Low-latitude Signature of Storm Enhanced Density on 8 November 2004 and Spatial Gradient of Ionospheric Total Electron Content

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Abstract

Ionospheric total electron content (TEC) anomalously increased after sunset over Japan, during a magnetic storm on 8 November 2004. The TEC enhancement was larger at higher latitudes, and it reached 90 TEC units at 45.0° N. The enhancement was interpreted as a low latitude signature of a storm enhanced density (SED) plume. Previously, SED/TEC plumes were only reported at the American longitudes, and this led to a hypothesis that a particular geomagnetic field configuration at those longitudes plays a role in formation of these plumes. The present observation indicates that SED/TEC plumes can be formed at any longitude on the earth.

INTRODUCTION

Anomalous enhancement of ionospheric total electron content (TEC) can be hazards for advanced GPS applications, such as satellite based augmentation systems (SBASs), e.g., the Wide Area Augmentation System (WAAS) in the US, and the MTSAT Satellite Augmentation System (MSAS) in Japan, because of increased transionospheric radio wave propagation delays. Analyses based on recent massive GPS receiver networks reveal that positive ionospheric disturbances are more dynamical than has been thought. Several mechanisms possibly enhance TEC. Among them, ionospheric disturbances owing to disturbed electric fields are significant, such as prompt penetrating (PP) and disturbance dynamo (DD) electric fields, both of which occur during periods of geomagnetic disturbance. TEC increases simultaneously in a wide latitude range when a PP electric field directs eastward in sunlit hours. Other examples of TEC disturbance are the so-called storm enhanced density (SED), which also occurs associated with geomagnetic disturbances, and the whole mechanism is not well understood. A significance of SED in SBASs that uses a coarse grid system is that TEC enhancement occurs in a narrow channel having several-degrees width of longitudes, which degrades differential corrections of ionospheric delay.

OBSERVATIONAL SETUP

The area covered by the dense GPS receiver network, GEONET, was divided into 32 bins 2×2° in longitude and latitude as shown in Fig. 1. From about 1100 GEONET receivers, we chose for the TEC calculation about 330 GPS receivers that were homogeneously distributed over the GEONET coverage area. The vertically converted TEC at a given time was assumed to be the same in each bin and values were determined every quarter hour. Ma and Maruyama [1] reported the details of the algorithm that we used. Ionospheric critical frequency (*foF*2) and maximum usable frequency factor (*M*3000*F*2) were scaled from ionograms at the four ionosonde stations, Wakkanai, Kokubunji, Yamagawa, and Okinawa, also shown in Fig. 1. Ionospheric peak height (*hpF*2) was derived from *M*3000*F*2 with an empirical formula.

GEOMAGNETIC CONDITIONS

A severe ionospheric storm occurred on 7 November 2004, during a declining phase of the solar activity. The upper panel of Fig. 2 shows the asymmetric disturbance index, *ASY-H*, which is a good indicator of auroral substorm activity, and the symmetric index, *SYM-H*, which is essentially the same as the *Dst* index. The magnetic field (*SYM-H*) started to decrease at around local sunrise (JST = UT + 9 hr) and reached its maximum depression of about -400 nT at around 1500 JST. The lower panel shows the three hourly *Kp* indices.

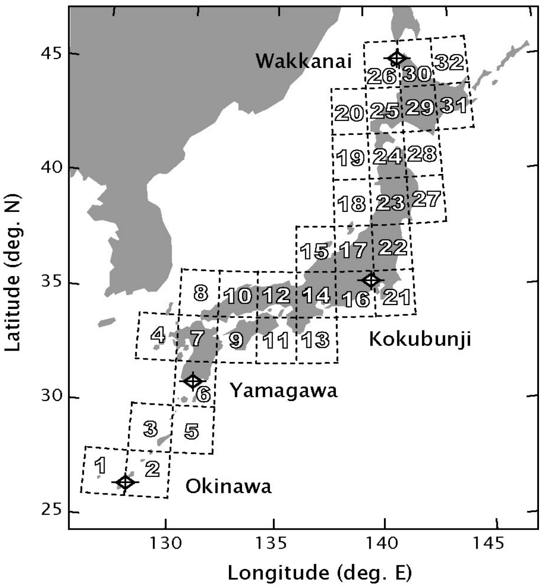

Fig.1 Sub-divided cells for TEC calculations

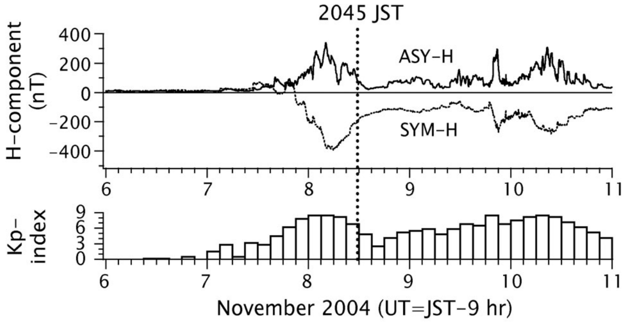

Fig.2 Geomagnetic conditions from 6 to 11 November 2004.

RESULTS

In order to visualize the perspective of the TEC disturbance, contour maps were drawn as a function of local time (JST) and latitude. The results are shown in Fig. 3. The upper panel is the TEC variation on 8 November 2004. The numbers at the contour lines are in TEC units or 1×10^{16} m^{-3}. The middle panel is the averaged TEC variation for a reference of quiet days from 1 to 6 November 2004. The TEC variation on 8 November was quite different from that on the quiet days. To depict the perturbation, the difference between the maps on the storm and quiet days is shown in the bottom panel. Soon after sunrise, the TEC started to increase, and enhancement reinforced it at least four times until midnight. The first peak was centered at 1030 JST. The second one was from 1400 to 1500 JST. The third one was 1700 to 1730 JST, for which the enhancement was confined to the latitudes lower than 37° N, and lasted longer at lower latitudes. The last one was centered near 2100 JST, which was distinct at latitudes higher than 35° N.

Fig. 4 shows *hpF*2 variations at Wakkanai, Kokubunji, Yamagawa, and Okinawa. Simultaneous uplift of the layer was observed at 0615 JST, and after that the layer was persistently high until 2000 to 2200 JST. After the simultaneous height increase in the morning, the TEC was gradually enhanced as seen in Fig. 3. For the second TEC enhancement centered at 1400 JST, no clear correspondence was seen in the height variations. Although determining the causes of the height changes is not always easy, the combined effects of a prompt penetrating electric field and an equatorward thermospheric wind might be required to maintain uplifted ionospheric conditions for long hours [2].

Another prominent height variation was at Wakkanai at 1800 JST where the layer rose above the reference level by 237 km. The height increase at Kokubunji was delayed by 45 minutes, occurred after that at Wakkanai, and was 180 km above the reference level. Thus, this perturbation could be attributed to a traveling ionospheric disturbance (TID) that quickly decayed, as a corresponding height variation at Yamagawa was not seen very clearly. The fourth TEC enhancement followed the TID.

DISCUSSION

During periods of magnetic disturbance, positive TEC storms often develop in sunlit hours. This is owing to a combined effect of the upward drift of the ionospheric layer into the region where the recombination rate is small and new ionization production in the bottomside region. For large and sustained TEC enhancement, a prompt penetrating electric field and an equatorward disturbance wind may act jointly [2]. However, after sunset, large TEC enhancements are quite unusual, and their mechanism is not well known. In the TEC storm event presented here, the daytime part might be explained by the known mechanisms. But the severe TEC enhancement near 2100 JST was different in many

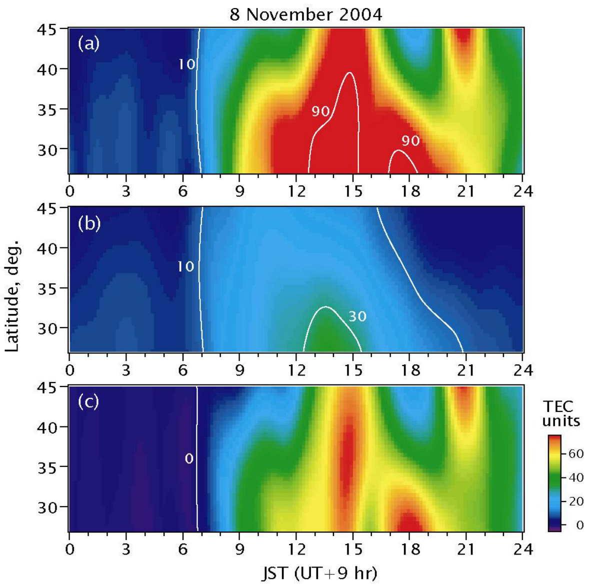

Fig. 3 Total electron content as derived from GEONET. (a) Storm on 8 November 2004, (b) reference averaged from 1 to 6 November 2004, and (c) TEC(storm)-TEC(reference).

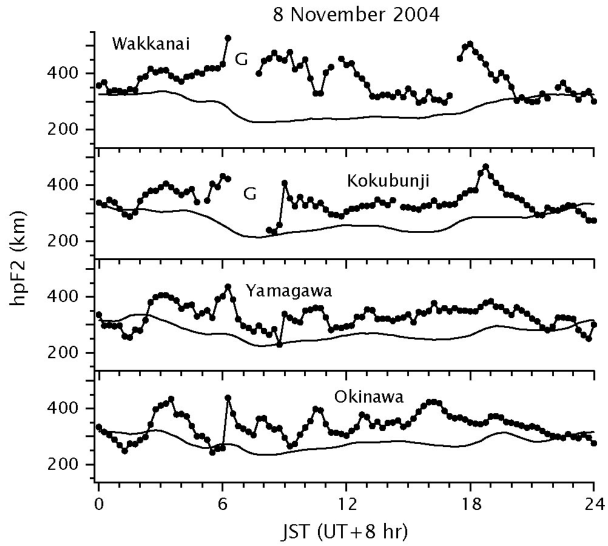

Fig. 4 Ionospheric peak height variations. Dots connected by line are for the storm day, 8 November 2004, and solid lines are for quiet days averaged from 1 to 6 November 2004.

aspects from the TEC disturbances in daytime on the same day and others in published literature. We will focus our discussion on this.

The daytime TEC and its perturbation shown in Fig. 3 were larger at lower latitudes, while the evening disturbance near 2100 JST was significant at higher latitudes. The delay of the enhancement peak toward lower latitudes invokes large scale traveling ionospheric disturbances. However, such a large TEC enhancement after sunset was quite difficult to interpret as solely an equatorward neutral wind effect. In the case of a fountain effect owing to disturbed eastward electric fields, advection can transport the dense plasma near the magnetic equator to mid-latitudes. However, higher TEC enhancement is expected at lower latitudes contrary to the present observations. Thus, to accept the fountain effect as the cause of the TEC disturbance near 2100 JST is difficult.

Frontal structure and advection of the disturbed area after sunset

Although Fig. 3 is suitable for displaying the perspective of the disturbance, longitudinal variations have been averaged over the bins with the same latitude, and the details of time variations have been smoothed. Fig. 5 depicts TECs for the bins selected for more discussion. One of the peculiar features we noted in Fig. 3 is the latitudinal variations in TEC near 2100 JST. Fig. 5a shows TECs for the bins aligned in the 141° E meridian (Nos. 22, 23, 24, and 25 in Fig. 1).

The TEC started to increase just after sunset; the start and peak times of the enhancement was delayed by 45 min from 43°N to 37°N. The disturbance apparently moved to the South at the rate of 2°/15 min. While, Fig. 5b shows TECs for the bins aligned in the East-West direction at 41°N (Nos.19, 24, and 28) the TEC enhancements near 1500 JST were nearly identical at the three different longitudes, and the small difference could be attributed to the changes in the solar zenith angle. After sunset, however, the start time of the TEC enhancement and peak were earlier at the East (No. 28), and the apparent westward drift velocity was 2°/15 min. Thus, the disturbance exhibited a frontal structure slanted to the West.

The true drift direction of the slanted structure is not easy to determine. The peak height variation at Wakkanai after 2000 JST shown in Fig. 4 did not exhibit a large deviation from the quiet level. If the structure was moved southward by the action of $\mathbf{E}\times\mathbf{B}$ drift, the peak height might be lowered. Thus, the disturbance could be assumed to move westward or northwestward. Such a slanted TEC enhanced region with an westward drifting component during a magnetically disturbed period strongly invoke the so-called SED/TEC plume [3].

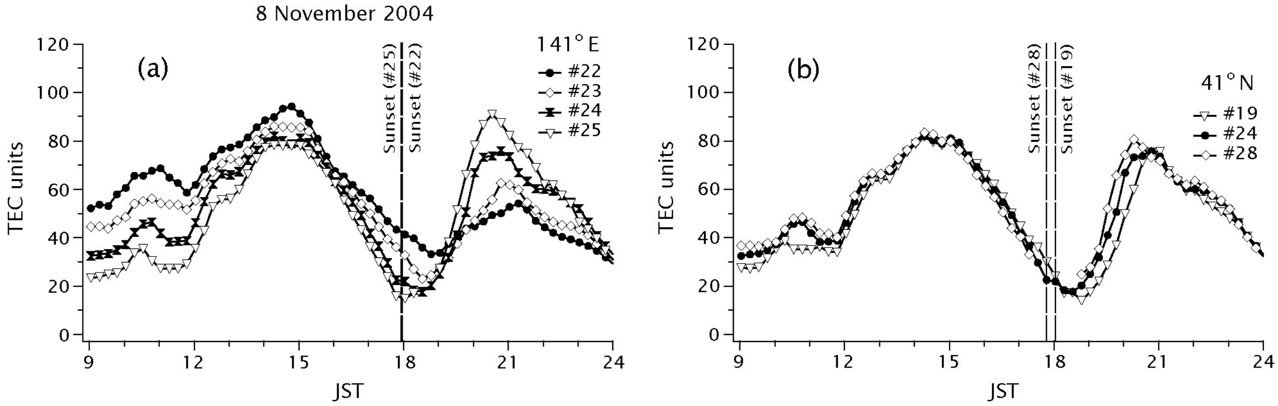

Fig. 5 TEC variations at individual cells. (a) North-south aligned cells at 141°E and (b) east-west aligned cells at 41°N

Origin of the dense plasma

There is no doubt that advection of dense low latitude plasma forms an SED/TEC plume at mid-latitudes [3]. This is achieved by a fountain effect driven by a strong eastward electric field. As we have seen, that the TEC enhancement is not a direct result of the fountain effect at that time is evident. The westward drift rate of the TEC disturbance was half the movement of the sunset terminator. This means that the plume originated at the east longitudes with early local times. If the eastward electric field was a PP electric field, it may be extended at wide longitudes. The best candidate for such a PP electric field event is that TEC enhancement started at around 1630 JST. Amplitude of PP electric field is the largest at the longitude of 1830-1900 LT, or 30-37° East from the Japan's longitude (135°E). At those longitudes, a stronger eastward electric field might cause a TEC enhancement at lower mid-latitudes, and the TEC enhanced region may have been moved westward by the northward electric field of a disturbance dynamo [4] at the rate of 8°/hr. Thus, it might take one and half hours to reach 145°E.

CONCLUSION

We observed anomalous TEC enhancement at the latitudes higher than 37°N in nighttime near 2100 local time at the Western Pacific longitudes during a period of magnetic disturbance. The TEC enhanced region had a frontal structure inclined 35° from North to West, moving toward West to Northwest. We believe that a narrow channel of TEC-enhanced region, a SED/TEC plume, might pass over Hokkaido, at the Northeast end of the observation area. Until now, SEDs were only reported at the American longitudes, which led to a hypothesis that a particular geomagnetic field configuration at those longitudes plays a role in the formation of SED. The present observation, however, indicates that SED, and the steep TEC gradients associated with it, can be formed at any longitude on the earth.

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