are also used to obtain the phase fluctuations (rate of change of TEC) and measurements of scintillations (S4, amplitude scintillation index). It should be mentioned that the VTEC is calculated in units of TEC (1 TEC unit$=10^{16}$ electrons/m^2) (Wanninger, 1993). As discussed by Adewale et al. (2012), the VTEC is calculated using the slant TEC (sTEC):

$$\mathrm{VTEC} = \frac{\mathrm{sTEC} - (B_R + B_S)}{M(E)} \quad (1)$$

where B_R is the interfrequency differential receiver biases and B_S the interfrequency differential satellite biases. According to Adewale et al. (2012) and Tiwari et al. (2013), the mapping function $M(E)$ employed is derived by the following equation:

$$M(E) = \frac{1}{\cos(Z')} = \left[1 - \left(\frac{R_E \times \cos(E)}{R_E + H_S}\right)^2\right]^{-1/2} \quad (2)$$

where Z' is the zenith angle of the satellite as seen from the observing station, H_S is the ionospheric pierce point altitude, normally taken as the F region peak, R_E is the radius of the Earth ($\sim$ 6378.1 km), and E is the elevation angle in radians.

Phase fluctuations are defined by the rate of change of TEC (ROT) in units of TEC/min which can indeed detect the presence of