Dayside global ionospheric response to the major interplanetary events of October 29–30, 2003 “Halloween Storms”

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1. Introduction

[1] We demonstrate extreme ionospheric response to the large interplanetary electric fields during the “Halloween” storms that occurred on October 29 and 30, 2003. Within a few (2–5) hours of the time when the enhanced interplanetary electric field impinged on the magnetopause, dayside total electron content increases of ~40% and ~250% are observed for the October 29 and 30 events, respectively. During the Oct 30 event, ~900% increases in electron content above the CHAMP satellite (~400 km altitude) were observed at mid-latitudes (~±30° degrees geomagnetic). The geomagnetic storm-time phenomenon of prompt penetration electric fields is a possible contributing cause of these electron content increases, producing dayside ionospheric uplift combined with equatorial plasma diffusion along magnetic field lines to higher latitudes, creating a “daytime super-fountain” effect. Citation: Mannucci, A. J., B. T. Tsurutani, B. A. Iijima, A. Komjathy, A. Saito, W. D. Gonzalez, F. L. Guarnieri, J. U. Kozyra, and R. Skoug (2005), Dayside global ionospheric response to the major interplanetary events of October 29–30, 2003 “Halloween Storms,” Geophys. Res. Lett., 32, L12S02, doi:10.1029/2004GL021467.

2. Observations

[4] Figure 1 shows data associated with two interplanetary coronal mass ejections (ICMEs) plus their associated shocks that were detected by the ACE spacecraft upstream of the Earth on October 29 and 30, 2003, including proton speed, temperature, density, and magnetic fields from ACE, and Dst index values. The ICMEs causing the magnetic storms were related to X-class solar flares that occurred on October 28 and October 29, 2003 [see Tsurutani et al., 2005].

[5] The first geomagnetic storm of interest is associated with an abrupt Dst decrease at ~1400 UT on October 29. Bz initially has a magnitude of +8 nT but continues to turn steadily southward, reaching a value of ~30 nT at 1910 UT. This Bz southward turning, part of a magnetic cloud [Skoug et al., 2004], combined with solar wind velocities in the range 1200–2100 km/sec, causes a geomagnetic storm and peak Dst excursion of ~350 nT recorded at 0125 UT on October 30. The shock of a second ICME occurs at ~1650 UT on October 30. The strong southward magnetic field at and just after the shock causes another geomagnetic storm that commences at 1845 UT (during the recovery phase of the previous storm). This last storm is the most intense, with peak Dst of ~390 nT at 2315 UT on October 30.

[6] The main topic of this paper are these Bz southward events followed by unusually large daytime ionospheric responses as measured by ionospheric total electron content (TEC) data obtained from Global Positioning System (GPS) receivers. Using techniques mentioned extensively in the literature [Mannucci et al., 1998, 1999] a dual-frequency GPS receiver can measure the total electron content of the ionosphere/plasmasphere system between the receiver and satellite, with high precision (0.01 TECU is typical, 1 TECU = 1016 el/m2) and reasonable accuracy (~1–3 TECU).

[7] Vertical TEC data derived from a global network of ~100 GPS receivers are plotted in Figure 2 for several days leading up to and through the geomagnetic storm periods of October 29–30, 2003. An obliquity function is used to estimate the vertical TEC from the slant TEC measurements obtained above 10 degrees elevation angle: we assume that
the ionosphere occupies a spherical slab of uniform vertical electron density between 450 and 650 km altitude. The latitude and longitude at which the ground-to-satellite line-of-sight intersects the ionosphere is computed using a spherical shell at 450 km altitude.

[8] The TEC measurements in the local time range 1400–1600 LT and magnetic latitude range ±40 degrees (IGRF) [Richmond, 1995] were averaged every 30-minutes of Universal Time (UT), to examine TEC behavior at low to middle latitudes. The resultant time series of average vertical TEC versus UT is plotted along with the computed interplanetary electric field (IEF), derived from the product $V_x \times B_z$ (GSM coordinates) measured by the plasma and magnetic field instruments onboard the ACE spacecraft [Skoug et al., 2004]. The IEF data is offset by the propagation time from ACE to the magnetospheric bow shock and is only plotted for values where the product $V_x \times B_z$ is positive.

[9] Also plotted in magenta in Figure 2 is the average TEC plus its standard deviation, computed from the scatter of all vertical TEC data contributing to the average value. The observed TEC increases of ∼50%–250% (after the larger IEF increase) are much larger than the day-to-day variability observed prior to the IEF increases. The number of points contributing to the averages ranged from 50 to 600, depending on UT, as the number of sites within the relevant local time varied.

[10] Variability of TEC with time shown in Figure 2 is likely due to two factors: variability of the ionosphere itself, and the fact that the GPS receiver distribution varies with longitude. Even if the ionospheric TEC were not changing, the latitude sampling of the receivers used to compute the average is changing with UT, thereby changing the locations at which TEC is measured. Ionospheric features that exhibit latitudinal structure will change the average as a function of time. Despite these sources of uncertainty, a strong correlation is observed between enhanced TEC and $B_z$ south (enhanced interplanetary electric field), which is clearly distinguished from the preceding quiet-time data. The local time/latitude range used to compute the average was chosen to emphasize effects within a broad daytime, low latitude region.

[11] Daytime observations of the TEC above the CHAMP satellite altitude of 400 km on October 30 were available from the upward-viewing GPS antenna, plotted in Figure 3. Slant measurements obtained above 40 degrees elevation are scaled to estimate vertical TEC above the satellite altitude, using a geometric factor derived by assuming the plasma occupies a spherical shell ionosphere of uniform density and 700 km thickness above the CHAMP altitude. There...
The twin peak features previously identified 1.5 hours later (black markers, second pass after southward Bz event at 1900 UT. Inspection begins approximately 1.25 hours after the onset of the IMF southward-Bz event at 2012 UT, measures a vastly increased TEC above CHAMP, and the ionospheric TEC above CHAMP altitudes has increased by an order of magnitude (900%) at mid-latitudes (~30° geomagnetic). Part of the difference between this pass and the previous one may be due to longitudinal TEC gradients, which have begun to build up on the North American west coast, according to ground-based TEC (not shown).

We have plotted selected vertical TEC from ground-based GPS receivers in North America (red and blue dots at 38 and 39 degrees geomagnetic latitude), for measurements located within ±6 minutes and within ±3 degrees longitude of the CHAMP ground track location at the latitude shown. Prior to the interplanetary event (blue dots), the integrated electron content above CHAMP comprises a smaller fraction of the TEC compared to after the interplanetary event (red dots), reinforcing the conclusion that plasma uplift has occurred.

3. Interpretation and Discussion

Figure 2 suggests a strong correlation between increased IEF and significant dayside increases in TEC (positive ionospheric storm). A large IEF event that occurred in November of 2001 was studied by Tsurutani et al. [2004], where analysis of multiple data sets led to the conclusion that prompt penetration electric fields contributed to the TEC increase and uplift. Another source of storm-time electric fields at equatorial latitudes is from the thermospheric disturbance dynamo [Blanc and Richmond, 1980], but, as discussed by Richmond and Lu [2000], such daytime electric fields are generally of opposite sign to those reported here. Prompt penetration electric fields tend to be eastward during daytime before shielding has built up [Nopper and Carovillano, 1978]. A daytime eastward electric field raises low latitude plasma upward due to E × B drift, so that more plasma resides at higher altitudes where recombination rates decrease, while additional plasma continues to be generated by solar illumination, resulting in a net increase of electrons above 400 km, consistent with the CHAMP data. We refer to this large TEC enhancement as the “daytime super-fountain effect” associated with magnetic storms, described further by Tsurutani et al. [2004]. Tanaka and Ohtaka [1996] describe a dusk “super-fountain” associated with prompt penetration electric fields that applies to that local time range. High-altitude plasma can take hours to recombine, so we cannot infer from our data the duration of the penetrating electric field. That will require detailed modeling.

To further assess our hypothesis that daytime eastward electric fields contribute to the large TEC increases, we used data from the DMSP satellite (F13) at 1745 local time, which shows evidence of enhanced electric fields between geomagnetic latitudes of ~10 and 10 degrees. The drift velocity at DMSP altitude (840 km) is predominantly negative during the days October 25–30 2003, except for three distinct periods when the drift velocity becomes significantly upward (>70 m/sec): October 29 at 0616 UT and at 1951–2313 UT; and during October 30 1941–2118 UT. The times of these large vertical drift velocities correspond to the periods of southward Bz shown in Figure 1.
The uplifted heavy ions (O$_2^+$, NO$^+$) will diffuse down the neutral wind system at the equatorial region. Secondly, neutral drag will be substantially reduced and will change the reduction of plasma density at 800 km or more, two prominent effects may occur. With assuming an average of 200 TECU (2 ionospheric/atmospheric effects. Following Figure 3 and their useful suggestions. One of the authors (AJM) wishes to thank the anonymous referees for Dallas and the US Air Force for making available the DMSP drift velocity data. We thank the ACE SWEPAM instrument team and under the auspices of the U. S. Department of Energy with support from the NASA ACE program. We thank the ACE SWEPAM instrument team and performed at the Jet Propulsion Laboratory, California Institute of Tech-

4. Conclusions

The dramatic TEC increase due to plasma uplift during geomagnetic storms is one of the most dramatic consequences of magnetosphere-thermosphere-ionosphere coupling. Transport of plasma poleward, and possibly uplift at mid-latitudes, causes major mid-latitude plasma increases that may contribute to the extreme TEC gradients at mid-latitudes that have been reported as part of TEC plumes associated with subauroral electric fields [e.g., Foster et al., 2002]. If prompt penetration electric fields are playing a role, a better understanding of magnetosphere-ionosphere coupling, including the role of shielding, will clarify our understanding of extreme space weather events over a wide range of latitudes.

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