Space weather effects on low latitude geomagnetic field and ionospheric plasma response

B. Veenadhari and S. Alex

Indian Institute of Geomagnetism, New Panvel (West), Navi Mumbai-410218, India

Abstract. Space weather disturbances caused by enhanced stream of solar plasma during solar flares and Coronal Mass ejections (CMEs) are known to disrupt communications, endanger satellite payloads and introduce severe errors in a variety of tracking and positioning systems. The phenomena known as geomagnetic storms are the most obvious features of space weather disturbances. Magnetic storms are fundamental disturbances in the magnetosphere and can significantly increase, or decrease ionopheric electron densities (termed positive or negative storms, respectively). Electric fields originating in the magnetosphere can penetrate to the equatorial and low-latitude ionosphere resulting in vertical motions that restructure the *F*-region density profiles due to the height dependence of the recombination rate. The effect of space weather related perturbations in electric fields and currents in the equatorial and low latitude magnetic field associated with the changes in magnetospheric convection can be investigated using simultaneous observations from ground as well as ionospheric measurements. The present solar cycle witnessed many solar flares and coronal mass ejections (CMEs) which gave rise to intense geomagnetic storms due to highly active solar environment. The series of X-class solar flares occurred from 2 – 15 April 2001. The geomagnetic field was intermittently disturbed during period due to the CME passages. The geomagnetic storm began on 31 March and 11April 2001 are considered for the present study. These events were selected to study from ground based geomagnetic data, multi satellite data of solar wind and interplanetary parameters. Influence of the magnetospheric storm time electric field changes are estimated by the changes in the equatorial electric field as evidenced by the disturbance parameter of the equatorial electrojet strength and corresponding ionospheric response.

Index Terms. Geomagnetic storms, electrojet, equatorial electric field, ionosphere, magnetosphere.

1. Introduction

Geomagnetic storms result when high speed plasma injected into the solar wind from coronal mass ejections (CME) or coronal holes impinges upon Earth's geomagnetic field. Reconnection process occurs if the arriving solar wind plasma has southward magnetic field energy is coupled efficiently into Earth's magnetosphere and upper atmosphere. The changes in terrestrial ring current are responsible for global decrease in the Earth's surface magnetic field. Perturbations associated with the changes in the earth's magnetosphere are known to have immense contribution to the structure and dynamics of the ionosphere.

During periods of enhanced geomagnetic activity low latitude ionospheric plasma densities, electric fields and currents undergo strong perturbations. Magnetic disturbances at the day side dip equator are often caused by dayside penetration of the convection electric field and correlated with disturbances at high latitudes (Kikuchi et al., 1996; 2000a). The direct penetration of the high latitude electric field to lower latitudes, and the disturbance dynamo, both play a significant role in restructuring the storm time equatorial ionosphere and thermosphere. The response of equatorial electric fields and currents to geomagnetic disturbances has been examined in detail in a large number of case by case and statistical studies and Empirical models of storm time equatorial zonal electric field. (Fejer and Scherliess, 1997; Richmond, 1995). Equatorial magnetic field variations and electrojet events are analysed during the magnetically disturbed periods in association with changes in interplanetary magnetic field. Study aims to bring out the ionospheric signatures as inferred from F region plasma parameters at low and equatorial latitudes in Indian region. The ground magnetic and ionosonde data are used to for the identification of electric field perturbations of ionospheric disturbance dynamo origin.

2. Data and analysis

For the present work, two major geomagnetic storms occurred 31 March to 2 April and 11-13, April 2001 are considered using ground geomagnetic digital data with one minute resolution from Alibag (Geomag. Lat = 9^0 N) and Tirunelveli (Geomag. lat = -0.36^0 S). Of the two magnetometer stations Tirunelveli is located on the axis of the equatorial electrojet in the Indian zone, while Alibag is well outside the influence of the electrojet. Simultaneous data from these two stations are thus well suited for estimating the strength of the equatorial electrojet, particularly during storm time conditions when the ground level magnetic variations receive contributions not only from the overhead currents in the ionospheric dynamo region but also from distant currents of magnetospheric sources (Rastogi and Patel, 1975;

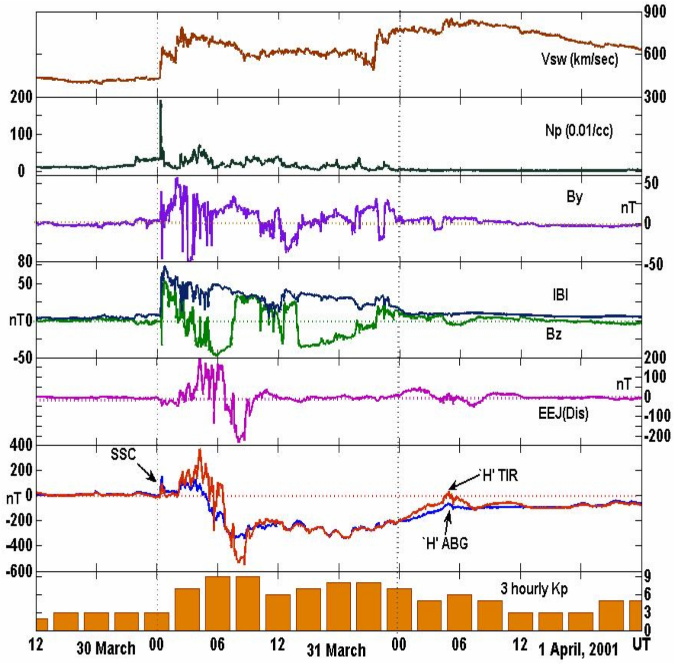

Fig. 1. Magnetic storm of 31 March – 1 April, 2001 with ΔH of TIR and ABG and Interplanetary parameters of Bz, By, IBI, Vsw and Np from ACE.

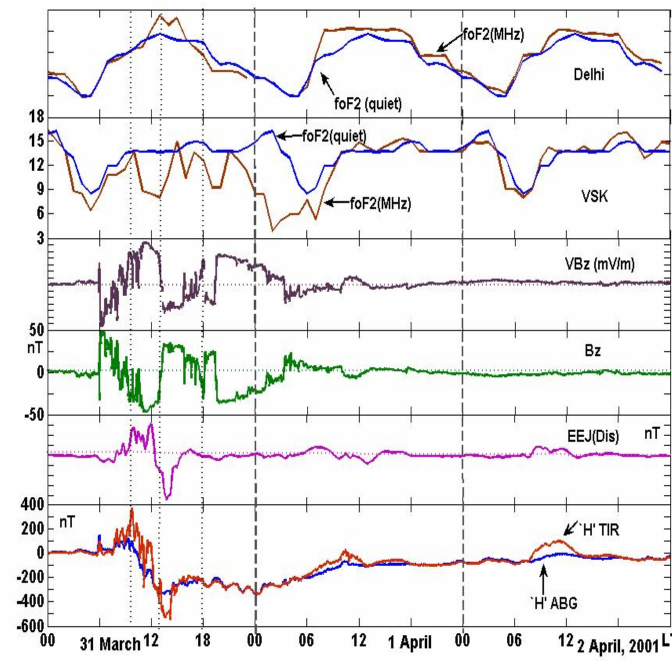

Fig. 2. Same as Fig. 1 with VBz, EEJ (Dis) and the diural pattern of ionospheric critical frequency foF2 from VSK and Delhi.

Bhargava et al., 1980). The Ionosonde data sets are from equatorial and low latitude stations (Geomagnetic Latitude given) Trivandrum (TRD, 0.28^0 S), Vishakapatnam (VSK, 7.95^0), Ahmedabad (AHD, 14.01^0 N) and Delhi (19.02^0). The on board ACE satellite measurements of solar wind parameters were also used. The equatorial storm time index (Alex et al., 1986) which is represented by EEJ (Dis) is calculated by the difference between ΔH (TIR) and ΔH (ABG). The ΔH is deviation from the night base, after the elimination of the quiet day trend from the respective locations.

2.1 Magnetic storm of 31 March – 1 April, 2001

A large halo coronal mass ejection (CME) with X1.7 X-ray flare in AR 9393 region occurred on 29 March at 1015 UT and leading to a shock at the Earth's magnetosphere starting at about 0014 UT on 31 March 2001 after 38 hours. A Storm sudden commencement noted at 0055 UT on 31 March 2001 with solar wind velocities increases to 830 km/s, a strong jump of in IMF total field intensity (to 73 nT), increased densities, and prolonged periods of southward IMF Bz with deflections as high as -46 nT (GSM). Fig. 1 shows the upstream solar wind taken by the ACE spacecraft positioned about 224 Re in front of the Earth on that date. The top four panels show the solar wind speed (Vsw), solar wind density (Np), IMF components of By, |B|, Bz, given in one minute data. The fifth panel shows the variation EEJ (Dis) with one minute data during magnetic storm interval. The two curves in the bottom panel are the ground geomagnetic variations, ΔH from ABG and TIR. The bottom most panel histograms are 3 hourly Kp during the magnetic storm period which is ideal index for geomagnetic activity. The time shift of 30 minutes calculated for geomagnetic data to adjust with ACE parameters. The vertical dashed lines are the separation of each day drawn at 0000 UT. On 31 March, after SSC, the strong initial phase persists for nearly 6 hours followed by main phase with Bz turning southward and particularly during 0500 to 0720 UT the Bz is less than -40 nT. But at later the day between 1400 and about 1930 UT, Bz again turned southwards to -20 nT. During the main phase, the maximum decrease of geomagnetic field of TIR is -500 nT at 09 UT and for ABG is about -350 nT at 09 UT. As the recovery phase picks up the northward turning of geomagnetic field persists. The EEJ (Dis) during intial phase and main phase is clearly shown in Fig. 2 with IMF parameters.

Fig. 2 shows the same magnetic storm of Fig. 1 with convection electric field (-VBz). The VBz is important parameter to represent the severity of the magnetic storm. Also the ionospheric parameters foF2 (MHz) from the VSK and Delhi with foF2 quiet day variations are given to represent the relatively quiet trend. The EEJ (Dis) data is in 15 minutes averaged values as ionospheric data presented here was in 15 minutes values. Apart from day separation vertical lines, the other dashed vertical lines on 31 March show the portion of strong EEJ (Dis) and CEJ. During initial phase, the striking large magnitude of equatorial disturbance index represented by EEJ (Dis). The strong field has sustained from 0900 LT to 1300 LT suggesting the strong Eastward electric field to give rise to ground magnetic field ΔH large amplitude of 200 nT. (the portion between the first two vertical lines). Corresponding to this strong initial phase the enhancement in strong southward field of Bz was – 40 nT, the VBz is 30 mV/m. Generally if Dst is less 100 nT, VBz will 5 mV/m (Lucmann, 1997). In this particular magnetic storm, the intensity of VBz is extremely high which reflects

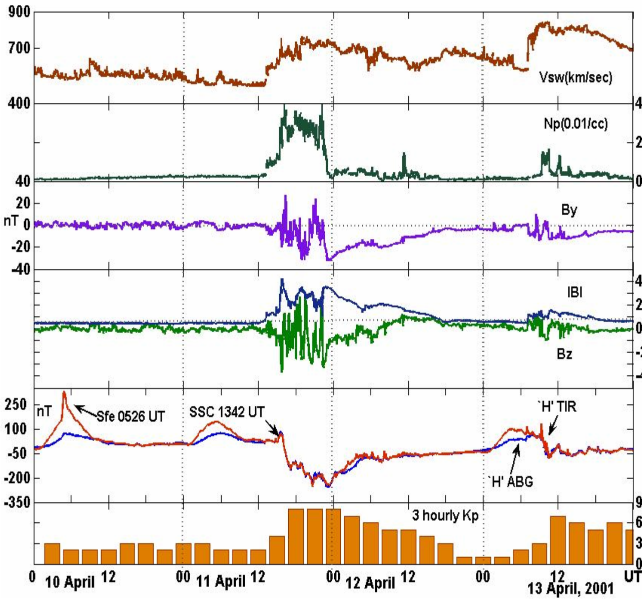

Fig. 3. Magnetic storm of 11 - 13 April, 2001 with ΔH of TIR and ABG and Interplanetary parameters of Bz, By, IBI, Vsw and Np from ACE.

how the strong southward interplanetary well interconnects with earth's magnetic field by mapping of solar wind electric field in to the magnetosphere and ionosphere a long the field lines. The perturbations in electric field evidenced in ionosonde data is considered as a signature of disturbance dynamo related to electric fields. The strong electrojet corresponds the F region plasma depletion of about 6.5 MHz ($5.23x10^5$ cm^{-3}) at VSK when compared to quiet day pattern and the rise in plasma around 3 MHz ($1.11x$ 10^5 cm^{-3}) is noticed in Delhi though it is away from anomaly crest and compared to 2 April which is normal day. The reducing electron density status corresponding to initial phase recordings as projected by VBz magnitude which is very high value. The magnetic storm recovery phase lasts for long time lasts almost 14 hours and storm ended on 1 April. During recovery phase the Bz was southward between 1400 and about 1930 UT and Bz ranged from -30 to -20 nT. At the same time 3 hourly Kp is again high with value of 8, means some disturbance is still persisting as the solar wind speed is more than 500 km/s. The other day 2 April is almost quiet day.

2.2 Magnetic storm of 11 – 13 April, 2001

Fig. 3 shows the magnetic storm of 11 – 13 April, 2001 and also strong X class solar flare on 10 April at 0526 UT (1056 LT) which is very much visible with ΔH of TIR and the positive(northward electric field) H Field was around 280 nT. The geomagnetic field was intermittently disturbed due to the CME passages occurred in 11 -13 April. Two CME shock fronts reached ACE on 11 April at about 1310 UT. The geomagnetic storm started with SSC at 1342 UT. The solar wind velocities increased about 780 km/s following the shocks and IMF Bz showed strong north/south variations. The top four panels show the solar wind speed (Vsw), solar wind density (Np), IMF components By, ⎮B⎮ and Bz, given in one

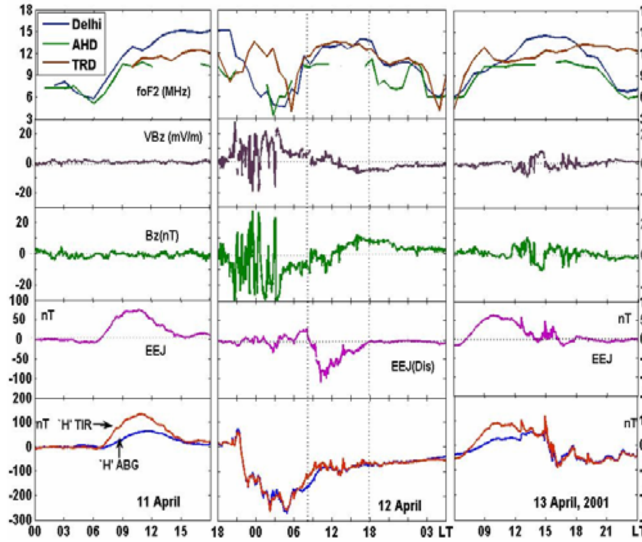

Fig. 4. Same as Fig. 3 with VBz, EEJ (Dis) and the diural pattern of ionospheric critical frequency foF2 from VSK and AHD and Delhi.

minute resolution data from ACE. The two curves in the bottom panels are the ground geomagnetic variations, ΔH from ABG and TIR. The last panel depicts the 3 hourly Kp for the period. The time shift of 38 minutes were taken care to adjust for ACE data with geomagnetic data of TIR and ABG. No strong initial phase exists for this storm as the main phase started after the SSC though highly modulating North South interplanetary field variation is persisting. The maximum decrease in geomagnetic field of TIR is around -250 nT at around 23 UT on 11 April. During main phase of the storm IMF Bz was directed southward but with variations. The solar wind speed was maximum around 780 km/s during main phase of magnetic storm and 3 hourly Kp is maintained at 9. During main phase the Bz was in range of +29 to -27 nT before turning northward at approximately 11/2300 UT and slowly turned to northward on 12 April 1000 UT, almost 10 hours. Hence recovery of the storm was prolonged and though the storm was in recovery phase, the Kp was still high around 7. So the magnetic storm recovery phase lasts for several hours and the solar wind was speed was almost above 600 km/s. During this long recovery phase the computed EEJ (Dis) index shows the strong counter electrojet during local noon of 12 April. The details of EEJ (Dis) are represented in Fig. 4.

Fig. 4 depicts the 11-13 April, 2001 magnetic storm in three columns in local time with convection electric field VBz EEJ and ionospheric plasma parameter foF2 from TRD, AHD and Delhi. The EEJ is averaged for 15 minutes as the ionospheric observations were taken in 15 minutes interval. The first column is showing normal electrojet (eastward electric field) during local noon on 11 April before commencement of the storm. The middle panel shows the complete magnetic storm period. The strong counter electro jet (west ward electric field) around -100 nT is noticed on 11 LT during the recovery phase of the storm where the Bz values are very fluctuating while turning to northward

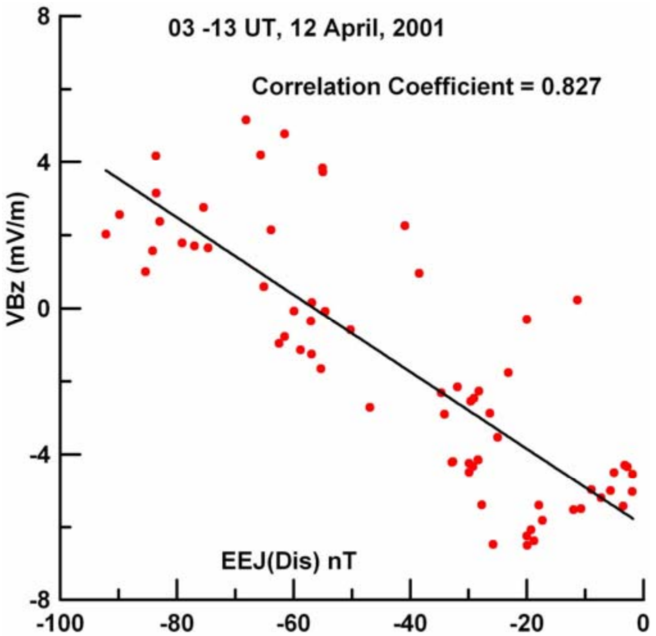

Fig 5. The correlation between the computed EEJ(Dis) and VBz. The solid line shows the linear fit through the data (Correlation coefficient = 0.827).

direction. The convection electric field VBz dropped during the recovery phase and strong counter electrojet noticed during the local noon. The counter electro jet period during recovery phase of the storm starts from 08 to 18 LT which was shown in dashed lines in middle column of the Fig. 4. The correlation was drawn between the EEJ (Dis) and convection electric field VBz during counter electro jet period from 8 to 18 LT (03 – 13 UT), which is shown in Fig. 5. No development of equatorial anomaly depicted on 12 April noon as strong CEJ is persisted and the normal anomaly noticed at local noon time of 11 April, 2001.

3. Results and discussion

During the day, the ionospheric electric field is mainly controlled by the E region dynamo process, in which the tidal forcing from the lower atmosphere plays a significant role (Richmond, 1995). On other hand, the F region dynamo plays a dominant role for the nighttime electric field (Milwards et al., 2001). In case of 31March storm, the initial phase, strong EEJ (Dis) shows the increase in equatorial eastward electric field and simultaneously ionospheric plasma depletion near equatorial latitude (Fig2). There are some empirical models which determine the plasma drift perturbations due to the combined effects of short lived prompt penetration and longer lasting disturbance dynamo electric fields (Fejer and Scherliess, 1997, Fejer et al., 1990). During the period of southward IMF, the development of the partial ring current causes a shielding effect on the penetrated convection electric field. This shielding electric field causes an intensification of the convection electric field at auroral latitudes, resulting in the intensification of the eastward auroral electrojet current (DP 1 current) in the afternoon to evening sectors (Kikuchi et al., 2000b and references there in). In case of 31 March 2001 magnetic storm, the correlation is drawn between EEJ (Dis) and convection electric field VBz during initial phase (00 – 08 UT) and got the scattered points with poor correlation due to the discontinuities in the Bz directions. The northward turning of IMF at 08 UT on 31 March caused the substantial decrease in the electric field and electrojet day side of equator. The over shielding effect reduces the intensity of the equatorial electrojet on the day side (Kikuchi et al., 2000b). In case of 11- 13 magnetic storm, the northward turning of IMF caused the appearance of CEJ during recovery phase of the storm. The correlation has drawn for the correlation is better with 0.827 which is during recovery phase (03 – 13 UT) on 12 April, 2001. Detailed investigation has to be done for more severe phases of magnetic storms for different phases to know the equatorial electric field variations during day time.

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