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[1] 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.

1. Introduction

[2] Boundary layers tend to form at the interfaces between plasmas that have distinctly different properties. The plasmapause is a site of geophysically important interactions between the plasmas of the hot plasma sheet and of the cool plasmasphere which involve significant wave-particle energy exchange, cross-boundary energy transfer, and particle precipitation. *Carpenter and Lemaire* [2004] have termed this region the plasmasphere boundary layer (PBL).

[3] The midlatitude ionosphere and overlying plasmasphere are known to respond in dramatic fashion to the electric fields associated with both moderate and severe magnetospheric disturbances. Across mid and low latitudes, ionospheric storms exhibit both a positive and a negative phase [e.g., *Buonsanto*, 1999]. The poleward extent of this region, the PBL, suffers severe erosion creating a sharp density gradient at the plasmapause, while a deep ionospheric total-density trough forms in association with the strengthening of the subauroral polarization stream (SAPS) electric field [*Foster and Burke*, 2002; *Foster and Vo*, 2002]. In this paper we address the large-scale enhancements of total electron content (TEC) which formed over the continental USA both inside and outside the PBL during the October 30/31, 2003 superstorm. We show that the intense erosion plume of storm-enhanced density (SED) is associated with a TEC increase in the outer plasmasphere, the source population for the SED material.

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2. Storm Enhanced Density: A Feature of the PBL

[4] 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.

[5] *Vo and Foster* [2001] examined a 20-year dataset of Millstone Hill radar observations of the midlatitude ionosphere to characterize the occurrence of spatial gradients in ionospheric total electron content (TEC) associated with the trough and other phenomena. They found that the steepest gradients occur in an environment of high TEC (solar max and adjacent to regions of storm- enhanced density, SED). Highest gradient values were found in the sunlit post-noon ionosphere. The most severe gradients identified in that statistical study were associated with the occurrence of SED and these resulted in TEC > 100 TECu over New England and TEC gradients of ~50 TEC/deg latitude.

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

[6] 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.

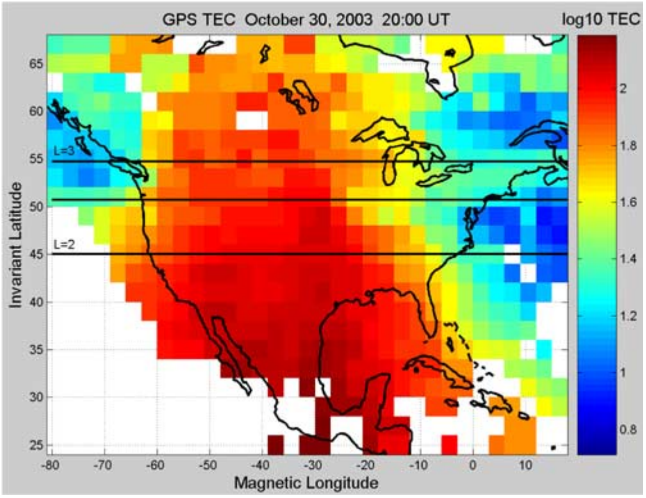

Figure 1. TEC derived from an array of ∼450 GPS receivers is displayed in magnetic coordinates as a major ionospheric disturbance forms over the US mainland during the October 30, 2003 superstorm. A broad plume of storm enhanced density streams poleward through central Canada from a source of elevated TEC below L = 2. At 20:00 UT, local noon lies near the central meridian of the figure.

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. *Vo 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/m^2, 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

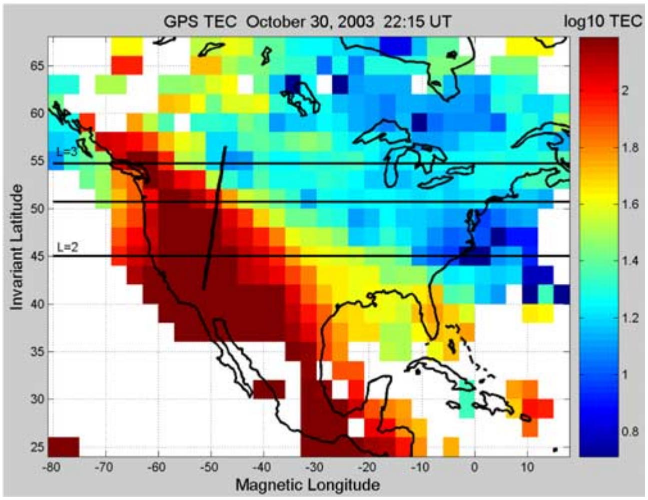

Figure 2. The evolution of the enhancements of TEC over the US mainland at 22:15 UT is displayed, following the format of Figure 1. The SED plume extends into the Pacific NW, TEC exceeds 250 TECu over the US southwest equatorward of L = 2 and the steep gradient region associated with the PBL (see text).

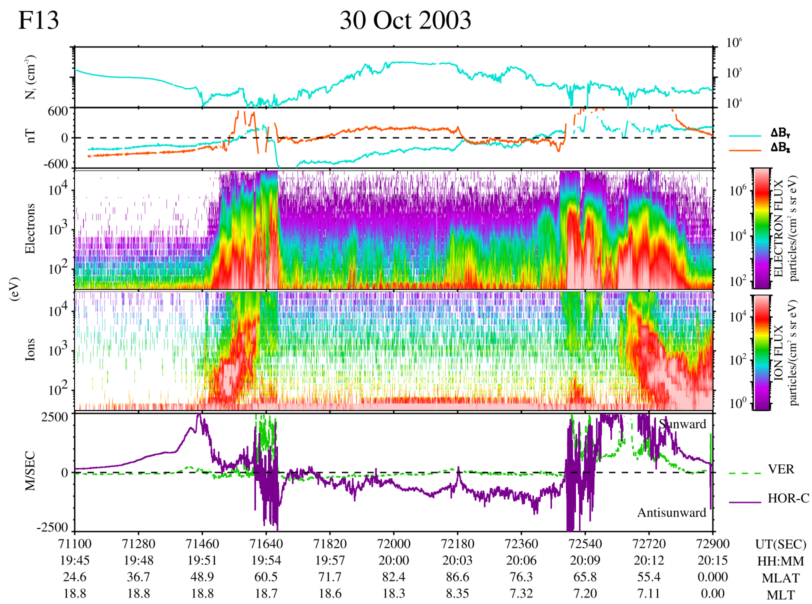

Figure 3. DMSP F13 flew poleward over the N Atlantic and across the polar cap over Greenland at the time of the TEC map of Figure 1. Strong SAPS convection (>2500 m/s) was observed at ~19:50 UT. The overlap of enhanced SAPS convection with the outer PBL (seen here from 19:47 UT–19:50 UT) leads to the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

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.

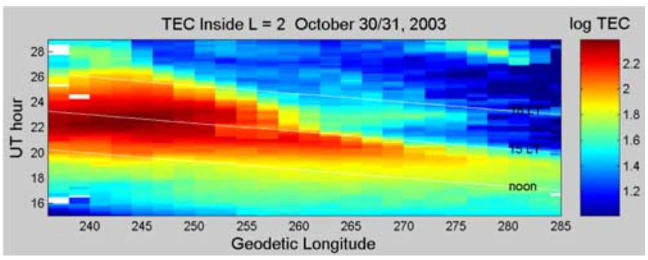

Figure 4. Vertical TEC at 43 deg invariant latitude is plotted as a function of geographic longitude and Universal Time for the extent of the October 30/31, 2003 event. White lines display the variation of local time, and indicate that the TEC enhancements are confined to the post-noon sector. TEC rises 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.

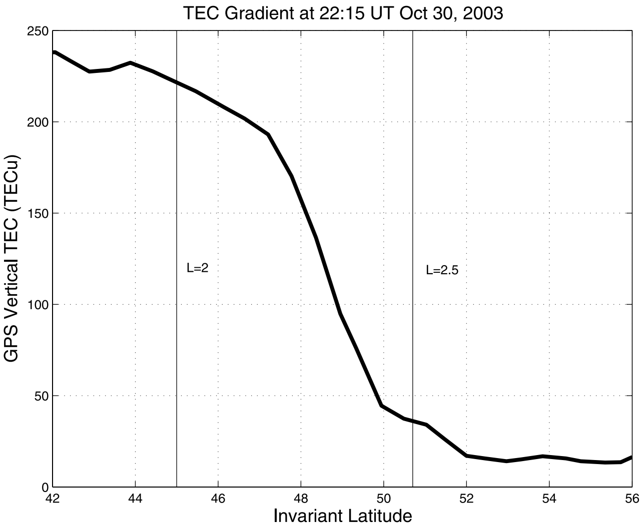

Figure 5. The TEC gradient across the poleward edge of the SED plume shown in Figure 2 is presented. TEC in excess of 230 TECu is observed equatorward of the PBL gradients. The steep decrease in TEC with latitude across the PBL extends over ~3 deg of latitude with a characteristic gradient of −60 TECu per deg of latitude.

[11] Following the method of Foster et al. (submitted manuscript, 2004a), the enhancement of TEC in the outer plasmasphere is investigated in Figure 4. We present vertical TEC at 43 deg invariant latitude, plotted as a function of geographic longitude and Universal Time. White lines indicate the variation of local time with respect to this data display and indicate that the TEC enhancements are confined to the post-noon sector. TEC increases equatorward of L = 2 across the continental US early in the event (18 UT–20 UT; see Figure 1), and then increases to values in excess of 250 TECu at 245 E longitude by 22 UT (see Figure 2). The progression of the trough/SAPS boundary across the US at this latitude is seen as the steep TEC gradient region between 15 LT and 18 LT, and the steepening of the slope of this feature between 21 UT and 01 UT on the 31st indicates an equatorward expansion of the SAPS channel. Dst (not shown) dropped sharply from −100 nT to −350 nT during that interval and TEC increased in the outer plasmasphere, equatorward of the PBL. In agreement with the events reported by Foster et al. (submitted manuscript, 2004a), a rapid increase in TEC inside the PBL, equatorward expansion of the SAPS, and intense SED erosion plumes accompany intervals of sharply decreasing Dst at post-noon local times in the American sector.

[12] Both the polar tongues of ionization and the SED plumes form steep density gradients along their flanks and these gradients can be the source region for cascades of density irregularities and ionospheric scintillations, which present a considerable space weather hazard at mid and high latitudes. We examine the mid latitude TEC gradient across the poleward edge of the SED plume shown in Figure 2 (along the thick line which traverses the plume from L = 2 to L = 3 near −50 deg magnetic longitude). Indications are that the plasmapause and the outer extent of the PBL lie at or inside L = 2 at this time. The variation of TEC across this region is presented in Figure 5. TEC in excess of 230 TECu 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 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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