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Ionospheric response over South Africa to the geomagnetic storm of 11–13 April 2001

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ABSTRACT

The mid-latitude ionosphere over South Africa is subject to severe F region ionospheric density perturbations during intense geomagnetic storm activity. Communication and navigation systems relying on trans-ionospheric propagation are adversely affected during strong storms. There is a need to compensate for the effects of the sharp ionospheric total electron content (TEC) gradients associated with the storm time disturbance effects at mid-latitudes. The South African ionosonde and Global Positioning System (GPS) database have been used to examine the spatial extent of the electron density structures during the super storm of 11–13 April, 2001. The ionosonde measurements have supported the observed negative (i.e. decreased electron density) and positive (i.e. increased electron density) storm effects over this region. The hmF2 and h'F ionospheric parameters showed higher and reduced values during the main and recovery storm phases respectively. The ionospheric TEC is a widely used parameter in the studies of the near Earth plasma environment. The derived *VTEC* and their perturbation components revealed TEC fluctuations of magnitude ≥ 10 TECU during the storm. The storm-induced TEC perturbations on 11–12 April, 2001 revealed a travelling ionospheric disturbance (TID) phenomenon. The source of the irregularities observed over South Africa during this super storm period has been attributed to TIDs generated by gravity waves due to auroral sub-storm activity. The equatorward propagating waves resulted in an uplift of the F2 layer by pushing the ionospheric plasma along magnetic field lines to higher altitudes where recombination is much lower, which in turn leads to plasma density enhancement.

1. Introduction

Geomagnetic storm induced perturbations in the ionosphere have been of great interest to space scientists for decades. Geomagnetic storm effects on the ionosphere at high and equatorial regions have been studied extensively by authors such as Hunsucker and Hargreaves (2003), Becker-Guedes et al. (2004) and Kumar and Singh (1982). Researchers such as Bowman (1982) and Buresova (2005) have investigated storm effects in the mid and low latitudes. These authors have associated effects in the F2 region ionosphere with the ionospheric response to storm effects in the thermosphere. Meanwhile the effects in the lower ionosphere are believed to be predominantly caused by the storm associated precipitating energetic particles emanating from auroral latitudes. It is also generally accepted that changes in the neutral atmosphere, ionisation and photochemical processes influences the F1 heights due to the shorter lifetime of free electrons compared with the F2 region (Buresova, 2005). According to Buresova (2005), during geomagnetic storms the F1 region becomes more important for ionospheric radio wave communications. In addition, Buresova (2005) stated the effect of a magnetic storm resulted in a substantially reduced F2 region which is screened by the F1 region and hence the F1 region serves as the radio wave reflecting layer.

A geomagnetic storm is a phenomenon of solar wind or magnetospheric origin during which the ionospheric F2 layer becomes unstable, fragment, and may even disappear completely. The growth of ionospheric irregularities increases substantially during geomagnetic storms initiated by solar disturbances (Belehaki and Tsagouri, 2002; Hunsucker and Hargreaves, 2003; Buresova, 2005). Various features of a geomagnetic storm act at different heights of the ionosphere and neutral atmosphere. In the mid-latitude F2 region, the storm effects are attributed to the ionospheric response to storm-induced changes in the neutral atmosphere, which are primarily a consequence of strong Joule heating in the auroral thermosphere (Fuller-Rowell et al., 1994;

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Danilov and Lastovicka, 2001). A negative F region storm effect (i.e. decrease in plasma density) due to auroral heating causes atmospheric circulation that changes the composition of the neutral atmosphere, which in turn increases the effective electron loss rate (Mikhailov and Schlegel, 1998; Belehaki and Tsagouri, 2001; Kelley, 2009). The fact that this heating takes place below the F layer and thus enhances the recombination rate, implies that the bottomside F2 layer is depleted, thus increasing the F2 layer height and consequently decreasing the electron density.

Solar wind energy, captured by the magnetosphere, is known to induce influences of varying degree on the morphology of the electric fields, temperature, winds and composition of the ionosphere. One of the main characteristics of the disturbed ionosphere is the variability observable on all ionospheric parameters (Buresova, 2005). Ionisation density perturbations at ionospheric F region heights associated with geomagnetic storms may last for days. The perturbations are known to vary with location, season, local time, solar activity and altitude (Buresova, 2005). Authors such as Bowman (1982) investigated spread F (SF) occurrence in mid and low latitude regions related to various levels of geomagnetic activity. Bowman (1982) found significant peaks in SF occurrence during moderate, high and very high geomagnetic activity in latitude regions closest to the auroral zone. The peaks were found to be delayed by a matter of days, with the delays being greater for the lower levels of activity and also greater for regions further from the auroral zone.

Mid-latitude nighttime ionospheric enhancement observations by Belehaki and Tsagouri (2002) during magnetic storms revealed a correlation between various solar wind, magnetospheric and ionospheric parameters. The nighttime ionospheric response was found to be strongly dependent on the conditions during which significant solar wind–magnetosphere coupling occurred. Belehaki and Tsagouri (2002) stated that storms with an initial compressive phase and rapidly evolving main phase cause a global ionisation depletion effect in the night-side at middle latitudes, independent of the storm intensity. These storms are caused by the abrupt dissipation of a large amount of energy input, resulting in the rapid expansion of the neutral composition disturbance zone equatorward, producing the observed negative effects at all middle latitude stations which were studied by Belehaki and Tsagouri (2002). In addition, Belehaki and Tsagouri (2002), added that gradually evolving geomagnetic storms, driven by a slowly increasing southward interplanetary magnetic field (IMF), result in the observation of nighttime positive effects at low to middle latitude stations. The weaker the intensity of the storm, the more likely are nighttime ionisation enhancements observed at the sub-auroral latitudes. There are two competing mechanisms causing the observed effects; the expansion of the neutral composition disturbance zone results in negative effects, while downward plasmaspheric fluxes produce ionisation enhancements at night. Furthermore, Belehaki and Tsagouri (2002) stated that gradually evolving storms are characterised by the restricted development of the neutral composition disturbance zone to higher latitudes, and the extent of its equatorward boundary depends on the intensity of the storm. During storms of this type, the role of plasmaspheric fluxes dominates at middle to low latitudes. Their effects are observable up to sub-auroral latitudes given that the neutral composition disturbance zone development is restricted to higher latitudes, as happens when the geomagnetic activity is of low or moderate intensity.

A review of storms in the ionosphere by Mendillo (2006) explained in detail that at mid and low latitude regions magnetic field lines extend upward into the plasmasphere and the positive phase disturbances occur as neutral winds and penetrating electric fields redistribute the low and mid-latitude plasma in latitude, longitude, and altitude. It is well known that in sunlight, ion production at lower altitudes increases the TEC as the F region peak height is raised while electric fields perpendicular to the magnetic field (B) redistribute the plasma in latitude and longitude. This occurs inside the plasmasphere boundary layer, the boundary between the co-rotating field lines of the plasmasphere and the outer magnetosphere (Buonsanto, 1999; Mendillo, 2006).

However, the mid-latitude effects have not been well covered, particularly in the southern hemisphere. South Africa is one such region where the effects of changing dynamics of the ionosphere on radio communication needs to be investigated routinely since South Africa hosts the regional space weather warning centre for Africa, associated with the international space environment service. This paper presents results from an investigation into the effect of the long lasting storm of 11–13 April, 2001 over the South African ionosphere. This was achieved by analysing ionosonde (HF-band) and GPS (L-band) frequency observations of the ionosphere over South Africa.

2. Data sources

The current South African infrastructure of ionospheric field stations operates four ionosonde stations, over 56 GPS receivers and one ionospheric scintillation and TEC monitor (GISTM) receiver within the country. For this study data from three ionosondes and four GPS stations were used, and the location of these particular instruments are shown in Fig. 1.

Currently the digisonde at Madimbo (30.88°E, 22.38°S), Grahamstown (33.32°S, 26.50°E) and Louisvale (28.51°S, 21.24°E) are being upgraded to the DPS-4D model. The geographical and geomagnetic longitudes and latitudes (denoted by (Glong, Glat) and (Mlong, Mlat) respectively) of the ionosonde and GPS stations are provided in Table 1 together with their station codes. The magnetic coordinates of the stations shown in Table 1 were computed using the on-line facility available on http://www.ukssdc.ac.uk/cgi-bin/wdcc1/coordcnv.pl. Ionosonde data from the three stations used in this study were analysed by means of the SAO Explorer software (Reinisch et al., 2004). The ionograms were viewed to identify any spread F (SF) events and their characteristics extracted during the storm period. The data for hmF2, h'F, foF2 and ionosonde TEC (ITEC) parameters were extracted for investigation of any possible mechanisms triggering the events. The dual frequency GPS L-band TEC values were

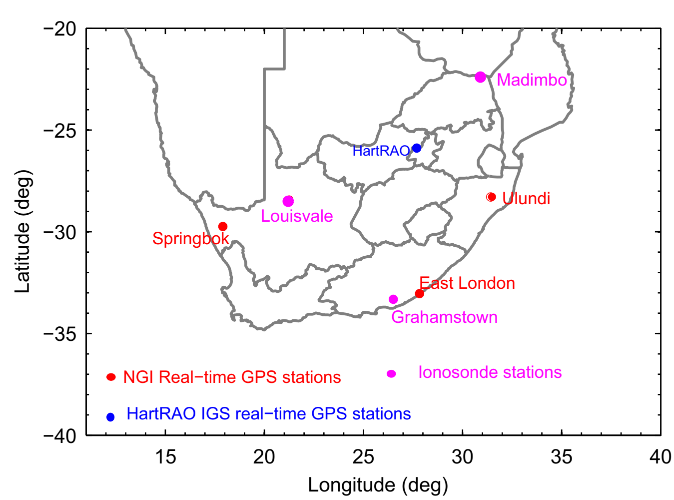

Fig. 1. Map of South Africa showing the three ionosonde and the four GPS stations used to obtain data in this study. The GPS receivers are owned by International GPS Service (IGS) and National Geo-spatial Information (NGI).