The Dayside Ionospheric "Superfountain" (DIS), plasma transport and other consequences

B. T. Tsurutani[1], A. Saito[2], O. P. Verkhoglyadova[3], A. J. Mannucci[1], M. A. Abdu[4], T. Araki[2], W. D. Gonzalez[4], B. A. Iijima[1], G. S. Lakhina[5], H. McCreadie[2], J. H. A. Sobral[4], T. Tsuda[2], K. Yumoto[6] and V. M. Vasyliunas[7]

[1]Jet Propulsion Laboratory, Calif. Inst. Tech., Pasadena, CA
[2]Kyoto University, Kyoto, JP
[3]University of California, Riverside, CA
[4]INPE, Sao Jose dos Campos, SP, Brazil
[5]Indian Institute of Geomagnetism, Mumbai, India
[6]Kyushu University, Fukuoka, Japan
[7]Max Planck Institute for Solar System Research, Lindau, Germany

Abstract. Prompt penetration electric fields (PPEFs) and the consequential dayside ionospheric superfountain (DIS) are reviewed. An example of O^+ uplift to ~840 km altitude at ~0940 local time (DMSP F15) during the superstorm of 30 October 2003 is illustrated. The SAMI-2 model is modified to incorporate intense superstorm electric fields. With an inclusion of a ~4 mV/m eastward electric field, SAMI-2* modeling results show many of the expected DIS effects.

Index Terms. Dayside ionospheric superfountain effects, ionospheric storms**,** magnetic storms, prompt penetration electric fields**.**

1. Results

It has been known for some time that short duration (~15 to 30 min) interplanetary/ polar cap electric fields can "promptly penetrate" to the equatorial and near-equatorial ionosphere (Nishida, 1968; Sastri et al., 2000; Kelley et al., 2003). More recently, it has been shown that very intense electric fields can propagate to the ionosphere and remain unshielded for ~2 hours (Tsurutani et al., 2004, 2006; Mannucci et al., 2005a,b,c) or possibly even longer (Huang et al., 2005).

The evidence for the presence of these long-duration unshielded electric fields at and in the dayside ionosphere is manifold. The following phenomena have been noted to occur during intense dawn-to-dusk interplanetary electric field (IEF) events: 1) enhanced global dayside ionospheric total electron content (TEC) (Tsurutani et al., 2004; Mannucci et al., 2005a,b,c); 2) ionospheric uplift to altitudes at and above polar orbiting satellites (Tsurutani et al., 2004; Mannucci et al., 2005a); 3) oxygen ion uplift to DMSP satellite altitudes (~840 km) (Saito et al. 2006); 4) displacement of the normal Appleton anomaly location (± 10° at satellite altitudes) poleward to as high as ± 30° magnetic latitudes (Mannucci et al., 2005a,b); 5) enhanced middle latitude ionospheric TEC values to ~400% above normal values (Tsurutani et al., 2006); 6) a strongly enhanced Equatorial Electrojet (EEJ) current (McCreadie et al., 2006).

All of the above phenomena have been observed during intense dawn-to-dusk interplanetary electric field events. These events occurred within fast interplanetary coronal mass ejection (ICME) events or their upstream sheaths. The electric fields are due to southward interplanetary magnetic fields which have been convected past the magnetosphere by the solar wind (the electric fields are due to the motional emf). The southward magnetic fields lead to magnetic reconnection between the interplanetary field and the Earth's magnetopause fields (Dungey, 1961), causing intense magnetic storms (Gonzalez et al., 1994). It is believed that the magnetospheric manifestations of the magnetic storm and the near-equatorial ionospheric phenomena are independent of each other, but both are caused by the intense interplanetary electric field/southward IMF $B_{Z.}$

In our estimation, the above six ionospheric phenomena can only be explained by the presence of eastward electric fields in the equatorial and near-equatorial ionosphere. The presence of these fields implies that there is **E** x **B** upward convection of equatorial and near-equatorial ionospheric plasma. This can explain items 2 and 3. When the dayside ionospheric plasma is uplifted, the recombination rates of this plasma will be reduced substantially (Tsurutani et al., 2005). Recombination will occur much more slowly than under the original conditions. Solar photoionization will regenerate a new ionosphere at lower altitudes. This will lead to an overall TEC enhancement, explaining item 1. With plasma transport to higher altitudes, gravitational forces will bring the plasma down the lines of magnetic force. This plasma will move to higher absolute magnetic latitudes, explaining item 4. Item 6 is a direct observation of the presence of

---

enhanced dawn-to-dusk electric fields in the ionospheric E-region above the dip equator. Anderson et al. (2004) have demonstrated that there is a one-to-one correspondence between E-region electric fields and F-region ionospheric uplift (the latter from incoherent radar measurements), e.g., the ionospheric electric fields are present in both the E- and F-regions simultaneously. Enhancements of middle latitude TEC values (item 5), are due to the combination of equatorial and near-equatorial uplift, creation of a new ionosphere below, and gravitational downdraft of the uplifted plasma. Schematics for the **E x B** convective uplifts and the gravitational downward flow to higher absolute magnetic latitudes were given in Figs. 11, 12 and 13 of Tsurutani et al. (2004). Due to space limitations, these figures will not be reproduced here.

It should be noted that we have been discussing the dayside equatorial and near-equatorial ionospheric effects of PPEFs. Eastward electric fields will cause vertically upward drift of the equatorial plasma. For slightly off-equatorial plasma, the **E** x **B** drift will be slightly poleward in addition to the vertical drift. This former effect will aid in plasma transport to higher magnetic latitudes.

In the night, dawn, and dusk regions of the ionosphere, there may be some possible confusion/ambiguity between prompt penetration electric field effects and disturbance dynamo effects. The propagation of winds associated with the disturbance dynamo takes a few hours to go from the auroral zones to the equator (Fuller-Rowell et al., 1997; 2002). Thus many of the above authors have been careful to limit their conclusions of ionospheric effects due to PPEFs to within ~2 hrs of initial penetration. It should be noted that disturbance dynamos associated with nightside auroral heating will take even longer to propagate to the dayside noon equatorial region. In fact computer simulation results (Lin et al. 2005) indicate that damping associated with high dayside conductivity, and ion-neutral drag significantly reducing the winds, may remove noon-time disturbance dynamo effects altogether.

The focus of this paper will be to discuss the effects of PPEFs in the local dayside equatorial and near-equatorial ionosphere within two hours of the impingement of an intense dawn-to-dusk IEF. By focusing on this limited region of the ionosphere, the PPEF effects will clearly be isolated from other possible phenomena.

A. Some consequences of the superfountain effect

Fig. 1 is taken from Saito et al. (2006). The data are taken from the SSIES ion instrument on the DMSP F15 satellite. The satellite was at an altitude of ~840 km and crossed the magnetic equator at ~0940 local time. The satellite location is indicated at the bottom of each of the two panels. Both panels contain data taken on the day of the superstorm of October 30, 2003. The associated solar flare occurred on October 29, one day prior to the ICME reaching the Earth. For more information on the flare, see Tsurutani et al. (2005), and for the ICME, see Mannucci et al. (2005a).

The solar wind propagation time from ACE to the magnetosphere (~30 min) is taken into account (the solar wind data [Skoug et al., 2004; Mannucci et al., 2005a] is not shown for brevity). The electric field first impinged upon the magnetosphere at ~1630 UT and reach its maximum intensity at ~2030 UT. It should be noted that for this IEF event, the field B_Z component was first oscillatory and then decreased steadily with time until the maximum value was reached. The B_Z component then increased steadily until ~0030 UT 31 October (Mannucci et al., 2005a).

The top of Fig. 1 displays the ion data for a pass from 1750 to 1820 UT and on the bottom is a pass from 1930 UT to 2000 UT. The equatorial crossings were at ~1803 UT and ~1945 UT, respectively. The first crossing occurred after the IEF had impinged onto the magnetosphere. Very little is noted in this panel. A possible explanation is that the ionosphere was being lifted up, but had not reached the extreme height of the DMSP satellite yet. In the bottom panel, a clear signature of enhanced ions is observed. Peak densities of ~9 x 10^5 cm^{-3} are noted. The two Appleton anomaly maxima can be found at ~ ±10°. It appears as if the entire ionosphere has been lifted up to ~840 km altitude.

The $O^+/(O^+ + H^+)$ density ratio is also noted at the bottom of each panel. For the ~1803 UT equatorial crossing, O^+ ions constituted ~94% of the ions detected. In the ~1945 UT crossing, O^+ represented 99% of all ions detected.

We perform simulations of evolving density distributions over latitude and altitude along magnetic field lines using a modification of the SAMI-2 ionospheric model (Huba et al. 2000). The original code includes a choice of two electric fields: a sinusoidal diurnal variation with local time (hereafter called the “sine” or background SAMI- 2 model) and the Fejer and Scherliess (1997; 1999) empirical model. The SAMI-2 model uses the middle latitude Ap indices and the Fejer-Scherliess model is based on the auroral electrojet (AE) indices. These electric field models proved to be useful for describing the ionosphere during quiet times or relatively low disturbance (substorm) intervals. We have chosen to use the quiet-time sine electric field model. The electric field is zero at 7 am and has a peak positive amplitude of 0.53 mV/m at 1 pm local time.

The effects associated with an intense superstorm electric field cannot be estimated using an empirical model with moderate (or extreme) values of Ap. A new model based on the ring current SYM-H index or a model of the fractional penetration of the polar cap electric field to low latitudes needs to be constructed. However neither of these models is currently available.

In order to study the dayside ionosphere during superstorm events, we introduce an additional block into the SAMI-2 code, which prescribes contribution of a storm-time PPEF (we call this the SAMI-2* code for short). We use the storm-time electric field value which was determined from the CHAMP magnetic perturbations (see McCreadie et al, 2006 for further details). We introduce a step-like electric field starting at 700 am (corresponding to 1700 UT) with a value of 4.0 mV/m.

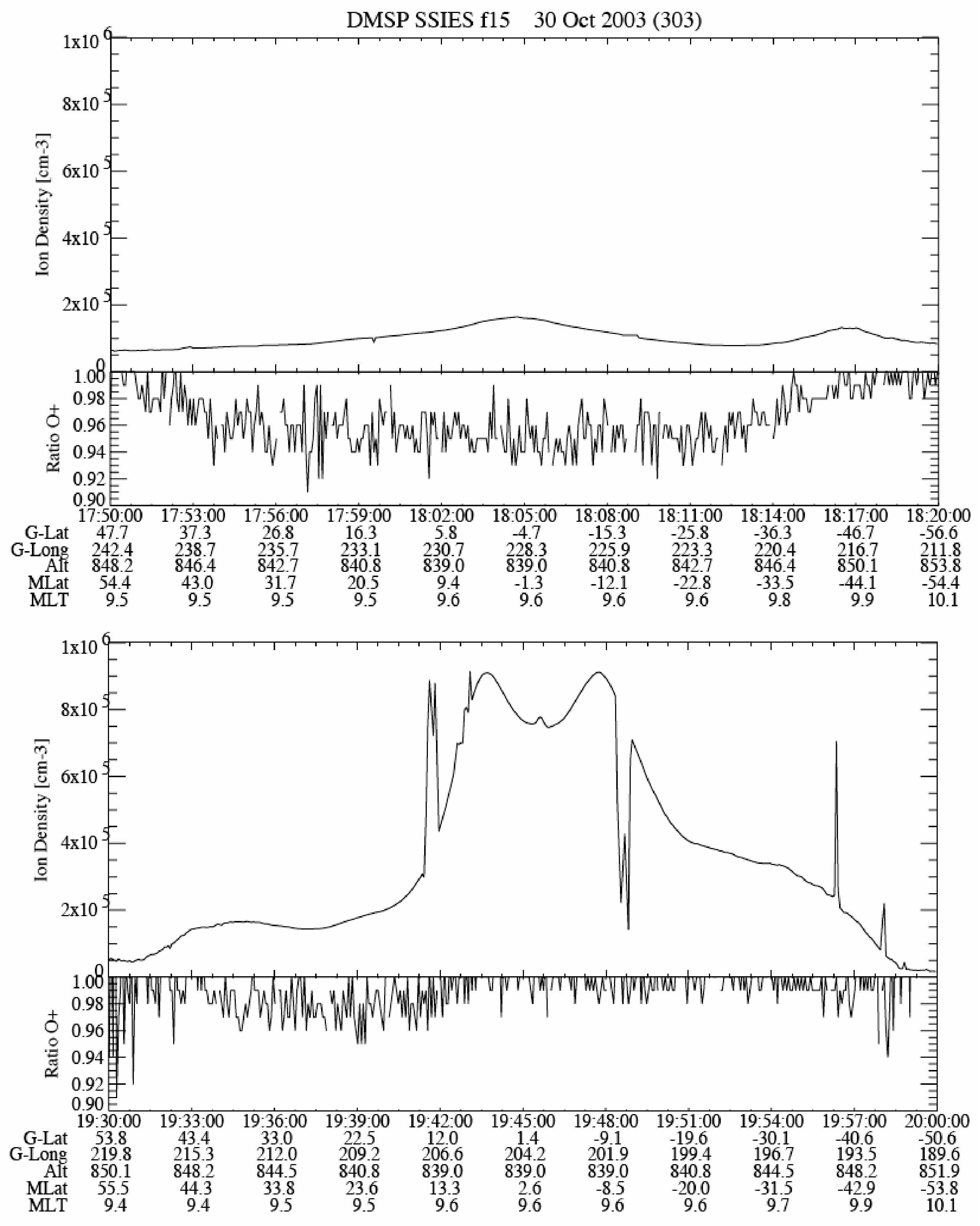

Fig. 1. O^+ ion densities and the $O^+/(O^+ + H^+)$ ion density ratios. These in situ measurements were taken by the DMSP F15 satellite (~ 840 km altitude) during the superstorm of 30 October 2003. The top panel shows an interval of time just after the impingement of the IEF. The bottom panel shows the densities and density ratios later during the IEF event.

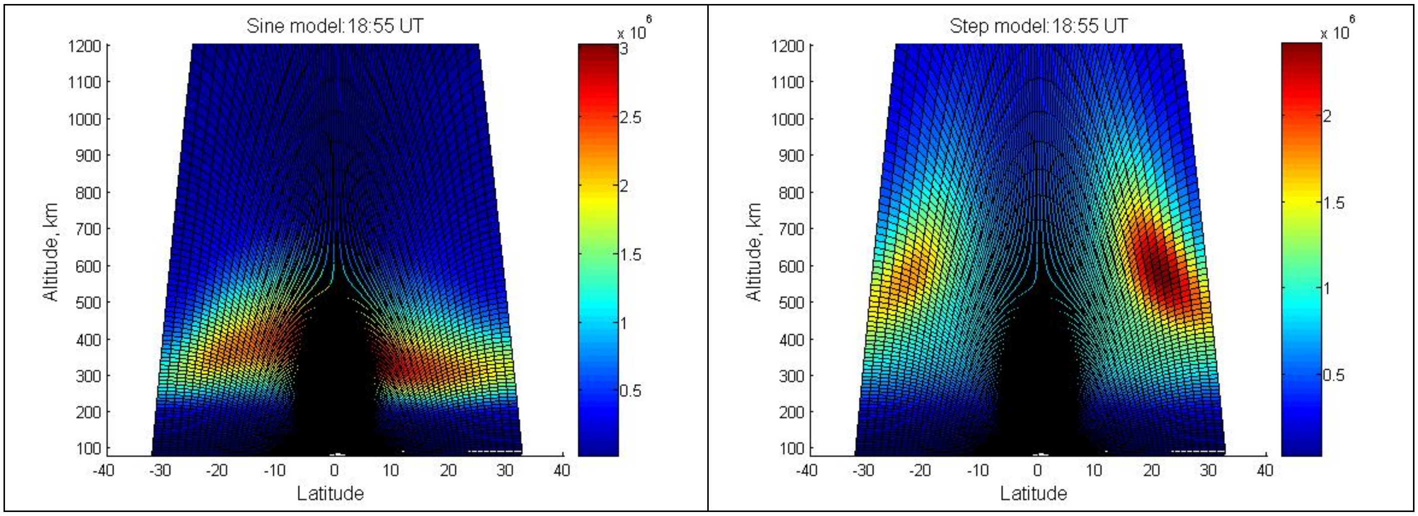

Fig. 2. Results of electron density modeling for the event shown in Fig.1 using the SAMI- 2* code. The panel on the left shows the quiet time background densities (cm^{-3}) versus altitude and latitude. The right-panel shows the ionospheric effects when the PPEF is imposed.

Our simulations are performed for the low-latitude region within ±35° latitude of the magnetic equator. The dynamics of electrons and 7 ion species are modeled on 30 magnetic field lines (separated by ~1° in latitude), extending from 85 km to 3000 km in altitude. Field-aligned transport and cross-field drifts are computed as described in Huba et al. (2000). Neutral winds are included in the simulation.

Fig. 2 shows some preliminary results for the ionospheric electron densities for sine electric fields alone (left panel) and for the sine electric fields plus the superposed 4 mV/m PPEF (right panel). The time for both panels is 1855 UT or 08:55 local time. Note that the plasma is uplifted to much higher altitudes by the PPEF and that significant plasma exists at ± 30°. There is now an absence of plasma at the normal location of the Appleton anomalies, ~ +10° and ~ -10°. This is clearly due to the equatorial uplift and the gravitational downdraft of plasma to higher latitudes, as prescribed in the superfountain model.

There is clearly much more modeling and experimental work that needs to be done. The change in the $O^+/(O^+ + H^+)$ density ratio at DMSP altitudes will be examined as a function of time using a more exact ionospheric electric field intensity-time profile. The ~1 pm CHAMP TEC features shown in Mannucci et al. (2005a) for the same superstorm will be studied to determine if the SAMI-2* model can replicate the observations or not. Predictions of middle latitude "inverted ionospheres" and the creation of a local dayside equatorial disturbance dynamo (Tsurutani et al., 2006) will be studied by both modeling and observations. Fine scale dynamics of plasma flows during the uplifts are also important and will be modeled as well. Finally, the possibility of uplift of atmospheric neutrals due to ion-neutral drag will be investigated. We will be providing answers to these questions in subsequent publications.

Acknowledgments. Portions of this research were performed at the Jet Propulsion Laboratory, California Institute of Technology under contract with NASA. The SAMI-2 code was developed by the Naval Research Laboratory, Wash. D.C. We appreciate their having made this program available for public use. GSL thanks CSIR, Gov. of India, for support under the Emeritus Scientist Program.

References

D. N. Anderson, A. Anghel, J. Chau and O. Veliz, "Daytime vertical E x B velocities inferred from ground based magnetometer observations at low latitudes", *Space Weather,* vol. 2, S11001, doi:10.1029/2004SW00095, 2004.

J. W. Dungey, "Interplanetary magnetic field and the auroral zones", *Phys. Rev. Lett.*, vol. 6, p. 47, 1961.

B. G. Fejer and L. Scherliess, "Empirical model of storm time equatorial zonal electric fields", *J. Geophys. Res.*, vol. 102, p. 24047, 1997.

B. G. Fejer and L. Scherliess, "Radar and satellite global equatorial F region vertical drift model", *J. Geophys. Res.*, vol. 104, p. 6829, 1999.

T. M. Fuller-Rowell, M. V. Codrescu, R. G. Roble and A. D. Richmond, "How does the thermosphere and ionosphere react to a geomagnetic storm?", in *Magnetic Storms*, vol. 98, B. T. Tsurutani, W. D. Gonzalez, Y. Kamide and J. K. Arballo, Eds. AGU., Washington D.C., p. 203, 1997.

T. M. Fuller-Rowell, G. H. Millward, A. D. Richmond and M.V. Codrescu, "Storm-time changes in the upper atmosphere at low latitudes", *J. Atmos. Sol. Terr. Phys.*, vol. 64, p. 1383, 2002.

W. D. Gonzalez, J. A. Joselyn, Y. Kamide, H. W. Kroehl, G. Rostoker, B. T. Tsurutani and V. M. Vasyliunas, "What is a geomagnetic storm?", *J. Geophys. Res.* vol. 99, p. 5771, 1994.

J. D. Huba, G. Joyce and J. A. Fedder, "Sami2 is another models of the ionosphere (SAMI2): A new low- latitude ionosphere model", *J. Geophys. Res,* vol. 105, p. 23035, 2000.

C.-S, Huang, J. C. Foster, L. P. Goncharenko, P. J. Erickson, W. Rideout and A. J. Coster, "A strong positive phase of ionospheric storms observed by the Millstone Hill incoherent scatter radar and global GPS network", *J. Geophys. Res.*, vol. 110, doi:10.1029/2004JA010865, 2005.

M. C. Kelley, J. J. Makela, J. L. Chau and M. J. Nicolls, "Penetration of the solar wind electric field into the magnetosphere/ionosphere system", *Geophys. Res. Lett.*, vol. 30, p. 1158, 2003.

C. H. Lin, A. D. Richmond, R. A. Heelis, G. J. Bailey, G. Lu, H. C. Yeh and S. -Y. Su, "Theoretical study of the low- and midlatitude ionospheric electron density enhancement during October 2003 superstorms: Relative importance of the neutral wind and the electric field", *J. Geophys. Res.*, vol. 110, doi:10.1029/2005JA011304, 2005.

A. J. Mannucci, B. T. Tsurutani, B. A. Iijima, A. Komjathy, A. Saito, W. D. Gonzalez, F. L. Guarnieri, J. U. Kozyra and R. Skoug, "Dayside global ionospheric response to the major interplanetary events of October 29-30, 2003 "Halloween storms" ", *Geophys. Res. Lett.*, vol. 32, doi:10.1029/2004GL021467, 2005a.

A. J. Mannucci, B. T. Tsurutani, B. A. Iijima, W. D. Gonzalez, F. L. Guarnieri and K. Yumoto, "Global dayside ionospheric response to interplanetary electric fields: Plasma uplift and increases in total electron content", in *Multiscale Coupling of Sun-Earth Processes*, A. T. Y. Lui, Y. Kamide and G. Consolini, Eds. Elsevier, New York, 2005b.

A. J. Mannucci, B. T. Tsurutani, B. A. Iijima, A. Komjathy, B. D. Wilson, X. Pi, L. A. Sparks, G. A. Hajj, L. Mandrake, W. D. Gonzalez, J. Kozyra and K. Yumoto, M. Swisdak, J. D. Huba and R. Skoug, "Hemispheric daytime ionospheric response to intense solar wind forcing", in *Inner Magnetsphere Interactions: New Perspectives from Imaging*, J. L. Burch, M. Schulz and H. Spence, Eds. AGU Mongr. Ser.,Washington D.C., vol. 159, 2005c.

H. McCreadie, T. Iyemori, B. Tsurutani, T. Araki, A. Saito and O. Verkhoglyadova, "The 2003 Halloween super-storm geomagnetic response from an equatorial perspective using CHAMP satellite and ground-based magnetic measurements", submitted to *Geophys. Res. Lett*., 2006.

A. Nishida, "Coherence of geomagnetic DP2 fluctuations with interplanetary magnetic variations", *J. Geophys. Res.*, vol. 73, p. 5549. 1968.

A. Saito and T. Araki, "DMSP observation of dayside oxygen ion uplift to ~840 km altitude during the October 30, 2003 magnetic superstorm", submitted to *Geophys. Res. Lett.*, 2006.

J. H. Sastri, N. Jyoti, V. V. Somayajulu, H. Chandra and C. V. Devasia, "Ionospheric storm of early November 1993 in the Indian equatorial region", *J. Geophys. Res.*, vol. 105, p. 18443, 2000.

R. M. Skoug, J. T. Gosling, J. T. Steinberg, D. J. McComas, C. W. Smith, N. F. Ness, Q. Hu and L. F. Burlaga, "Extremely high speed solar wind: October 29-30, 2003", *J. Geophys. Res.*, vol. 109, A09102, doi:10.1029/2004JA010494, 2004.

B. T. Tsurutani, F. L. Guarnieri, T. Fuller-Rowell, A. J. Mannucci, B. Iijima, W. D. Gonzalez, D. L. Judge and P. Gangopadhyay, "Extreme solar EUV flares and ICMEs and resultant extreme ionospheric effects: Comparison of the Halloween 2003 and the Bastille day events", *Radio Sci.,* in press, 2006.

B. T. Tsurutani, D. L. Judge, F. L. Guarnieri, P. Gangopadhyay, A. R. Jones, J. Nuttall, G. A. Zambon, L. Didkovsky, A. J. Mannucci, B. Iijima, R. R. Meier, T. J. Immel, T. N. Woods, S. Prasad, L. Floyd, J. Huba, S.C. Solomon, P. Straus and R. Viereck, "The October 28, 2003 extreme EUV solar flare and resultant extreme ionospheric effects: Comparison to other Halloween events and the Bastille day event", *Geophys. Res. Lett*., vol. 32, 3 L03S09, doi:10.1029/2004GL021475, 2005.

B. T. Tsurutani, A. Mannucci, B. Iijima, M. A. Abdu, J. H. A. Sobral, W. D. Gonzalez, F. Guarnieri, T. Tsuda, A. Saito, K. Yumoto, B. Fejer, T. J. Fuller-Rowell, J. Kozyra, J. C. Foster, A. Coster and V. M. Vasyliunas, "Global dayside ionospheric uplift and enhancement associated with interplanetary electric fields", *J. Geophys. Res.*, vol. 109, A08302, doi:10.1029/2003JA010342, 2004.