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Ionospheric Day to Day Morphology during the storm of 12 August, 2000.

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Abstract. The morphology of ionospheric F-region variability using critical frequency foF2 and hmF2 in American sector has been studied. The ionosonde data for the storm of 12 August, 2000 were analyzed. It was found that the leading single magnetospheric process responsible for both the first and second Dst decrease was the enhancement of the plasma sheet. The observed simultaneous intense depletion of foF2 at all latitudes is as a result of negative storm phases, which tend to form during summer when the higher molecular density contributes to more rapid recombination between electrons and ions. As for the variation with storm intensity, though DfoF2 was found to vary even between two storms of different Dst_{min}, within the same classification of storm intensity, the amplitude of a negative phase, DfoF2 maximum peak showed a distinct upper limit for each intensity category of storms. At mid latitude, the noontime ionospheric storm signatures are concomitantly depleted and intense, while it is insignificant and enhance at the high latitude. The D(hmF2) during the sunrise/post-noon periods is simultaneously increase/decrease, of which, the corresponding foF2 during the sunrise show a progressive decrease. At a low temperature, the electron density decrease was taken to the lower peak height. The increase in D(hmF2) during the SSC is corresponding to the reduction in ionospheric F2 electron density. The diurnal variation provides in D(foF2) for different American sector show that electron density is more intense during the post-sunset than sunrise.

Key words: F- region variability, Critical frequency, Magnetic activity, depletion, enhancement .

Introduction

The Study of the day-to-day variability of ionospheric parameters is of scientific interest in view of the causative mechanism and the result of such study should assist in the application of correction factors or the choice of another prediction capabilities. The study of variability of ionospheric F2 electron density is of practical importance in communication system and navigation control application.

However, Mendillo et al., (1980) reported that geomagnetic activity has the strong ordering influence of electron concentration variation at middle latitudes. Geomagnetic storms and substorms are a way for the magnetosphere to release excess energy. A majority of the magnetospheric energy is transmitted into the upper atmosphere at high latitudes through aurora particle precipitation and ionospheric plasma convection. It is therefore not surprising that the high variability of storms and substorms often cause complex dynamical and chemical disturbances in the ionosphere. The most observed ionospheric variables are the total electron content (TEC) and the increase or decrease of the F layer electron density concentration, which is referred to as a positive or negative storm phase respectively. A strong seasonal dependence is found in storm responses. Negative storm phases tend to form during the summer when the higher molecular density contributes to more rapid recombination between electrons and ions whereas, positive storm phases more frequently form under winter condition (Lu et al., 2001).

This paper is aimed at investigating the probable variability factors during intense geomagnetic storms of 12 August, 2000 and the height at which the large variation occurs. A series of rapid changes take place in the global thermospheric and ionosphere following the onset of geomagnetic storms. High latitude thermosphere gets heated and expands, which causes equatorward neutral winds, surges and TADs (traveling atmospheric disturbances), which all together change the thermospheric composition (Vijaya et al., 2011 and reference therein). The changes in the thermosphere and ionospheric electric fields produce rapid and sometimes dramatic changes in the ionospheric electron density which is called ionospheric storms. The ionospheric electron density (Ne), peak electron density (Nmax) and total electron content (TEC) often increase/decrease very much from their average quiet time levels, which are known as positive/negative ionospheric storms (Vijaya et al., 2011).

Data and Methods of Analysis

The data used consists of OMNI hourly average data; proton temperature, proton density, wind flow speed, and interplanetary magnetic field (IMF) B_z component. The data were obtained from the NSSDCs OMNIweb service (http://nssdc.gsfc.nasa.gov/omniweb). The ionospheric F2 parameter (foF2 and hmF2) data used were obtained from some of the National Geophysical Data

Center's SPIDR (Space Physics Interactive Data Resource) a network of ionosonde stations located in the American sector: Millstone Hill, Gakona, Boulder, Point Arguello, Dyess, Eglin AFB. These stations are listed in Table 1. The present study is concerned with variations in foF2 due to the intense geomagnetic storm of August 12, 2000. However, the F2 region response to geomagnetic storms is most conveniently described in terms of D(foF2), that is the normalized deviations of the critical frequency foF2 from the reference.

$$D(foF2) = \frac{foF2 - (foF2)ave}{(foF2)ave}$$

Hence, the data that were analyzed consists of D(foF2) of respective hourly values of foF2 on August, 11-13, 2000, which represent the initial, main and recovery phases of the storm. The reference for each hour is the average value of foF2 for that hour calculated from the four quiet days in August 17-20, 2000, exceeding the storm. The important criterion for choosing the quiet days is that these days must have no significant geomagnetic activity (i.e. Ap < 26 corresponding to disturbance storm time Dst ≥ -25 (Adeniyi, 1986)) but also there must be an absence of any considerable solar activity (Adekoya et al., 2012).

Similarly, hmF2 due to geomagnetic storm was considered. The term D(hmF2) is the normalized deviations of the critical frequency hmF2 from the reference.

$$D(hmF2) = \frac{hmF2 - (hmF2)ave}{(hmF2)ave}$$

The use of D(foF2) rather than foF2 and D(hmF2) rather than hmF2 provides a first-order correction for temporal, seasonal and solar cycle variations so that geomagnetic storm effects are better identified. It should be noted that in the present analysis of D(foF2) variations, positive and negative ionospheric storms are defined by changes in amplitude (the maximum absolute value of D(foF2) of more than 10% and changes of D(foF2) of 20% are regarded as intense or large (Danilov, 2001).

Result and Discussion

Interplanetary and Geomagnetic Observations

Fig. 1 shows the composition of the interplanetary and geomagnetic parameter of solar wind plasma for the period of August 10-14, 2000, representing the plot covering two days before and two days after the storm. Attention will be focused on an event that occurs between Aug. 11-13 which represents the initial phase, main phase and recovery phase of the storm respectively. Inclusion of Aug 10 and 14 was to know the trend at which the storm is being generated. The storm is summarized using the low latitude magnetic index Dst (see Kamide, 2001; Gonzalez et al., 2001; 2002; Vieira et al., 2001) and is interpreted using available interplanetary data. The plots in Fig. 1 show from top to bottom the low latitude magnetic index Dst, the interplanetary magnetic field component Bz, proton temperature, the proton number density, the solar wind flow speed, Electric field and plasma beta.

The storm was observed to have two Dst depression of minimum values of -106nT and -235nT around 0600 and 1200UT on Aug. 11 and 12 respectively. Both depressions developed with the southward turning of Bz. According to Shweta et al., (2010) the storm showing two step developments is a consequence of the two overlapped growth phase ring current. Kamide et al., (1998) argued that the two-step storm may result from the superposition of two successive modest storms. During the slow evolvement passage of interplanetary corona mass ejection (ICME) the first step of the storm was developed with minimum value of -106nT around 6:00UT in the morning, the injection of a new major particle leads to a further development of the ring current with Dst index decreasing for the second time with a minimum value of -235nT at 9:00UT on Aug. 12. We may thus assume the presence of both sheath field and magnetic cloud field and both fields have the proper orientation and there is magnetic reconnection from both phenomena resulting in a double storm. This is so as it is likely that the first step of the storm was caused by the sheath Bz while the second was from the magnetic cloud field. According to Gonzalez et al., (1999), if the fields are southward in both of the sheath and solar ejecta, two-step main phase storms can result and the storm intensity can be higher.

The Bz panel in Figure 1 was in the southward orientation with an intense field value of 11.6nT and 28.7nT at 0800 and 0500UT on Aug 11 and 12 respectively, which are in near coincidence with the Dst minimum. According to Kamide et al., (1998) and Kozyra et al., (2002), two-step storms result from successive impacts of different regions of southward IMF Bz on the magnetosphere. For intense magnetic storms, the IMF intensity must be less than -10nT (i.e. Bz ≤ -10nT) and long duration greater than 3hours (Gonzalez & Tsurutani, 1987), and the solar wind speed also higher than 400km/s (Gonzalez et al., 1999). Both the first and second southward magnetic field Bz was characterized with the aforementioned features. According to Gonzalez et al., (1994) the intense interplanetary magnetic fields can be thought of as being associated with essentially two parts of a higher-speed stream, the intrinsic fields, and plasma associated with the coronal ejecta (called driver gas), and the shocked and compressed field and plasma due to the collision of the high-speed stream with the slow solar wind preceding it. This compression is related to the strength shocked. Also it was observed from the figure 1 that the higher the relative velocity, the stronger the shock and the field compression.

Since the storm was driven by both sheath field and magnetic cloud field, the magnetic field orientation is comparable (i.e. the difference in magnetic field Bz magnitude and time duration). At the first step the magnetic field was recorded with -13.2nT at 00:00UT which preceded the first step Dst minimum. At this period, the solar wind flow speed was slow, and proton number density was reduced to 4.2N/cm^3 and the temperature of the electron density at the period was 426°K. As the first step is recovering gradually, there come a sudden impulse which was followed by a storm main phase with a great increase in solar wind flow speed high plasma temperature, northward orientation of the fields, reasonable high proton density, and plasma beta of 0.54 increases. The pre-shock solar wind speed was 421km/s and post-shock speed of 591km/s at 14:00UT on Aug. 11 and 12 respectively.

The proton density increases across the shock from 6.6 N/cm^3 with a high solar wind speed of 639km/s, as a result of this, the increased ram pressure exerted on the earth's magnetosphere, ρu^2, causes a sudden compression of the magnetosphere and a positive jump in the horizontal component of the equatorial-region field. An upward jump in Dst was noted at the time of the shock.

The second step main phase occurred in near coincidence to interplanetary magnetic field (IMF) sharp southward turning and low ratio of magnetic pressure and thermal pressure (plasma beta) coincides with the storm minimum depression. The electric field generated in the period was higher with a temperature lower than the SSC period. It is suggested from the figure with all the features and characteristics of the storm, that the second step of the storm was driven by magnetic cloud. Following Gonzalez et al., 1999; Wang et al., 2003, a geomagnetic storm driven by magnetic cloud is characterized with an enhanced magnetic field strength, long and smooth rotation of magnetic vector, and low proton temperature. In all kinds of the interplanetary ejecta, magnetic clouds are of most geoeffectiveness (Wang et al., 2003, and reference therein).

Given the variations of the solar wind parameters as presently observed, it is convenient to suggest that the same magnetospheric process played the leading role in the two successive enhancements in the ring current. Both the first and second enhancements in the ring current, that is, the first and second Dst decrease, may be due to the enhanced solar wind density which drove under southward Bz conditions, the plasma sheet density leading to the injection of the ring current and this caused the observed sharp depressions in Dst. Borovsky et al., (1998) and references therein have shown that the solar wind density drives plasma sheet density with the source of the ring current particles being the plasma sheet. Furthermore, according to Wang et al., (2003) and references therein, variations of the Dst index can be interpreted as a measurement of the kinetic energy of the particles that make up the ring current.

Ionospheric observations

The F layer critical frequency foF2, which is directly related to the F layer peak electron density NmF2 [foF2 (Hz) = 9.0* $\sqrt{NmF2(m^{-3})}$], increased over the high-latitude auroral zone where the precipitation of keV electrons and ions effectively help ionize the neutral gas at the F layer height. Ionospheric storms represent large global disturbances in the F region electron density in response to geomagnetic storms. The dissipation of solar wind energy continuously affects the density structure of the polar upper atmosphere. Major changes observed in this region are an in heavier gases and decrease in the lighter gases, with the electron concentration in this region is directly proportional to [O]/[N_2] ratio at F2-layer maximum height. Positive and negative storm phases are used to describe increases and decreases in the ionospheric electron density during storms. Seaton (1956) had earlier suggested that negative ionospheric storm are resulted from the neutral composition changes, most especially increase in O_2 density, could cause decrease in electron density of F2 layer. Later it became evident that the negative phase is due to decreases in the O/N_2 and O/O_2 neutral density ratios or increase in mean molecular mass forming the composition disturbance zone (Buosanto, 1999). The F peak electron density in the mid-latitude ionosphere may be reduced by a factor of 2–5 during negative storm phases. A widely accepted mechanism for the generation of negative storms is neutral composition changes. The magnetospheric energy input to the atmosphere at auroral latitudes is greatly increased during magnetic storms. Enhanced Joule heating at high latitudes reduces the normal pole ward wind on the dayside and reinforces the regular equator ward wind on the nightside and creates a storm circulation that can transport air with increased molecular species to mid latitudes. The neutral composition disturbances move to lower latitudes, and the enhanced loss rate will result in a significant decrease in the F region electron density. A number of model calculations verify the role of N_2 during negative storms and show good agreement with measurements of ionospheric incoherent scatter radars and ionosonde (Fuller-Rowell et al., 1994).

Figure 2 depicts the ionospheric F2 morphology during the geomagnetic disturbances of August 10-14, 2000. The ionospheric response corresponding to the geomagnetic storm are presented base on the signature of the Dst minimum peak value. The geomagnetic storm under study is two-step, so the ionospheric response is analyzed base on this signature. As shown, following the storm commencement there is an immediate effect on foF2 in the ionosphere at all stations which is preceded by negative storm. Discernible changes were also detected in the D(foF2) variation during the two main phases of the storm for all station. Negative storm phase dominates the period under consideration. This was in consistent with the study of geomagnetic storm effect at mid latitude (Danilov and Lastovicka 2001; Patowary et al., 2013). From the above discussion, the most important result obtained was the detection of a strong and well pronounced dependence of foF2 trend on geomagnetic latitude. Danilov, (2001) had suggested that strong dependence of the foF2 trends on geomagnetic latitude may be related to the F2 layer reaction to geomagnetic disturbances.

The ionosphere over Millstone Hill shows an initial insignificant negative storm phase (i.e. the D(foF2) variation is below the reference level) form 0000-0800UT. Thereafter, it sharply depleted to a peak value of 36% at 1600UT post-noon, then it further depleted, reaching a minimum peak value of 64%, which coincide with the first step of the Dst_{min} signature. This negative storm phase was fit to the SSC, second step and recovery phase respectively. But the largest ionospheric storm was corresponding to the minimum Dst peak. Obviously, as the storm is recovery, the corresponding ionospheric storm started decreasing its intensity. Boulder, Point Arguello, Dyess and Eglin AFB did not show any significant ionospheric storm deviation compared to Millstone Hill. Furthermore, it is very important to note the D(foF2) variation during the quiet period preceding the storm first step and the SSC. Buresova and Lastovicka (2008), during their investigation into pre-storm (i.e. SSC) electron density enhancements at middle latitudes, they found a significant increase in electron density of ionospheric F2 before storm main phase. The D(foF2) variation was low during the quiet period and the variation during the SSC was concurrently reduced compared to the main phase. This may be connected to the existing fact that low-moderate variations in ionospheric F2 variation during SSC signal the upcoming of large ionospheric storm effect at the main phase (see Danilov, 2013; Adekoya et al., 2012).

Prior to the two step Dst decrease, the ionosphere over Gakona exhibits a similar trend with the mid latitude station. Preceding the first step of the storm the D(foF2) was depleted with a weak storm appearance, thereafter, it increased, reaching a peak magnitude below the reference level. This non-significant negative ionospheric storm phase at mid-night was trailed by a noticeable negative storm at 0700UT sunrise. Similarly, intense negative storm at sunset during the second step of the storm was preceded by a positive storm at noon. Observation shows that, throughout storm period, the low D(foF2) variation at noontime was immediately trailed with large ionospheric storm effect. According to Buosantos (1999), during geomagnetic storms the cross-polar-cap potential drop increases markedly, leading to intensification and expansion of the magnetospheric convection electric fields to encompass lower latitudes. At the same time the auroral zone expands due to enhanced energetic particle precipitation. These magnetospheric drivers have strong effects on the high latitude plasma structure.

Although studies have shown that the nature of an ionospheric storm depend on local time, season, and latitude (Vijaya et al., 2011), but for the current studied period, the variation in electron density was depleted intensively and concomitantly across the stations. This may be unconnected to the mid latitude ionospheric F2 mechanism discussed above. The further analysis of the D(foF2) plots appears to reveal these significant features:

(i) Occurrence of a negative ionospheric storm at all stations before the beginning of a geomagnetic storm (ii) The second step of Dst decrease was associated with very intense ionospheric storm compared to the first step periods (iii) The shock period across all the latitude is observed to have a reduction in electron density variation compared to the first and second step periods except for the high latitude station. This was in support of the recently studied Pre-Storm event by Danilov (2013) and Adekoya et al., (2012) (iv) Absence of positive ionospheric storm effects at all the stations was observed throughout the storm periods, except for Gakona which recorded a significant intense positive storm of 35% at the coincide time of second step Dst minimum, and Dyess, Eglin AFB and Point Arguello which recorded a non significant electron density variation within an interval of 4-8 of Aug. 11. (v) Simultaneous existence of negative storm at high and middle. (vi) The variation of electron density during the nighttime is large compared to the daytime period. (vii) At mid latitude, the noontime ionospheric storm signatures are concomitantly depleted and intense, while it is insignificant and enhance at the high latitude. (viii) As for the variation with storm intensity, though DfoF2 was found to vary even between two storms of different Dst_{min}, within the same classification of storm intensity, the amplitude of a negative phase, DfoF2 maximum peak showed a distinct upper limit for each intensity category of storms. (ix) The storm study occurs during the summer period, large negative storm phase form during this period may result from higher molecular density contributes to more rapid recombination between electrons and ions.

Figure 3 illustrates the deviation of the peak height D(hmF2) vs. time UT during the geomagnetic storm event of Aug. 10-14, 2000 for American sector. Insufficient of data restricted the study ionospheric F2 peak height (hmF2) over Gakona. However, the existing hmF2 data for the mid latitude station show a concurrent D(hmF2) variation during the daytime and nighttime. Starting from 0:00-12:00UT on Aug. 11, the D(hmF2) variation increased for all station, this was coincides with the first step of the storm main phase. These enhancements in peak height of F2 layer at all stations followed by depletion which signifies the recovery phase of the first step. The SSC period is observed to enhance across the latitudes, this enhancement extended through the period of the second step with records of intense negative ionospheric foF2 storm. It is observed that the increase in D(hmF2) during the SSC is corresponding to the reduction in ionospheric F2 electron density. Further, the D(hmF2) during the sunrise/post-noon periods is simultaneously increase/decrease, of which, the corresponding foF2 during the sunrise show a progressive decrease. This D(foF2) decrease spanned through the nighttime. The point of the fact is that large concentration of electron density occurred at the peak height of F2 layer and reduction in temperature reduces the concentration of electron density which occurs at the lower height of the ionospheric F2 layer.

In addition to general depression in foF2 several ionospheric stations at high and mid latitude showed a wave like phenomena. Figure 4 shows the variation in foF2 at four American stations (Millstone Hill, Point Arguello, Dyess, and Eglin AFB). The curve labeled quiet day and disturbed day in figure 4 correspond to average of quiet days (i.e. Aug. 17-20) and Aug. 12 the disturbed day of major concentration. From the visual inspection of figure 4, it is apparent that all the stations show an oscillation in foF2 below that of non activity day. It is understood that electron density for the non geomagnetic storm and the solar activity day is more stable than any disturbed days. So in this regards, reduction in foF2 on a disturbed day as compared to average quiet day signify large negative intense variation in the ionospheric F2 layer.

The simultaneous intense depletion of foF2 at all latitudes on August 12 appear to suggest that during the intense geomagnetic storm of August 12, 2000, the foF2 depletion at all stations may not be mainly due to changes in neutral composition resulting from neutral wind produced predominantly in the region of Joule heating in the aurora zone. According to Prölss (1995) and reference therein, during very intense geomagnetic activity soft particle precipitation will increase the vibration excitation of molecular nitrogen which will in turn increase the loss of ionization at F2 region heights as shown in figure 3. And precipitating particles have also been suggested as the source of heating of the lower part of the thermosphere (Danilov, 2001), which may lead to thermospheric composition changes. Given that particle precipitation is known to occur at both higher and lower latitudes during very intense geomagnetic disturbances (Prölss, 1995 and references therein), particle precipitation as a mechanism may be account for the present simultaneous depletion in foF2.

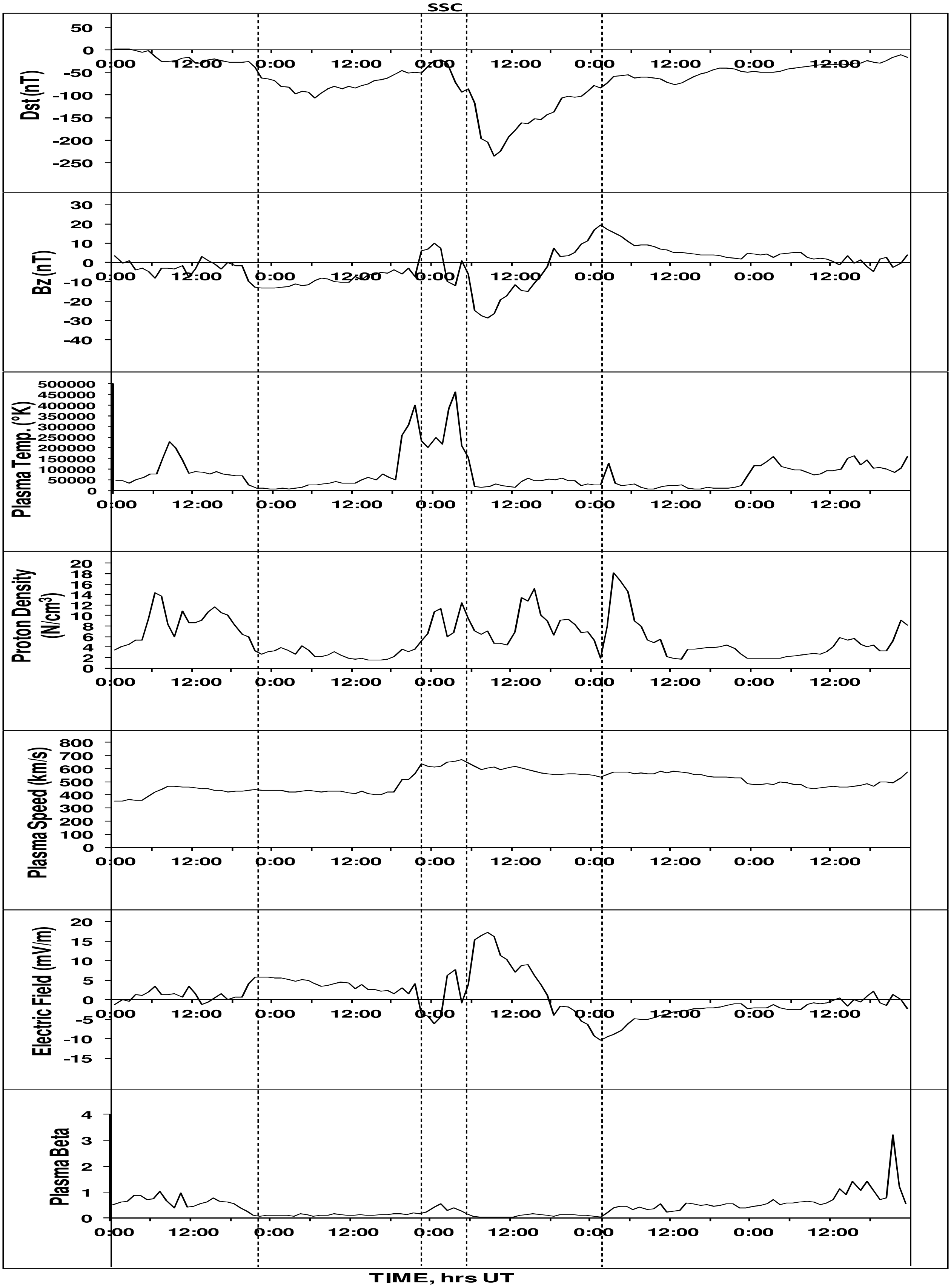

Fig. 1: Composition of interplanetary and geomagnetic observations for Aug. 10-14, 2000

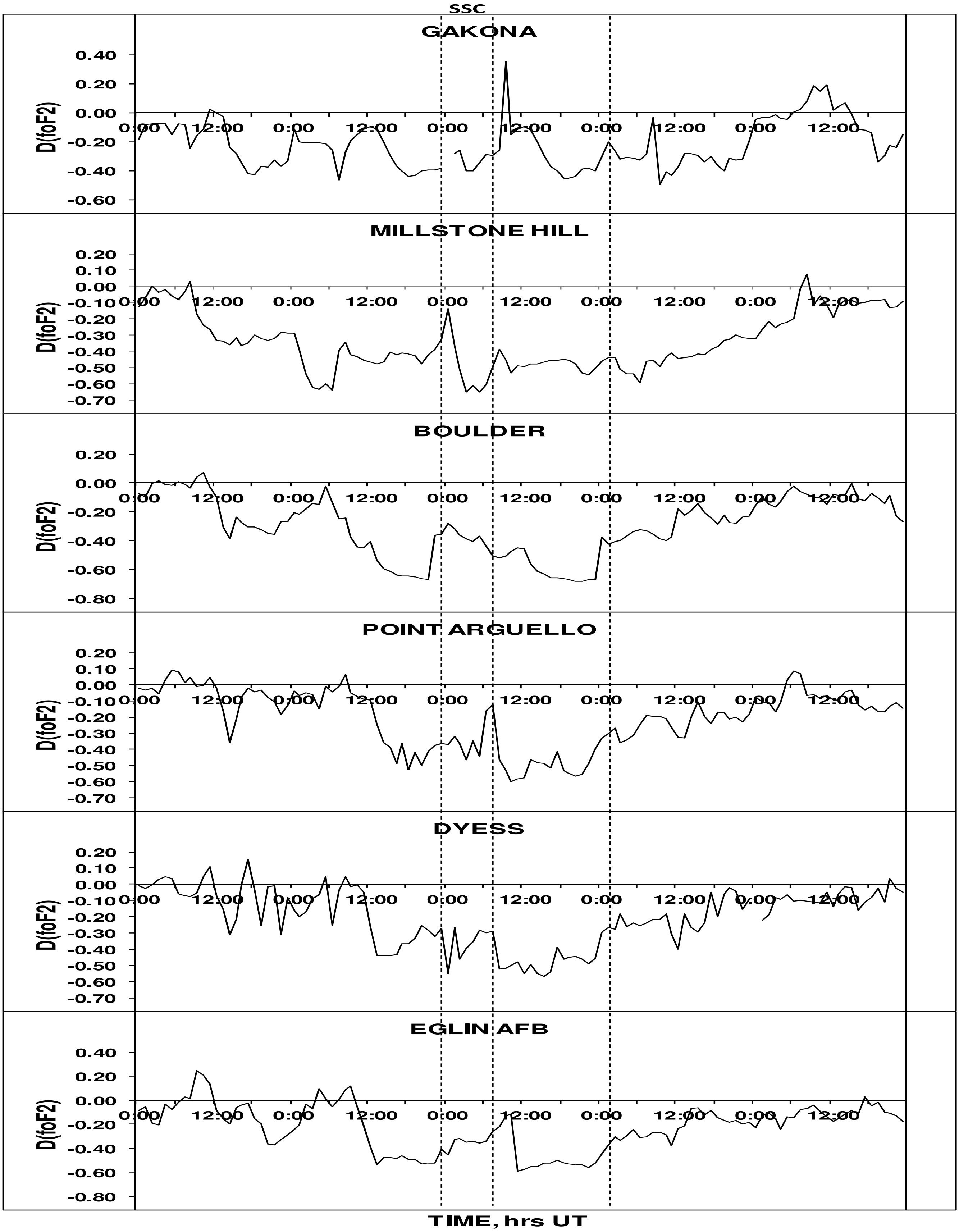

Fig. 2: Variation in D(foF2) in America sector for August 11-13, 2000.

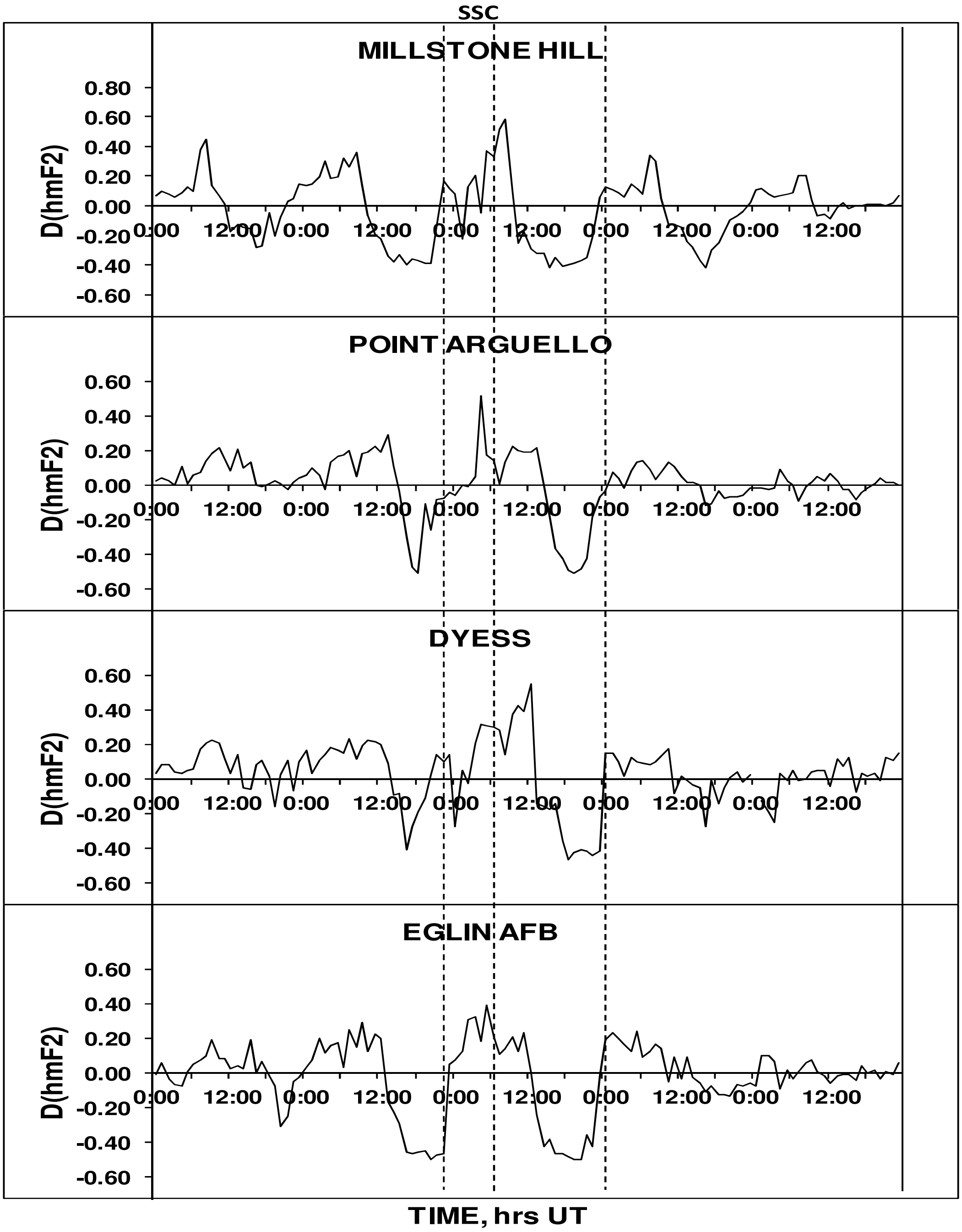

Fig. 3: Variation in D(hmF2) in America sector for August 10-14, 2000

Table 1: List of ionosonde stations with their Geographic coordinates.

Station	CODE	G. Lat	G. Long	GM. Lat	GM. Long	UT to LT Diff.
Eglin AFB	EG931	30.40°N	-86.7°E	40.80°N	343.7°E	-6
Dyess	DS932	32.4°N	99.7°E	41.90°N	328.8°E	+7
Point Arguello	PA836	35.60°N	-120.6°E	41.20°N	58.50°E	-8
Boulder	BC840	40.00°N	-105.3°E	48.90°N	43.00°E	-7
Millstone Hill	MHJ45	42.60°N	-71.5°E	82.3°N	2.50°E	-5
Gakona	GA762	62.40°N	-145.0°E	63.54°N	265.69°E	-10

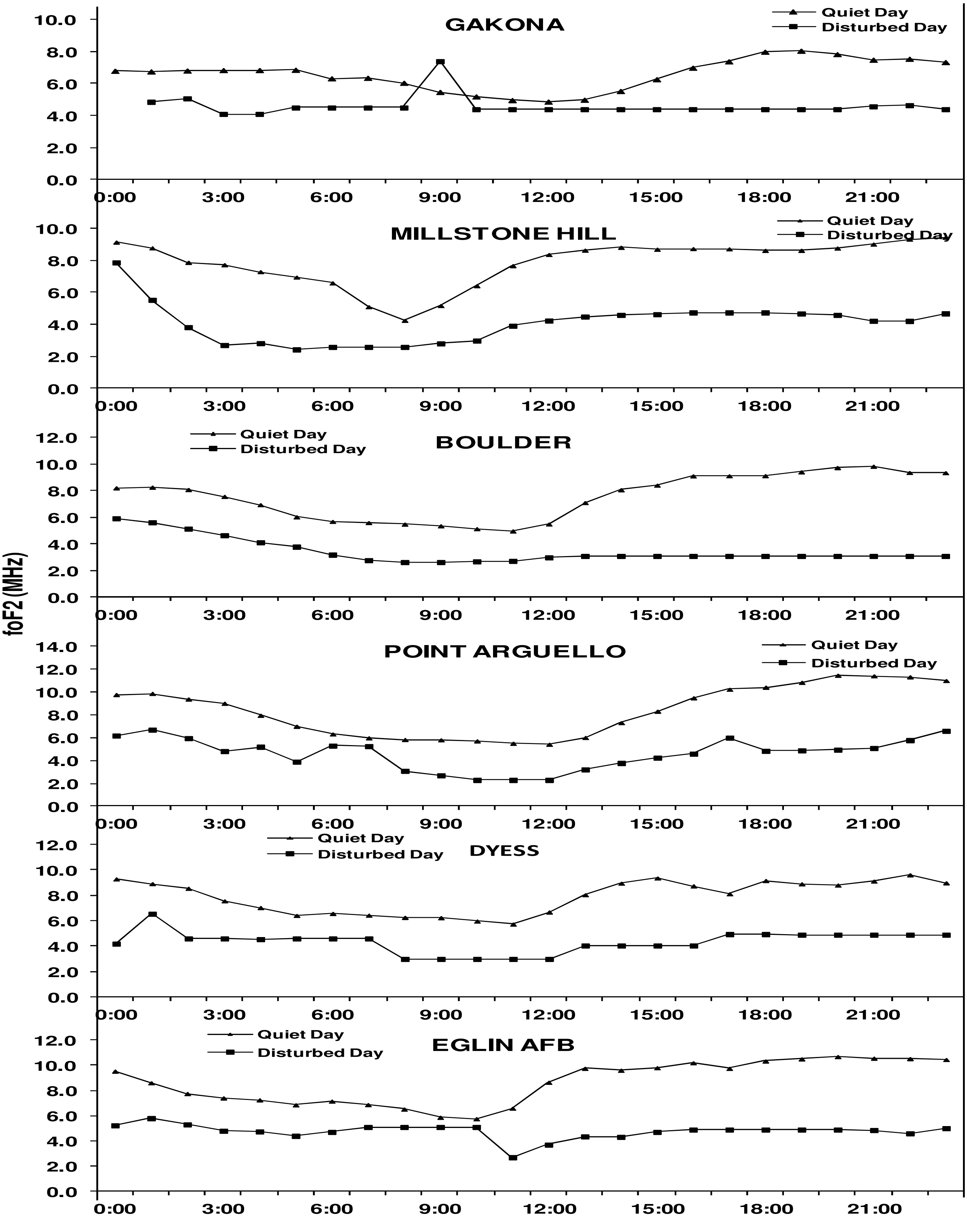

Fig. 4: Variation of foF2 for the disturbed day and average foF2 for the Quiet day in American sector

Conclusion

We have studied the double step intense geomagnetic storm of August 12, 2000 and the F2 region response using foF2 and hmF2 data obtained from the ionosonde stations in American longitudinal sectors. It was found that the leading single magnetospheric process that was responsible for both the first and second Dst decrease was the enhancement of the plasma sheet. An enhanced solar wind density drove, under southward Bz conditions, the plasma sheet density leading to the injection of the ring current. The magnetic storm induced variations depend on the growth of the ring current in the main phase of the storms. Also, it was found those two different driver gas fields are responsible for the first and second step of the storm; the first step is driven by sheath field while the second is driven by magnetic cloud field.

The ionospheric response to this storm is related to the changes in Dst index and Bz component of the interplanetary magnetic fields. It is understood from the observations of geomagnetic storm events that the occurrence of geomagnetic storms is highly connected with the southward turning of Bz, the z component of the IMF and the intensity of the storm also depends upon the sudden storm commencement (SSC). The variation in F2 layer parameters at the time of geomagnetic storm are strongly depends upon the intensity of storms. Though the magnitude of negative storm i.e. (DfoF2) varied a lot from storm to storm even within the same intensity category, the upper bound of DfoF2 maximum peak, the maximum deviation was found to have a relation with the storm intensity indicated by the Dst index. Existence of simultaneous negative storm effects at all latitudes is observed. This decrease may be unconnected to the neutral composition changes during geomagnetic disturbances and season. During summer, negative storm phases tend to form when the higher molecular density contributes to more rapid recombination between electrons and ions. At mid latitude, the noontime ionospheric storm signatures are concomitantly depleted and intense, while it is insignificant and enhanced at the high latitude.

Furthermore, the reduction in foF2 on a disturbed day as compared to average quiet day signifies large negative intense variation in the ionospheric F2 layer. The D(hmF2) during the sunrise/post-noon periods simultaneously increases/decreases, of which, the corresponding foF2 during the sunrise show a progressive decrease. This implies that at a low temperature, the electron density decreases, which occurs at the lower height of the ionospheric F2 layer. The increase in D(hmF2) during the SSC is corresponding to the reduction in ionospheric F2 electron density.

Acknowledgments

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