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Ionosonde observations of the effects of the major magnetic storm of September 22–26, 1999 at equatorial station in west Africa

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A B S T R A C T

A new approach to study the mechanisms of storm-time variations in the F-layer height and critical frequency at dip-equator is proposed. The latitudinal variations in the magnetic disturbance index DP were combined with *h*'F and *fo*F2 data from an IPS 42-type ionosonde at Korkogo (9.2° N, 5° W; 2.4° S dip lat), Ivory Coast, to investigate the nighttime ionospheric effects of the geomagnetic storm of September 22–26, 1999 in the West-African sector. A clear equatorward penetration of magnetic disturbances from high latitudes regions was observed. At dip-equator, the DP magnetic disturbance pattern showed up to four distinct regimes of disturbance electric fields, each associated with a specific phase of the storm. A regime of westward transient electric fields followed by a regime of eastward transient electric fields occurred during the main phase of the storm. This was preceded by a period of quasi-absence of disturbance during the compression phase, the whole followed by a regime of westward persistent disturbance electric fields during the recovery phase. From the latitudinal variations and the shapes of these perturbations, we could associate the regime of westward (resp. eastward) disturbance electric fields with prompt penetration (resp. overshielding) occasioned by magnetospheric convections and the persistent one with a cumulative effect of storm-time winds and magnetospheric convections from high latitudes regions. The *h*'F variations were found to be strongly correlated with the DP ones, clearly providing evidence for the prevalence of these electric fields on the observed F-layer motions. Additionally, the *fo*F2 variations showed two periods of depleted electron density, one in the evening during the compression phase of the storm and the other near midnight. We discussed the mechanisms of these ionospheric negative storms in the light of earlier investigations of storm-time ionospheric disturbances and validated our method by comparison of the above results with those based on criteria by other authors.

1. Introduction

The ionospheric zonal electric field often undergoes strong perturbations during geomagnetic storm periods due to different disturbance processes. Several experimental and theoretical investigations conducted on that subject since the last thirty years pointed out two mechanisms as main sources of disturbance electric fields in the ionosphere. The first mechanism, the magnetospheric disturbance dynamo process results from the interactions between the solar wind and the magnetosphere. These interactions occasion the circulation of electrical currents between the magnetosphere and the high-latitude ionosphere some of which, along with their associated electric fields, penetrate directly to lower latitudes, leading to short-lasting (1–2 h duration) disturbances in the zonal electric fields (Senior and Blanc, 1984; Spiro et al., 1988). The second mechanism, the ionospheric disturbance dynamo process is occasioned by modifications in the global circulation due to Joule heating at auroral latitudes and leads to longer-lasting (several-hours duration) disturbances in the zonal electric fields (Blanc and Richmond, 1980). Numerous studies have established the basic features of these disturbance electric fields (Senior and Blanc, 1984) and it is known that the magnetospheric disturbance electric fields can instantaneously penetrate to dip-equator when the interplanetary magnetic field (IMF) *Bz*, brutally, changes to southward. A westward (resp. eastward) transient penetration electric field during night (resp. day) is associated with a sudden increase in polar cap potential ϕ, and a westward (resp. eastward) transient penetration electric field during day (resp. night) is associated with a sudden decrease in ϕ. The transient behavior of the penetration electric field and its relationships with *Bz* and ϕ have been verified in experimental reports (Sastri et al., 1992, 2002).

The major difficulty frequently encountered when studying the ionospheric effects of geomagnetic storms lies in the identification of the

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signatures of the two mechanisms sources above. This is because the currents and plasma drifts during disturbed conditions show highly variable signatures due to the simultaneous occurrence of several disturbance processes. Most often, the duration and the latitudinal variations of the disturbance patterns are combined to distinguish between these two mechanisms. As an example, when investigating the effects of the storm of July 15, 2000 on the nighttime F-layer height variations, Sastri et al. (2002) observed a rapid downward perturbation in the *h*'F variations pattern (∼215 km/h), with amplitude depending on the dip angle. They associated this perturbation with westward transient penetration electric fields. Then, from the disturbed geomagnetic conditions prior to the onset of the storm and the high global energy injection rate of ∼300 GW, about 4 h 45 min earlier, they argued that ionospheric disturbance dynamo electric fields could contribute to this layer height perturbation. In view of a better description of the mechanisms involved in the storm-related disturbances, models have been elaborated (Mazaudier et al., 1987; Fejer and Scherliess, 1995, 1997). The model by Fejer and Scherliess (1995) pointed out that equatorial zonal electric field disturbances of magnetospheric and ionospheric dynamos origins can be separated if their storm time evolutions are taken into account. Conversely, Fejer and Scherliess (1997) determined the zonal disturbance electric field resulting from the cumulated effects of the magnetospheric and ionospheric disturbance dynamos by combining vertical drift measurements and auroral electrojet indices. Although the storm-time perturbations in the ionosphere were extensively studied, there still remain difficulties for the identification of the signatures of the driving mechanisms. Therefore, it would be useful to issue repeated observations on this topic.

The storm-time zonal disturbance electric fields are often studied from the vertical plasma drift velocity. When data of the bottom altitude *h*'F of the F layer are available, the pattern of these electric fields can be inferred from the variations in the apparent drift velocity taken as the time derivative of the *h*'F variations (Sastri et al., 1992). However, the variations pattern of the magnetic field disturbance *DP*, i.e. caused primarily by intense electrojets flowing in the ionosphere of polar regions and their associated currents in the ionosphere and the magnetosphere (Kobea et al., 1998), can be used to study that of the disturbance electric fields (Zaka et al., 2009; Mene et al., 2011).

The ionospheric effects of the storm of 22–26 September 1999 (which is the subject of the current paper) have been investigated by means of GPS and VHF/UHF communication systems (Basu et al., 2001). It was shown that the penetration to the dip-equator of transient magnetospheric convection electric fields can cause TEC increases and fluctuations, and saturated 250-MHz scintillations. In the current work, we provide additional information from IPS 42-type ionosonde data of *h*'F and *fo*F2. In section 2, we will briefly present the data acquisition and treatment. Section 3 is devoted to the analysis of our data. Particularly, we will identify the different regimes of disturbance electric fields involved in the storm on the night investigated using the variations in the magnetic field disturbance *DP* and will compare the ionospheric effects expected from each regime with our observations of *h*'F and *fo*F2 to determine its involvements. In section 4, we will discuss our results based on earlier works and, in section 5 we will draw our conclusion.

2. Data and processing

The storm-related perturbations in the ionosphere were studied by analyzing the temporal variations in the bottom altitude *h*'F and the critical frequency *fo*F2 of the F layer, the ring current index *Dst* and the auroral electrojet index *AL*, and the rate of total auroral Joule heating J_H, over the period of 22–26 September 1999.

The F-layer parameters were derived from ionograms recorded at Korhogo (9.2° N, 5° W; 2.4° S dip lat), Ivory-Coast, by means of an IPS 42-type vertical-sounding transmitter-receiver whose antenna was 80 m wide and 25 m high. The transmitter pulse had a rise time of 2 μs and was 10 μs wide. The peak power transmitted was 5 kW. The ionosonde operated in the high frequency (HF) range [1–22 MHz] and provided the plot of the virtual height as a function of frequency every 15 min. The bottom altitude *h*'F was determined from the low-frequency asymptotic value of the virtual height and the critical frequency *fo*F2 from the ordinary trace of the ionogram.

The data of the ring current index *Dst*, the auroral electrojet index *AL* and the horizontal magnetic field *H* (*Hr* for a reference quiet night), for a given time, were collected from the World Data Center (Kyoto, 1999). The magnetic disturbance *DP* represents the magnetic effects of the ionospheric electric current systems generated by the penetration of magnetospheric convection electric fields at equator (DP2) and the ionospheric disturbance dynamo (Ddyn). Its value at any time, for a given station, was calculated using expression (1) in which, θ denotes the dip latitude of the station, (Kobea et al., 2000; Mene et al., 2011). The rate of total auroral Joule heating J_H was calculated using expression (2) for the equinox periods (Chun et al., 1999) based on the PCN index (NASA OMNIweb SPDF Goddard Space Flight Center, 1999).

$$\mathrm{DP} = \mathrm{H} - \mathrm{Hr} - \mathrm{Dst} \times \cos\theta \,, \tag{1}$$

$$\mathrm{J_H} = 4.14 \times \mathrm{PCN}^2 + 25 \times \mathrm{PCN} + 8.9\ [\mathrm{GW}] \,. \tag{2}$$

In order to determine and characterize the level of geomagnetic activity, two indices are most often used, namely, the Kp (Ap) and Km (Am) indices (Menvielle et al., 1995; Zerbo et al., 2013). Both describe the geomagnetic activity at the planetary scale and provide the same measure of geomagnetic activity on two different scales (Kp and Km are given on a scale from 0 to 9 whereas Ap and Am are expressed in nT). The main difference between the two sets of indices lies in the distribution of the observatories from which they are computed. The Km and Am indices are determined from 12 observatories in the northern hemisphere and 9 in the southern one while the Kp and Ap indices are computed from 12 observatories in the northern hemisphere and only 2 in the southern one. Similarly, the longitudinal coverage of these observatories is better in the case of the Km (Am) indices than in that of the Kp (Ap) ones. Menvielle and Berthelier (1991) reviewed and discussed the derivation of the K-derived planetary indices. They pointed out that it is better to use the Am or Km index because both give a better description of the geomagnetic activity than the Ap or Kp one. Therefore, in this paper, in order to characterize the magnetic activity, we used the Am index. We should note here that, most often, geomagnetic indices tables list the mean daily index Am calculated from 00:00 to 24:00. Certainly, the Am value so determined takes into account the night-time period from 18:00 to 24:00 on a given day but, it excludes that from 00:00 to 06:00 on the next one and, therefore, may not be suitable for the description of the magnetic activity in that period. In the current paper, in order to characterize the geomagnetic activity over an entire night, we considered as Am data the mean values of the nightly tri-hourly indices am, calculated from 18:00 to 06:00. The am indices used for that purpose were collected from the website of the International Service of Geomagnetic Indices (ISGI France, 1999).

In all the paper, the time was expressed in SLT. Note that at Korhogo, SLT ≈ UT - 20 min.

3. Results and analysis

3.1. Characteristics of the storm

The temporal variation in the *Dst* index shown in Fig. 1a indicates that the storm began on 22 September 1999 at 10:30 LT. The brutal increase, i.e. sudden storm commencement (SSC), observed at that time took the *Dst* index up to 25 nT, to a nearly-steady state until about 19:30 LT. This was followed by the main phase of the storm characterized by a single-step falloff of the *Dst* index which, rapidly, reached the minimum value of −175 nT at about 22:55 LT on the night of 22–23 September 1999. The next event was the recovery phase of the storm, with the *Dst* index increasing asymptotically to 0 beyond 23 September 1999 (Fig. 1a). Conjointly, strong disturbances in the auroral electrojet activity occurred, indicating an important magnetospheric convection. This is characterized by the presence of high-amplitude impulses in the *AL*-index