Effect of magnetic storms and substorms on the low- latitude/ equatorial ionosphere

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Abstract. Magnetic storms and substorms occupy the center stage of research in Solar-Terrestrial Physics as they epitomize the couplings within the Sun-Earth system. Noteworthy progress has been achieved in recent times in understanding the solar and interplanetary cause(s) of magnetic storms and the storm-associated disturbances in the terrestrial magnetospheric and upper atmospheric environment, which collectively constitute an easily identifiable form of 'Space Weather'. In this paper, I shall endeavor to present a brief summary of recent studies of the effect of magnetic storms and substorms on the low latitude/equatorial ionosphere properties, profiling the incremental additions to our understanding of the storm/substorm-related disturbances. The outstanding scientific questions that warrant further work are projected which include the manifestation at the day side dip equator of storm sudden commencement (ssc or sc) and geomagnetic and ionospheric effects of substorms of various types, appearance and interplay of electric field disturbances due to prompt penetration (pp) and ionospheric disturbance dynamo (IDD) processes, and impact of the electric field disturbances on the generation of equatorial ionospheric F - region irregularities (ESF) that are detrimental to trans-ionospheric telecommunications.

Index Terms. Low latitude geomagnetic and ionospheric effects, magnetic storms, substorms.

1. Introduction

Geomagnetic storms and substorms are short-lived disturbances in the plasma and magnetic field characteristics of the near-Earth Geospace; they are specific and readily recognizable forms of enhanced geomagnetic activity conditions that result primarily from the interaction of solar wind disturbances with the Earth's magnetosphere. Storms and substorms have been the subject of intensive studies, both experimental and theoretical, since a long time. Rapid strides are being made in recent times in comprehending the many facets of magnetic storms such as the causative interplanetary structures and their solar origins on the one hand, and the terrestrial magnetospheric manifestations of storms and the associated global upper atmospheric effects on the other (see, for example, Webb et al, 2001; Fuller-Rowell, et al., 2001). The scenario is no different for substorms which continue to fascinate and engage the attention of magnetospheric physicists as regards the varied forms of their occurrence and the physical mechanisms responsible for them, and equally importantly the complex storm-substorm relationship (see, Sharma et al., 2003). In this paper, I shall attempt to profile in brief the recent studies of the low latitude geomagnetic and ionospheric disturbances associated with magnetic storms and substorms. No claim is made to the comprehensiveness of the effort, it is only indicative of the current trends and their significance.

2. Geomagnetic storm effects

2. 1 Storm sudden commencement (SSC)

The equatorial Dst index computed from low- latitude geomagnetic data and traditionally used to study magnetic storms shows that storms develop either suddenly or gradually. The former category of storms start with a sharp increase of magnetic field, referred to as the storm sudden commencement (SSC or SC) which is observed throughout the magnetospheric cavity. The SC is not just a timing signal of the impending magnetic storm but a noteworthy large-scale geophysical phenomenon by itself. It arises because of the impact of shocks and discontinuities in solar wind on the dayside magnetopause that leads to sudden magnetospheric compression and consequent enhancement of magnetopause currents, the net result being a sharp increase of ground level magnetic field all over the globe. It is established from experimental studies that the actual physical situation however is far from being this benign, and the SC waveform exhibits temporal structure with a complex dependence on latitude and local time (see for example, Araki, 1997, 1994 and references therein) clearly indicating a role of not only distant currents but near-earth ionospheric currents as well. The effect of sudden magnetospheric compression is cleanly seen at low latitudes away from the influence of the intense auroral and equatorial electrojet currents. But, even here, the sensitivity response to sudden increases in solar wind dynamic pressure is found to depend on local time and the orientation of the interplanetary magnetic field, IMF (Russell et al., 1992; Russell, Ginskey and Petrinec, 1994a, b).

In the dip equatorial region, SC manifests in two basic forms on the dayside with more or less equal frequency at the diurnal maximum around local noon, namely, the conventional SC characterized by a monotonic increase of H-field called the main impulse, mi, and SC* wherein the mi is preceded by a short-lived (1-2 min duration) but distinct negative pulse, referred to as the preliminary reverse impulse, pri. The two-pulse structure is seldom seen at low latitudes but reappears again at high latitudes simultaneous with that dip equatorial latitudes (see, Araki, 1977 and references therein). This global pattern of SC* occurrence has been explained in terms of the superposition of the magnetic effects of twin-vortex DP2 type ionospheric current system of polar origin that extends all the way to the dip equator, on that due to the basic magnetospheric compression, the DL field (Araki, 1977, 1994). Recent MHD simulations of the magnetospheric response to a solar wind impulse lend substantial support to the physical model of Araki (Slinker et al., 1999; Fujita et al., 2002 a, b).

Though the prevalence of SC* is known for a long time, it is only in recent years its characteristics received some attention due to the availability of high time resolution data from several magnetometer networks including the equatorial region. This led to new information on the equatorial pri of SC* and also led to some controversy as regards the physical mechanism responsible for it. Sastri et al (2001) conducted a case study of the longitudinal characteristics of equatorial pri of SC* in the context of the global manifestation of the SC using ground level magnetometer as well as satellite data. As shown in Fig. 1, they found the equatorial pri to appear only in the forenoon (09 LT) sector simultaneous with that in subauroral region of the afternoon sector, but not in the afternoon sector. From theoretical calculations, this behavior indicative of a marked longitudinal dependence of the equatorial pri. has been attributed to a possible azimuthal rotation of the twin-vortex ionospheric current system in the polar ionosphere. The study of Chi et al (2001), on the other hand, cast doubts on the validity of the Earth-ionosphere waveguide model for the instantaneous propagation of the pri from polar ionosphere to the equator, based on the observation of small but clear differences in the arrival time of preliminary impulse at high latitude and low latitudes on the dayside. The latitudinal pattern of these time delays finds a logical explanation in terms of the propagation of compressional mode waves in the magnetosphere. In response, Kikuchi and Araki (2001) defended the waveguide model for the equatorial pri by pointing out the differences in timing the impulse (time of onset used by them versus the time of maximum amplitude of impulse used by Chi et al). It is imperative that further focused studies with high time resolution magnetometer data with GPS synchronization are required to assess the actual physical situation for a large number of SC events and corresponding to different IMF and magnetospheric conditions, are necessary to ascertain the efficacy of the two mechanisms. This will help enrich our understanding of the electrodynamic coupling of the solar wind-magnetsophere - high latitude ionosphere - low latitude ionosphere coupling central to the physics of SSC.

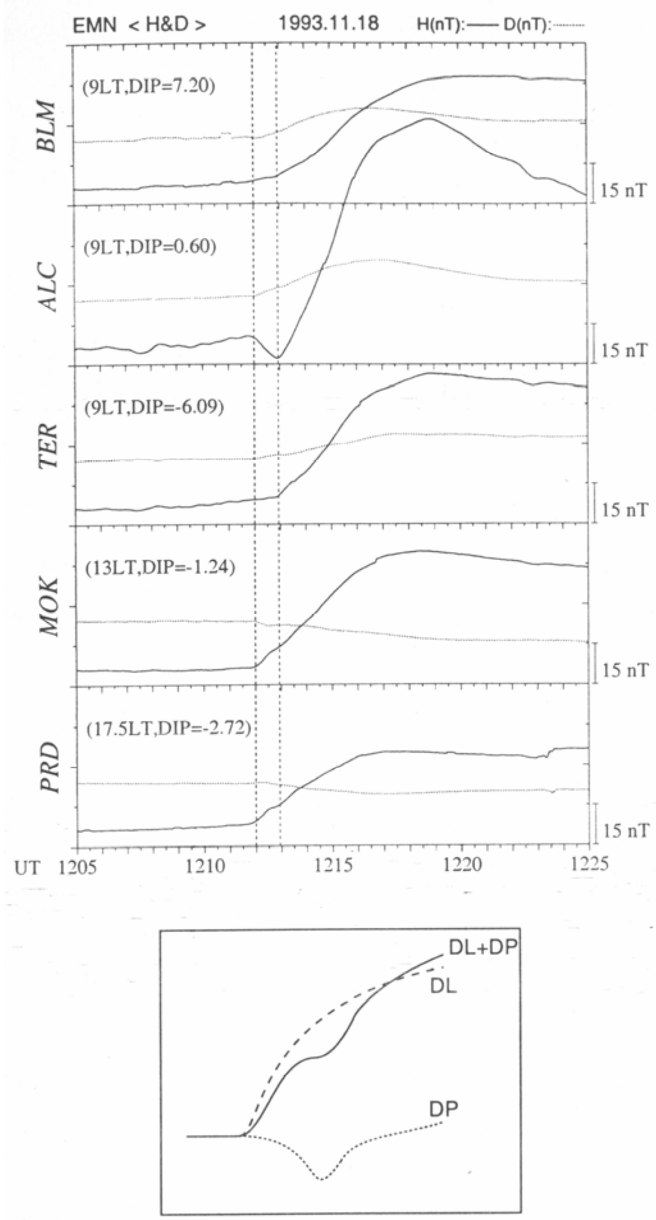

Fig. 1. SC waveform on November 18, 1993 at stations of the equatorial magnetometer network (EMN) encompassing the Brazilian (BLM, ALC, TER), African (MOK) and Indian (PRD) sectors. The vertical dashed lines mark the preliminary reverse impulse (pri) of the SC, which is prominently seen only at ALC in the forenoon sector. Though the pri didn't appear at stations in the afternoon sector (MOK , PRD), it showed up as a distinct reduction in the rate of increase of H-comp coincident with the pri at ALC, superposed on the field (DL) due to magnetospheric compression, as illustrated in the schematic (after Sastri et al., 2001).

2. 2 Effects during storm main and recovery phases

After the passage of the IP shock and the associated sudden commencement of the storm, the physical and dynamic state of the upper atmosphere gets altered on a global scale during the main phase and recovery phases of the storm due to deposition of energy and momentum to the high latitude upper atmosphere and its redistribution to other regions of the globe through various physical processes. The consequent departure from the average quiet-time patterns of the ionosphere properties constitutes the ionospheric storm, analogous to the magnetic storm. The study of ionospheric storms is important as they are an extreme form of space weather that has a direct bearing on transionospheric communications as also the performance of technological systems in space and on the ground vital to modern human activities.

Central to the storm-time behavior of the low latitude and equatorial ionosphere with which we are primarily concerned here, are the electric field disturbances originating in enhanced solar wind-magnetosphere-high latitude ionosphere couplings that characterize the storm conditions. This is but natural because the global system of currents and electric fields of ionospheric wind dynamo determine the geomagnetically quiet-time behavior of the low latitude ionospheric plasma (e.g., Kelley, 1989, Hargreaves, 1992, Rishbeth, 2000). Recent work of low latitude ionospheric storm effects have focused on evaluating the response to specific magnetic storm events that the Sun had provided in good measure. Specific examples are the studies related to the Halloween storm of July 15, 2000 (e.g., Basu et al, 2000; Sastri et al, 2002), the storms of March 31, 2001 (Maruyama et al, 2005) and November 6, 2001 (Maruyama et al., 2004; Tsurutani et al., 2004), the space weather events of March 2002 (Lima et al., 2004) and the violent Sun - Earth connection events of October-November 2003 (see the special section in September 2005 issue of *J. Geophys. Res*, Vol 110 (9); Zhao et al., 2005; Sahai et al., 2005; Lin et al., 2005 a,b, Basu et al., 2005; Dabas et al., 2005). These and other studies, both observational and theoretical, have not only helped consolidate the basic framework of our current understanding of the storm-time characteristics of low latitude ionosphere (see, Abdu, 1997; Fejer, 2002; Sastri et al., 2003 and references therein), but also created awareness of new aspects which must be pursued in the years to come. In the former category are the experimental evidences and theoretical support for the origin of changes in the electrodynamics and dynamics of the upper atmosphere with various time delays from the storm onset. As regards the electrodynamics is concerned, fresh supportive evidences are reported for short-lived electric field disturbances (2 hours) due to direct or prompt penetration to low latitudes of the high frequency component of time varying high latitude electric fields associated with rapid and prominent transitions in the Bz and By components of IMF and attendant changes in the polar cap potential distribution and auroral electrojet activity.

The behavior seen in the superstorms of 29-30 October 2003 are a case in point. In association with the rapid main phase development on 29th October, Lin et al (2005a) found a large enhancement in low and midlatitude TEC in the American sector (70° W), by a factor of almost 2 from prestorm day. This remarkable TEC response has been attributed to the effect of an eastward penetration electric field inducing a strong upward plasma drift and thereby a greatly enhanced equatorial plasma fountain. ROCSAT-1 observations of plasma drifts during the same period did support the interpretation. Since modifications in thermopsheric neutral winds and composition can also effect TEC, a theoretical study was also made using Thermosphere-Ionosphere-Electrodynamics- General Circulation Model , (TIEGCM) and Sheffield University Plasmasphere Ionosphere Model (SUPIM) to simulate the global thermosphere-ionosphere responses to the storm event and evaluate the relative role of neutral wind and electric field (Lin et al., 2005b). The results showed that though storm-time eastward penetration electric field can expand the low latitude equatorial anomaly to higher latitudes and produce TEC enhancements, an in-phase contribution from the storm-generated equatorward neutral winds is required to account for the observed magnitude of TEC enhancements. This storm event thus reinforced the view (e.g., Fesen et al., 1989; Sastri et al., 2000) that modifications in global thermospheric circulation play a significance role in some storms and must be given due consideration in predicting storm-time ionosphere variations.

During this same storm, in close association with sharp decreases in equatorial Dst index characterizing the storm main phases, a rapid uplift of equatorial F layer was noticed in the dusk and dawn longitudes sectors (Brazil and East Asia) indicative of magnetospheric penetration electric fields (Sahai et al., 2005). This work also brought to light the fact that the storm-time response of the low latitude ionosphere could be quite different at locations separated in longitude by as small as 2 hrs in local time, a situation that is sometimes encountered even in geomagnetic quiet conditions. Simulations with the TIEGCM and comparison with the observations in Brazil and East Asia sectors separated by 12 hrs in LT, showcased the inadequacies of the global circulation models and indicated the inputs that need improved specification for predictions.

The recent past has witnessed a few but specific studies of ionospheric disturbance dynamo (IDD) electric fields during storms. Huy and Amor-Mazaudier (2005) examined the longitudinal extension of IDD in the daytime using ground magnetometer data of stations in the Asian, African and American sectors for a carefully selected set of six storms. They found the presence of IDD fields (reduction in equatorial electrojet strength) in all the three longitude sectors but only in one storm; in the rest IDD fields were seen but with a limited longitudinal extent. The factors that determine the longitudinal confinement or why IDD fields are not always seen at a given location though the time history of the geomagnetic forcing is considered conducive for the prevalence of IDD fields (see, for example, Sastri, 1988) are unclear at the moment and require further concerted studies. On the theoretical front, the study of Maruyama et al (2005) addressed such questions as the relative importance of prompt penetration electric fields (pp) and IDD fields and their mutual interactions through simulations for the March 31, 2001 storm, using the Rice convection model (RCM) and Coupled Thermosphere – Ionosphere - Plasmasphere-Electrodynamics (CTIPe) models. They found that the pp fields to dominate at an early stage of this storm and during daytime, while at night the two fields are comparable. But the more important result here is the feedback effect of pp fields on the DD fields at night when pp fields significantly impact the development of DD fields through the changes they produce in the low latitude ionospheric conductivity and the ion drag on neutral winds. This can be seen from Fig. 3 wherein the vertical plasma drift patterns are shown for simulations with both DD and pp effects (run4-run1) and with only either DD (run2) or pp effect (run3). It is obvious that during the nighttime and irrespective of longitude, the total contribution of DD and pp processes to vertical plasma drift is smaller than the sum of drifts due to DD and pp clear indicating that pp fields modify the nighttime DD process. This line of work has to be continued to grasp the nature and magnitude of mutual interactions between pp and IDD fields for a variety of storm conditions.

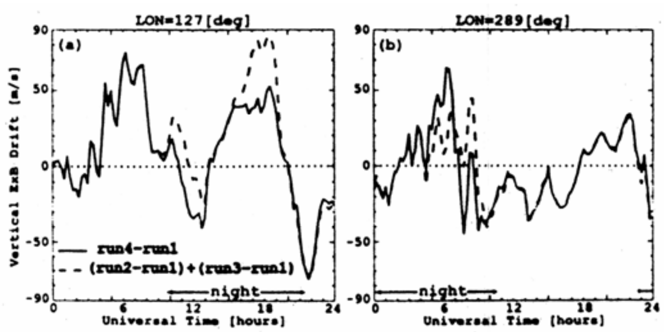

Fig. 2. Comparison of the vertical ExB drifts at the magnetic equator for two longitude sectors (127deg and 289 deg) obtained with CTIPe model simulations with both IDD and pp effects (run4-run1) and linear summation of the effects from separate simulation with only IDD (run2) and only pp (run3). Run 1 corresponds to quiet time reference (after Maruyama et al., 2005).

Huang et al. (2005) conducted a theoretical study of the delayed effects of geomagnetic activity on low latitude ionospheric electric fields due to modifications in global neutral winds set up by Joule heating and ion drag forcing the auroral and polar cap regions, by using the Thermosphere – Ionosphere – Electrodynamics – General Circulation Model (TIEGCM) for equinox conditions. The novelty of this work is that it removed the contribution of direct or prompt penetration electric fields from the total fields, so that the simulation results mainly correspond to the ionospheric disturbance dynamo (IDD) effects. It is found that (maximum positive charge accumulation develops at low latitudes in the premidnight sector due to disturbance winds, and) the local time of reversal of the equatorial perturbation zonal electric field varies with longitude by 2-3 hours, depending on the level of geomagnetic activity. An important feature of the perturbation electric field set up by disturbance winds is a reduction of the postsunset upward drift with respect to quiet times, which has a direct relevance to the postsunset occurrence of equatorial spread F, as will be discussed later in the paper. After the cessation of geomagnetic activity, the zonal disturbance winds persist longer than the meridional winds resulting in a longer life for the meriodional rather than for the zonal disturbance electric fields.

A new perspective was brought to light very recently concerning the duration of prompt penetration (pp) electric field disturbances at low latitudes, which is commonly taken as ≈ 30 min, based on extensive theoretical and empirical results (see, for example, Senior and Blanc, 1984; Peymirat et al., 2000; Fejer, 2002 and references therein). The data analysis effort of Huang et al (2005), however, showed that the ionospheric eastward (westward) electric field at low latitudes can be enhanced continuously without any decay for many hours (ranging from 1.6 h to 10 h in individual events) during the main phase of magnetic storms and under steady southward IMF conditions. The reason as to why this condition of prolonged ineffective shielding of low latitude ionosphere prevails remained obscure. The possibility that a high ionospheric conductivity and an imbalance between region 1 and region 2 currents may facilitate such a behavior of penetration electric fields has been indicated by Huang et al (2005) and this remains to be assessed.

Credible evidence for the possibility that the penetration to low latitudes of the interplanetary electric field (IEF) can contribute to the short-term temporal variability of OI 630nm night airglow emissions during geomagnetically disturbed periods has been presented by Chakrabarty et al (2005). They showed through a case study that the OI 630nm night airglow intensity at low latitudes (dip 12.5°N) fluctuated with periodicities of about 30 min and 60 min coherent with those in F layer height close to the magnetic equator (and hence in equatorial zonal electric field) and in the Y-component of the interplanetary electric field, IEF on a disturbed night (Ap=30), a feature that is not seen on a quiet night. These studies brought into focus the need to address the question of shielding of the low latitude ionosphere, and improve our understanding of the factors that govern the frequency dependence of electric field penetration and other related issues.

The destabilized condition of nighttime equatorial ionospheric plasma referred to as equatorial spread F (ESF) is one of the key elements of space weather with immediate applications in areas such as operation of telecommunication links…etc. ESF refers to the presence of a wide spectrum of field-aligned ionospheric F region irregularities spanning about seven orders of magnitude in spatial scale that get generated due to a hierarchy of plasma instabilities driven by favorable ionospheric and thermospheric conditions that prevail in the postsunset region. It is well established that the prereversal enhancement of upward plasma drift (PRE) over the magnetic equator which is determined by the longitudinal gradient in E region conductivity across the sunset terminator and zonal winds, is an essential ingredient for the growth of the collisional Rayleigh-Taylor (RT) instability that is widely accepted as the primary destabilizing mechanism (see, for example, Abdu, 2001; Sastri et al., 2003 and references therein). Meridional and vertical neutral winds, initial seed perturbations in the plasma, and ion composition have been shown to affect the RT instability growth rate.

Since magnetic storms are generally accompanied by modifications in all ionospheric and thermospheric drivers of ESF, the normal diurnal cycle of postsunset ESF initiation, growth and sustenance through the night gets disrupted, leading to myriad global patterns of ESF manifestation in individual storm events. The storm-time behavior of ESF therefore continues to receive much attention (e.g., Becker-Guedes et al., 2004; Sahai et al., 2004; Basu et al., 2005) so as to improve our comprehension of the role of various physical factors and thereby develop eventually reliable predictive capabilities. In this context, the work of Martinis et al (2005) is noteworthy as they have attempted to develop a unified framework for understanding the storm-time ESF taking the vertical upward plasma drift as the key controlling parameter and using the AE-parameterized Fejer-Scherliess model for disturbance drifts fields as a function of storm time and local time. The model which accounts for both the direct or prompt penetration and the delayed IDD mechanisms helps ascertain the longitude sectors susceptible to generation of ESF irregularities at various epochs in the life time of the magnetic storm. This approach has been successfully validated against the observations for the storm of April 6, 2000 which showed a marked longitude confinement of postsunset ESF that find a ready explanation in terms of the presence of favorable/unfavorable vertical drift conditions at the time of local sunset. Moreover, Martinis et al (2005) pointed out a consistent relationship between postsunset ESF and rapid temporal changes in the interplanetary electric field (IEF) induced by transitions in IMF Bz that would facilitate prompt penetration electric fields of eastward polarity to occur in their wake, a situation favorable for the growth of the RT instability. This linkage of solar wind parameters with storm-time ESF needs to be established for a variety of geophysical conditions to take us that much closer to developing the forecasting capability. This essential because as pointed out by Martinis et al (2005), the Fejer-Scherliess model for disturbance vertical drifts is a climatological one and there are other processes and factors that are not taken into consideration by them such as the the By component of IMF, and these could influence the polarity and amplitude of the electric field perturbations (see, Fejer, 2002).

As regards postmidnight ESF is concerned, the widely documented finding is that it manifests afresh at this local time in close association with a conspicuous upward drift of F layer, due to ionospheric disturbance dynamo (IDD) mechanism that sets in after some hours of enhanced geomagnetic activity (see Abdu, 2001; Sastri et al., 2003 and references therein). The relationship of postmidnight ESF to anomalous upward reversal of the normal downward drift may be solar cycle dependent, being more effective at solar minimum when the ambient downward drifts are small than at maximum when they are large, and thus requiring sufficiently large amplitude upward drift disturbance to cause the reversal plasma drift (Fejer et al., 1999). While postmidnight ESF is always seen during geomagnetically disturbed conditions in association with an upward drift, the reverse situation doesn't prevail. That is a large upward drift of equatorial F layer doesn't always lead to ESF in the postmidnight period (Sastri, 1980, Abdu et al., 1997), clearing pointing to a role of inhibiting factors, just like in the postsunset period. The longitudinal extent of disturbance electric fields due to IDD mechanism and its event-to-event variability has been very recently explored by Huy and Amor-Mazaudier (2005) for the daytime and a similar effort for the nighttime sector is required for a comprehensive understanding of storm-time postmidnight ESF.

2. 3 Substorm effects

There is a resurgence of interest in recent times in the study of the low latitude effects of magnetopsheric substorms (e.g., Rostoker, 1993, Kamide, 1994; Sastri, 2002). This situation stems from the undeniable need to bring in contextual clarity for the varied short-lived (duration ≈ 2 hrs) disturbances that one commonly finds ionospheric and geomagnetic observations at in low latitudes, and to assess the contribution of substorms to the high frequency component of ionopsheric temporal variability. Most studies in the past used the auroral electrojet indices (usually of 1-hr time resolution) or localized magnetic observations at high latitudes for the purpose. This could be quite misleading at times because there are many forms of auroral electrojet activity that bear similarities to substorms, such as pseudo-breakups and poleward boundary intensifications, PBI (see, Lyons, 2000) but are distinctly different phenomena. The more compelling reason is the broader perspective that such studies may help comprehend the large-scale properties of substorms and help improve our understanding of magnetosphere-high latitude ionosphere - low latitude ionosphere couplings. Very recent studies have substantiated the reasonableness of these concerns and rendered the subject an interesting one to pursue in future because of the unsettled issues of a fundamental nature.

The global-scale disturbances in ground-level magnetic field during substorm expansion phase are conventionally understood in terms of the effects of the substorm current wedge (SCW) according to which one can expect to see a positive H-comp bay on the nightside and weaker negative bay on the dayside at low latitudes, with a dominant contribution from the distant field-aligned currents (FACs) of the wedge current circuit (see, McPherron, 1991 and references therein). While this is found to be the situation on the nightside, that on the dayside was found very recently to be quite different. Analysis of data pertaining to carefully identified substorms showed the presence of a significant ionospheric component in the dayside H-component bay during the growth phase and/or expansion phase (Kikuchi et al., 2000; Sastri et al., 2001). It is also found in the fortuitous auroral event of May 15, 1996 wherein a pseudo-breakup was followed by a global substorm expansion onset that a rapid and precipitous reduction in the cross polar cap potential (magnetospheric convection) in close association with a northward swing IMF at the expansion phase onset is responsible for the ionospheric component (Sastri et al., 2003). As may be seen from Fig. 3, the occurrence of pseudo-breakup at 0623 UT was accompanied by a negative H-comp bay only at the high latitude station, MGD and there is no indication of any bay-like disturbance at the lower latitude stations, YAP, GUA and BIK in the afternoon sector. In contrast, the onset of the expansion phase at 0706 UT led to a coherent bay-like H-comp disturbance at all the stations with remarkable enhancement of its amplitude at YAP, close to the dip equator. Such a dip equator increase is an unambiguous signature of the contribution of ionospheric currents. An identical behavior in H-comp was also seen at equatorial and low latitude stations in the Indian local noon sector (not shown here), confirming that ionospheric currents dominated the substorm-related negative bay disturbance over the 1200-1600 LT region in this event. Varied opinion has been advanced as to the origin of the ionospheric component. Kikuchi et al (2000) explained the latitudinal dependence of the H-comp response to the substorm on March 22, 1979 (CDAW-6 event) in terms of the effects of ionospheric currents of polar origin, namely reduction of region 1 currents and delayed enhancement of region 2 currents. Sastri et al (2001, 2003), on the other hand, considered the H-comp bays associated with both substorm growth and expansion phases as due to direct or prompt penetration electric fields generated by rapid changes in the cross polar cap potential brought by the swift transitions in IMF responsible for the growth and expansion phases.

The subsequent work of Huang et al (2004) demonstrated that the onset of either an isolated substorm with an apparent association with a reduction in southward IMF or periodic substorms during magnetic storms under conditions of a steady southward IMF can lead to a positive bay disturbance in H-comp not only on the nightside as can be expected from the prevailing paradigm, but on the dayside as well. This evidence which is a strong indicator of an eastward perturbation electric field in the equatorial region on the dayside may be seen from the data graphed in Fig. 4. The onset of the substorm at 0305 UT on 13 April 2000 is accompanied by a positive H-comp bay (and a eastward swing of the ambient westward electric field) at Jicamarca on the nightside, as well at the low latitude stations along the 210 MM on the dayside. Huang et al proposed that the positive H-comp bay on the nightside may be related to the magnetic depolarization process at the time of the substorm expansion

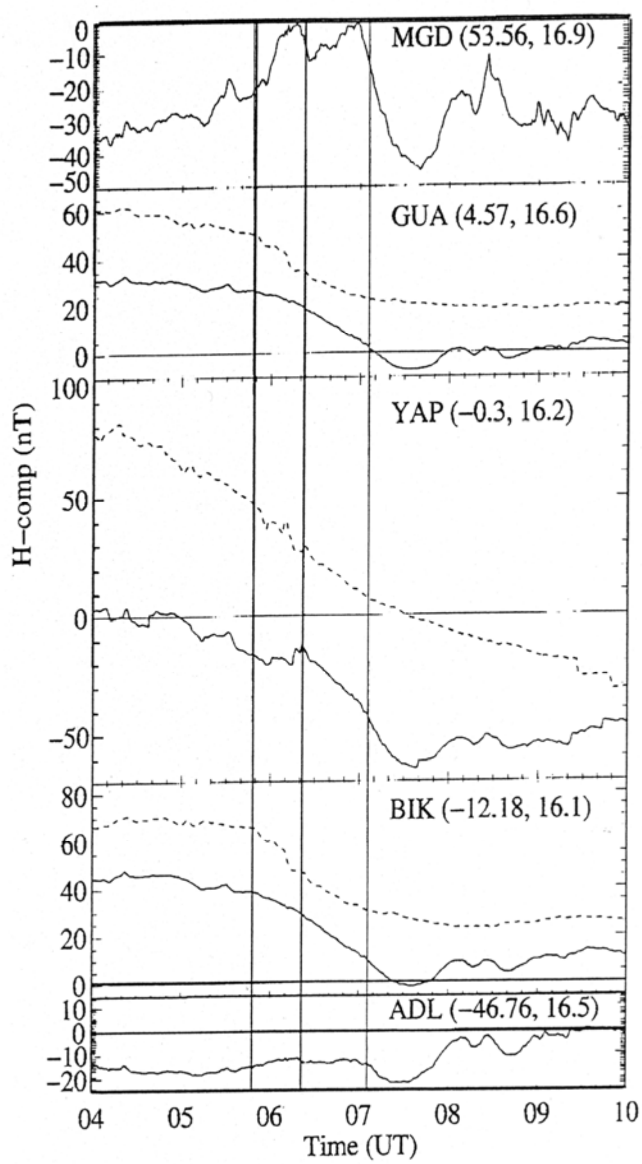

Fig. 3. Geomagnetic H-field variation at sub-auroral and equatorial stations of the 210MM network in the Pacific sector on May 15, 1996 (solid curves). The vertical lines at 0548 UT, 0623 UT and 0706 UT indicate the start of substrom growth phase, ude pseudo-breakup, and the substorm expansion phase, respectively. The geomagnetic latitude and magnetic local time at 0700 UT of the stations are indicated in brackets by the side of the station code. The conspicuously enhanced negative bay at YAP close to the magnetic equator that occurred with the onset of the substorm expansion phase may be noted. The quiet day (May 23, 1996) variation at the equatorial stations, YAP and BIK and GUA is shown by dashed curves (after Sastri et al., 2003).

phase, with no ionopsheric contribution, while the positive H-comp bay on the dayside receives a contribution from an eastward perturbation ionospheric electric field. The origin of the eastward dayside electric field disturbance remained intriguing and obscure as Huang et al (2004) offered no explanation for its origin. The equatorial geomagnetic and ionospheric effects of substorms thus remain an unsettled and open subject. Since a only a very limited number of substorm events were analyzed so far to document evidence for particular physical situations, it is imperative that a large sample of substorms of various categories (externally triggered, spontaneous, storm–time and non-storm time events) needs to be studied. This effort will help develop a comprehensive picture of the response characteristics of the equatorial H-comp and ionospheric zonal electric field on the dayside to substorms including the event-to-event variability, and seek plausible physical mechanisms that can account for the observations. This task remains for the future.

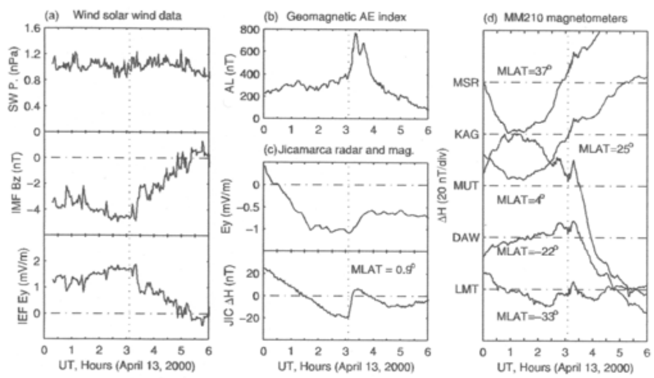

Fig. 4. Observations over the interval 00-06 UT on April 13, 2000 of (a) solar wind pressure, IMF Bz and interplanetary electric field , IEF from WIND satellite, (b) Auroral electrojet index, AE, (c) equatorial ionospheric electric field and magnetic field at Jicamarca on the nightside, and (d) magnetic field at equatorial and low latitude stations along the 210MM on the dayside. Magnetic latitude are given for each of the stations. The vertical dashed line marks the onset of a substorm apparently associated with a northward swing of IMF Bz (after Huang et al., 2004)

3. Concluding comments

An overview of recent work concerning the response of the low latitude / equatorial ionosphere to magnetic storms and substorms is presented to document concisely the incremental additions to our empirical knowledge and its theoretical understanding. An attempt is also made to identify emerging new dimensions of storm effects that merit further concerted studies. A multi-pronged approach of focused experimental campaigns with multi-site, multi-diagnostics, data assimilative modeling and numerical simulations, and innovative analysis of historical data are necessary to forge ahead leading eventually to forecast / nowcast capabilities that have immense practical applications. The ongoing cooperative programs, CAWSES and ILWS can be expected to maintain the collective efforts on course so as to keep up the momentum of all round research and development activity with due scientific returns and practical societal benefits.

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