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Midlatitude TEC enhancements during the October 2003 superstorm

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1. Introduction

We use observations from the array of North American GPS receivers to examine the formation and severity of midlatitude enhancements and steep gradients in total electron content (TEC) during the October 30–31, 2003 superstorm. A large (~10x) enhancement in dayside TEC was observed over the US mainland during these events as Dst decreased sharply and strong SAPS electric fields eroded the outer reaches of the post-noon plasmasphere boundary layer (PBL) forming poleward-streaming plumes of storm enhanced density. TEC increased to >250 TECu equatorward of the PBL. TEC gradients across the PBL over the central US exceeded 60 TECu per deg latitude. While intense, these features are qualitatively similar to those seen in lesser storms. Citation: Foster, J. C., and W. Rideout (2005), Midlatitude TEC enhancements during the October 2003 superstorm, Geophys. Res. Lett., 32, L12S04, doi:10.1029/2004GL021719.

2. Storm Enhanced Density: A Feature of the PBL

Storm-enhanced density (SED) is low-latitude thermal plasma transported sunward (towards noon) by the convection electric field. Based on an analysis of Millstone Hill radar observations of the disturbed midlatitude ionosphere, Foster [1993] described SED plumes in the pre-midnight and afternoon sector which stream sunward from a source at the equatorward edge of the main ionospheric trough (where field lines map to the outer plasmasphere) carried by the equatorward edge of the SAPS electric field. Combining ground (GPS TEC) and space-based (IMAGE EUV) thermal plasma imaging techniques, Foster et al. [2002] demonstrated that one such ionospheric SED plume mapped into the low-altitude signature of a plasmaspheric drainage plume. Foster et al. [2004] used direct radar observations of the sunward $\mathbf{E} \times \mathbf{B}$ plasma convection to quantify the flux of ions carried by the SED plume to the noontime $F$-region in the vicinity of the cusp. Foster [1989] reviewed observations which indicate that this streaming low-latitude plasma is a source for the tongues of ionization which appear at polar latitudes during disturbed conditions.

3. TEC Enhancement Inside the PBL: Redistribution From Lower Latitudes

The source plasma of the SED erosion plumes is found in the outer reaches of the PBL. Recent observations during major storms indicate that a significant enhancement of the midlatitude TEC occurs in the North American sector, equatorward of field lines mapping to the PBL [Immel et al., 2005; J. C. Foster et al., Redistribution of the stormtime ionosphere and the formation of the plasmaspheric bulge, submitted to Global Physics of the Coupled Inner Magnetosphere, Geophysical Monograph Series, edited by J. Burch, M. Schultz, and H. Spence, AGU, Washington, D. C., 2004a, hereinafter referred to as Foster et al., submitted manuscript, 2004a]. Observations presented in these studies quantify the rapidity and spatial extent of the TEC enhancement at the base of the erosion plume.
They present evidence for a rapid poleward redistribution of equatorial thermal plasma to low and mid latitudes due to the effects of enhanced stormtime eastward electric fields in the vicinity of the South Atlantic magnetic anomaly (SAA). (Earlier, Foster and Rich [1998] had found evidence for prompt midlatitude ionospheric perturbations near the SAA in association with such rapid enhancements of the eastward electric field.) Huang et al. [2005] review the mechanisms associated with the formation of positive-phase ionospheric disturbances and examine in detail one such localized enhancement using radar and GPS data. Both this and a similar midlatitude study by Buonsanto and Foster [1993] found for the cases examined that midlatitude positive-phase enhancements in the Atlantic sector could not be explained by plasma uplift driven by stormtime neutral winds, but were associated with plasma redistribution from lower latitudes by disturbance electric fields. Yin et al. [2004] combined GPS tomography with long-range Millstone Hill radar observations inside L = 2 during the July 15, 2000 storm and found that the large TEC enhancement at the base of that event’s erosion plume was associated with thermal plasma flowing down field lines to enhance the F-region ionosphere and TEC in the PBL. These studies indicate that an enhancement of the equatorial ion fountain, and the formation of widespread equatorial TEC anomalies, frequently occurs in this longitude sector, and that a poleward redistribution of low-latitude ionospheric plasma constitutes the source for the intense erosion plumes reported in the recent literature.

4. Observations

[7] The October 29–31, 2003 superstorm produced ionospheric disturbances over the continental US of record proportion. The magnitude and spatial extent of the TEC enhancements both within the SED and in its lower-latitude source region were very large (the July 15, 2000 storm also produced >250 TECu in the SED source region). TEC gradients along the poleward edge of the SED region in the dusk sector were severe [cf. Yo and Foster, 2001]. For such recent storms, the expanding network of GPS TEC receivers in the US sector provides a detailed picture of the evolution and extent of the ionospheric disturbances, and the above-referenced studies using ground-based and satellite observations describe a framework within which to characterize and understand these extreme events.

[8] The satellites of the GPS constellation are in 12-hr circular orbits (~20,000-km altitude) with orbital inclination ~55 deg, giving coverage to L ~ 4. The vertical TEC presented here is the combined contribution of the ionosphere and overlying plasmasphere. For the severe disturbance event of October 30, 2003, we have determined 2-D maps of vertical TEC from a closely-spaced network of ~450 North American GPS sites [Coster et al., 2003]. Figure 1 presents a map of log TEC in magnetic coordinates showing a region of dense TEC over the central US in which TEC exceeds 200 TECu (1 TECu = 1.E16 electrons/m², column density). In preparing the TEC maps, 10-min of GPS observations have been binned into 2 × 3-deg latitude/longitude bins (invariant latitude is used and the vertical TEC is calculated assuming a 350-km altitude ionospheric penetration point). The broad plume of TEC streaming poleward through central Canada is an intense region of SED being carried through the noontime cusp and into polar cap latitudes. At this time the noon meridian is in central Canada. Although we have no radar or satellite observations of the streaming plasma motion coincident with the image of Figure 1, we present below DMSP observations over the north Atlantic of the intense SAPS convection channel which drives this broad SED plume. Past studies [e.g., Foster et al., 2004] have shown that the poleward/eastern border of the SED plume lies in the overlap region of the SAPS with the PBL. In addition to the SED at higher
latitudes, enhanced TEC is found equatorward of the PBL on field lines mapping to the outer plasmasphere (e.g. over Texas). The relationship of the GPS TEC enhancements seen over the central US to enhancements in mass loading on plasmaspheric field lines is investigated by Chi et al. [2005].

[9] In Figure 2 we display a similar map for 22:15 UT, when the region of enhanced TEC equatorward of the PBL had further intensified, reaching values in excess of 250 TECu equatorward of L = 2 over the SW USA. The position of the SED plume has shifted to the west as the continental US rotated eastward under the magnetospherically-driven SAPS-erosion features. The intense TEC erosion plume extended into the Pacific northwest, and a steep TEC gradient formed across the eastern (later local time) edge of the enhanced TEC region (see discussion, below) marking the approximate extent of the plasmasphere boundary layer.

5. Discussion

[10] The papers referenced above describe the enhanced TEC in the SED plumes as signatures of the erosion of the dusk-sector plasmasphere and low-latitude ionosphere by strong inner-magnetospheric SAPS (sub auroral polarization stream) electric fields [Foster and Burke, 2002]. In Figure 3 we present DMSP F13 dusk-sector observations near the time of the TEC observations shown in Figure 1 along a track which carried it through intense SAPS convection (westward ion drift velocity > 2500 m/s) near 45 deg magnetic latitude over the north Atlantic, just beyond the eastern extent of the GPS TEC coverage of Figure 1. In situ plasma density (at ~845 km altitude) is shown in Figure 3 (top). The lower-latitude portion of the SAPS channel (~800 m/s westward convection from 35–45 deg maglat, seen on this pass from 19:47 UT–19:50 UT) overlaps the higher densities of the outer plasmasphere, carrying this plasma westward into the plume seen streaming into Canada in Figure 1. In the center of the polar cap over Greenland (sampled by F13 at 20:00 UT–20:03 UT) the satellite intersects the anti-sunward streaming polar tongue of ionization. The studies of Foster [1989, 1993] suggest that the SED plumes streaming from lower latitude into the cusp ionosphere are the source of such polar tongues of ionization (TOI). A detailed study of the November 20, 2003 storm (J. C. Foster et al., Multi-radar observations of the polar tongue of ionization, submitted to Journal of Geophysical Research, 2004b) using combined GPS imagery, incoherent scatter radar, DMSP, and SuperDARN observations confirm the temporal/spatial continuity of the SED plumes arising from the PBL on the dayside and the anti-sunward streaming TOI which span polar latitudes from noon to midnight.

Figure 3. DMSP F13 flew poleward over the N Atlantic and across the polar cap over Greenland at the time of the TEC map of Figure 1. Strong SAPS convection (>2500 m/s) was observed at ~19:50 UT. The overlap of enhanced SAPS convection with the outer PBL (seen here from 19:47 UT–19:50 UT) leads to the formation of the SED plume apparent in Figure 1 (see text).

Figure 4. Vertical TEC at 43 deg invariant latitude is plotted as a function of geographic longitude and Universal Time for the extent of the October 30/31, 2003 event. White lines display the variation of local time, and indicate that the TEC enhancements are confined to the post-noon sector. TEC rises equatorward of L = 2 across the continental US early in the event (18 UT–20 UT), and then increases to values in excess of 250 TECu at 245 E longitude by 22 UT.
is observed equatorward of the PBL gradients, on field lines mapping into the outer plasmasphere. This represents a ~10X enhancement in TEC over undisturbed conditions. The steep decrease in TEC with latitude across the PBL extends over ~3 deg of latitude with a characteristic gradient of ~60 TECu per deg of latitude.

[13] Very similar characteristics to those presented here were observed during the preceding storm on Oct. 29/30, 2003, and the characteristics of these extreme events as described here are seen to a lesser degree and amplitude in disturbance events of lesser magnitude reported in the literature. The ionospheric effects seen during the October 2003 superstorms were intense, but not unusual.

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