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A broad climatology of very high latitude substorms

Anand K. Singh *, A.K. Sinha, Rahul Rawat, Bulusu Jayashree, B.M. Pathan, Ajay Dhar

Indian Institute of Geomagnetism, Kalamboli Highway, New Panvel (W), Navi Mumbai 410218, India

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Abstract

Magnetic data from a newly commissioned Indian Antarctic station Bharati (corrected geomagnetic (CGM) coordinates 74.7°S, 97.2°E) and closely-spaced IMAGE chain observatories (∼100° magnetic meridian in Northern hemisphere) has been analyzed to study the climatology of substorms which were localized poleward of the standard auroral oval. We considered four austral summers (year 2007–2010) when data from Bharati was available. Several very high latitude substorms were observed in this duration when the solar activity remained unexpectedly low for a long time. Various features of very high latitude substorms, e.g., local time dependence, interplanetary state, hemispherical asymmetry and their nightside low latitude signatures are examined. Events studied here, suggested the following properties of substorms occurring at very high latitudes: (1) maximum occurrence was observed near magnetic midnight (21:00–02:00 MLT). (2) In contradiction to earlier reports, many substorms were observed even during negative IMF *Bz* condition. In addition, majority of substorms occurred during low or moderate solar wind streams. (3) Magnetic signatures were often pronounced in the winter hemisphere. (4) Even if widely used standard *AE* indices fail to monitor very high latitude substorms, their low latitude signatures are often evident.

Keywords: Substorm; *AE* indices; Positive bay; Pi2 pulsations

1. Introduction

The solar wind continuously buffets the Earth's magnetosphere and deposits enormous amount of energy into the magnetotail due to the solar wind magnetosphere interaction. Magnetic field lines on the day side of the Earth's magnetosphere connect with oppositely directed interplanetary magnetic field (IMF) lines, which are subsequently dragged to the night side magnetotail region by the solar wind (Dungey, 1961). The storage of magnetic and particle flux in the magnetotail is the first stage of a substorm activity, which is known as growth phase (McPherron, 1972). The stored energy is explosively released into the inner magnetosphere during next stage of a substorm called onset or expansion phase, followed by recovery phase (Akasofu, 1964). Auroral latitudes (magnetic 60°–70°) are the most severely affected region due to a substorm activity. Nevertheless, nearly all regions of the magnetosphere undergo significant magnetic and electric field changes during substorms (McPherron et al., 1973a; Sastri, 2002).

A fraction of tail current is diverted into the inner magnetosphere along the magnetic field lines during the course of a substorm, entering from the dawn and flowing back to the tail on the dusk side via night side auroral ionosphere (McPherron et al., 1973b). The strong ionospheric current flowing from the dawn to the dusk (i.e., westward) casts dramatic magnetic field changes at night side auroral latitudes. In addition to it, the high latitude two cell convection pattern, observed as an effect of ionospheric plasma convection (Clauer and Kamide, 1985), perturbs the magnetic field in other local times at auroral latitudes. Normally, an eastward flowing ionospheric current in the dusk hours is observed at auroral latitude due to the two cell convection pattern, which in turn enhances the magnetic field during the course of a substorm.

* Corresponding author. Tel.: +91 22 27484000; fax: +91 22 27480762.
E-mail addresses: singhaaks@gmail.com (A.K. Singh), ashwini@iigs.iigm.res.in (A.K. Sinha), rahuliig@gmail.com (R. Rawat), bulusujayashree@gmail.com (B. Jayashree), bmpathan@iigs.iigm.res.in (B.M. Pathan), ajaydhar@iigs.iigm.res.in (A. Dhar).

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Disturbances in the horizontal (H) components, observed at selected 10–12 longitudinally distributed auroral observatories in the northern hemisphere (magnetic latitude range ~65°–71°), have been used over several decades to derive various auroral electrojet (AE) indices to monitor substorms (Davis and Sugiura, 1966). The upper envelop of the H component disturbances is called as AU index, which is a measure of the maximum intensity of the eastward electrojet. The lower envelop of H disturbances, AL index, gives an idea of the maximum intensity of the westward electrojet. The difference between AU and AL is termed as AE index which is expected to represent the maximum intensity of the auroral electrojet. The three indices, AU, AL and AE, are collectively known as AE indices.

Often during a substorm, both eastward and westward electrojets get intensified – AU index increases rapidly, whereas AL index shows even sharper depression. The AE index (AU–AL) attains sharp positive values during a substorm. It is known that the intensification of the westward auroral electrojet is closely related to the substorm activity (e.g. Meng and Akasofu, 1968). As a result, the AL index is the most suitable index for studying the dynamics of magnetospheric substorms (Dobias and Wanliss, 2009).

Despite the fact that substorms initiate at night side auroral latitudes, they cause fairly noticeable magnetic disturbances at mid and low latitudes as a result of changes in tail current and field-aligned currents (McPherron et al., 1973a; Ritter and Lühr, 2008). A typical positive bay in the H component having the maximum amplitude ~10 nT near the onset meridian and decreasing amplitude towards the dawn and dusk is often observed at mid/low latitudes due to the substorm current wedge (McPherron et al., 1973a). The disturbance in D component is asymmetric about the onset meridian having maximum amplitude on the dusk and minimum amplitude on the dawn (McPherron et al., 1973a).

Different magnetic signatures of a substorm in different local times at low/mid latitudes invoked computation of asymmetric (ASY) indices for monitoring of substorms (Iyemori, 1990). A substorm appears as a positive bay in $ASYH$ and $ASYD$ indices, which correlate well with the AE indices. However, in addition to substorm currents, various other current systems, e.g., partial ring current (Shi et al., 2005), ionospheric currents driven by intense solar flares (Singh et al., 2012a) or prompt penetration of interplanetary electric field (Singh et al., 2012b), etc. can substantially modify substorm signatures in the ASY indices.

At the onset of substorms, Pi2 pulsations in the period range 40–150 s (frequency range 7–25 mHz) are often observed at mid and low latitudes over a wide range of longitude. It makes Pi2s as a good indicator of substorm onset (Olson, 1999).

The auroral oval is often confined between 60°–70° magnetic latitude (Newell et al., 2002), however it expands equatorward and contracts poleward in accordance with changes in IMF, solar wind pressure variations and level of geomagnetic activity (Allen and Kroehl, 1975; Kamide and Akasofu, 1983). Sometimes, onset of a substorm and its various manifestations are localized beyond the standard auroral oval, as a consequence the AE stations may not be able to monitor substorm electrojets precisely (e.g. Kamide and Akasofu, 1983; Singh et al., 2011). Earlier reports suggest that substorms, localized poleward of the standard auroral oval, are quite frequently observed in the winter hemisphere during the descending phase of a solar cycle (Loomer and Gupta, 1980; Papitashvili et al., 2002). In an event based study Lui et al. (1976) demonstrated that a substorm localized poleward of the standard auroral oval during contraction and normal substorms (initiated in the auroral region) represent the same physical phenomenon. The high latitude substorm (mag. lat. ~70.4°) presented by Lui et al. (1976) did not exhibit the typical low latitude characteristics.

It is a general belief that the substorm disturbances are mirror images in the opposite hemispheres, though conjugate auroral observations have shown significant asymmetries between the two hemispheres during a substorm (Laundal and Østgaard, 2009; Østgaard et al., 2007; Stenbaek-Nielsen et al., 1972; Newell et al., 2010). However, limited availability of magnetic records in Southern auroral region (most of the oval region being in ocean) restrains the study of conjugate characteristics of auroral electrojets (Maclennan et al., 1991; Weygand and Zesta, 2008).

Geomagnetic data from Antarctic station Bharati (BHA) and its near-conjugate IMAGE chain station Horsund (HOR) provide an opportunity to investigate very high latitude substorms characteristics during the recent extended solar minimum (Nandy et al., 2011). BHA and HOR are located in opposite hemispheres at ~74° magnetic latitudes and have about an hour MLT difference. Moreover, using magnetic data from Alibag (ABG) observatory, low latitude signatures of such substorms have been examined.

2. Data set and events selection

Third Indian Antarctic station Bharati at Larsemann Hill (geographic coordinates 69.4°S, 76.2°E) is being established in Antarctica. However, during last four Indian Scientific Expeditions to Antarctic (year 2007–2010), Digital Flux-gate Magnetometer (DFM) was operated at BHA during austral summers to monitor geomagnetic field fluctuations. The variations in the geomagnetic field components H, D and Z were sampled at 1 h, 1 min and 1 s intervals. As shown in the top panel of Fig. 1, around 100 days good quality data was collected at BHA in this duration.

The geomagnetic location of BHA (CGM latitude 74.7°S) is ideally suited for the study of substorms localized poleward of the standard auroral oval. The Indian station BHA and IMAGE chain station HOR lie nearly in same magnetic flux tube and form a near-conjugate pair. Hourly,

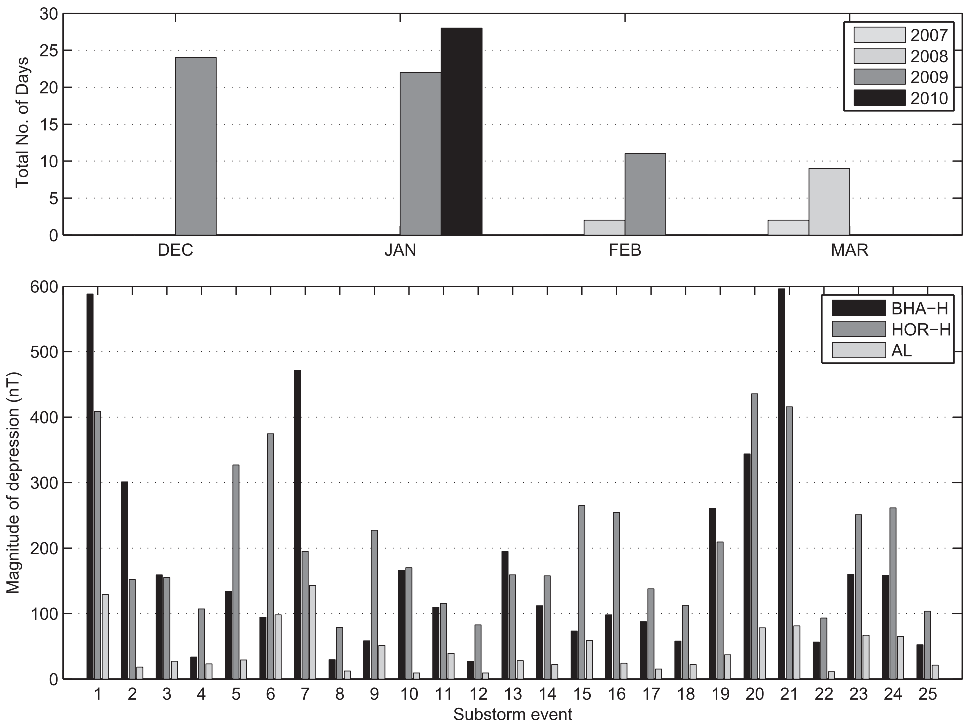

Fig. 1. Top panel: availability of magnetic records at BHA during last four summer expeditions (year 2007–2010). Austral summer months (December to March) are shown on the *X*-axis and bars in different shades show number of days when data was recorded. Bottom panel: magnitudes of *H* depressions observed at BHA and HOR as well as $|AL|$ for 25 selected events.

minute and 10 s resolution magnetic data from IMAGE chain stations in the Northern hemisphere is available online. In the present study, we have used 1-min magnetic data from BHA and IMAGE stations as listed in Table 1. The CGM coordinates (Gustafsson et al., 1992) of stations (geomagnetic coordinates for ABG) are given for year-2010 in the table. Simultaneous 1-s resolution magnetic data from low latitude station ABG, located at the western coast of Indian subcontinent, has been used to examine the low latitude signatures of substorms which were not registered by the standard *AE* indices.

Geomagnetic indices (AU, AL and $ASYH/D$) are obtained from the webpage of WDC Kyoto. Interplanetary and solar wind conditions were recorded by instruments aboard ACE satellite and were made available by CDA Web.

Auroral electrojet indices are quite frequently used for identification of substorms (Rostoker et al., 1980). However, there is no certain criteria about the magnitude or the duration of *AE* enhancement to be itendified a substorm or even to rule out a possibility of a substorm. On one hand *AE* enhancement larger than 200 nT could be associated with steady magnetospheric convection (SMC) without a substorm onset (Sergeev et al., 1996), whereas on the other hand there are occasions when a depression in $AL \simeq -50$ nT is regarded as a substorm (Lui, 2009).

In this study, onset of transient depression in *H* component and its subsequent recovery at stations (BHA or HOR) during local night time (16:00–04:00 UT) is termed as very high latitude substorm when following two criteria are fulfilled:

Table 1
List of ground stations and their geographic and magnetic coordinates.

Station name	Code	Geographic		Magnetic		MLT
		Lat. (°N)	Long. (°E)	Lat. (°N)	Long. (°E)	
Ny Ålesund	NAL	78.9	12.0	76.4	109.6	UT+02:58
Longyearbyen	LYR	78.0	15.8	75.3	110.2	UT+03:01
Hornsund	HOR	77.0	15.6	74.3	108.2	UT+02:54
Bear Island	BJN	74.5	19.2	71.6	107.0	UT+02:50
Sørøya	SOR	70.5	22.2	67.5	105.4	UT+02:44
Abisko	ABK	68.4	18.8	65.5	101.1	UT+02:27
Tartu	TAR	58.3	26.5	54.7	102.7	UT+02:35
Alibag	ABG	18.6	72.9	10.2	146.6	UT+04:58
Bharati	BHA	−69.4	76.2	−74.7	97.2	UT+ 01:47

1. Magnitude of AL index ($|AL|$) < 150 nT,
2. Magnitude of transient depression in H component at any of the conjugate stations (BHA or HOR) must be greater than twice the value of corresponding $|AL|$.

These two criteria will ensure the occurrence of very high latitude substorms which were not identified in the standard AE indices. With this criteria, we found 25 substorm events in 100 days data, which were mainly localized at very high latitudes. Bottom panel of Fig. 1 shows magnitudes of H depressions observed at BHA and HOR as well as $|AL|$ in different shades for individual events. It is evident from the figure that fairly intense substorms (up to 600 nT depression in H) occurring at very high latitudes, remain unnoticed in the standard AL index.

3. Observations

Firstly, a few cases of very high latitude substorms are presented which is followed by statistical results.

3.1. Case 1: event of 2 March 2008

Top four panels of Fig. 2 depict the IMF and solar wind conditions as observed by instruments aboard ACE satellite located outside of the Earth's magnetosphere at $\sim 240R_E$ on the Sun–Earth line ($L1$ point). In order to compare the interplanetary observations with ground magnetic data, IMF and solar wind data have been delayed by 40 min taking into account the travel time of solar wind at an average speed of ~600 km/s from the location of the satellite to the magnetopause of the Earth.

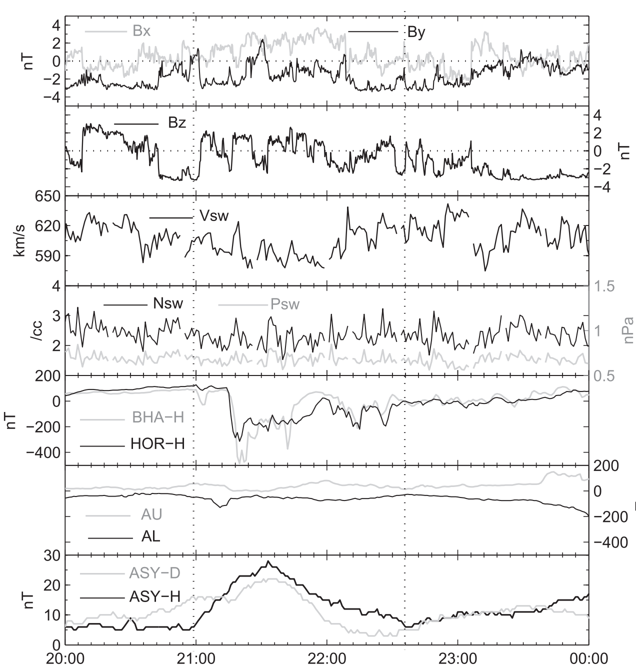

Fig. 2. (Top to bottom) Components of IMF, solar wind velocity, density and dynamic pressure variations as observed by ACE satellite, H disturbance at high latitude near-conjugate stations, AU, AL and ASY indices on March 02, 2008. Interplanetary observations are delayed by 40 min to compare with the ground data. Event marked between vertical dashed lines clearly shows a substorm localized to high latitude.

Components of IMF are shown in the top two panels of Fig. 2, whereas next two panels show solar wind velocity and density as well as dynamic pressure, respectively during 20:00–00:00 UT on 2–3 March 2008. In fifth panel from the top, H disturbances at BHA and HOR show sharp depression of ~ -500 nT as marked between a pair of dotted vertical lines. Substorm indices AU and AL do not show significant changes during this interval. Bottom panel of Fig. 2 shows typical $ASYH$ and $ASYD$ enhancements despite the fact that the event was not identified in AU and AL indices.

Ground and satellite based observations of auroras have proved that the auroral breakups are the best indicator of substorm onset (Wu et al., 2004). For the event of 2 March 2008, Singh et al. (2011) have shown auroral breakup in the vicinity of BHA at 20:57 UT that subsequently expanded poleward and faded away. The auroral brightening was followed by sharp magnetic field depression at very high latitude stations.

Closely spaced IMAGE chain stations in the northern hemisphere provide an opportunity to investigate the latitudinal characteristics of these substorms. H (black lines) and Z (grey lines) component disturbances at selected IMAGE chain stations are shown during 20:30–23:30 UT on 2 March 2008 in Fig. 3(a). Standard AE observatory, ABK lying near midnight (where maximum disturbance is expected), does not show appreciable field change during the event. Consequently the AL index does not indicate significant change during the event.

An intensified westward electrojet normally depresses H component over a wide range of latitude (Kisabeth and Rostoker, 1974). Stations, poleward of ABK, witness sharp depression in H field component which gets maximized at HOR as shown in Fig. 3(a). Maximum disturbance in H component is expected near the center of westward electrojet. It can be precisely estimated using Z disturbance plots along a meridian. Poleward of the center of electrojet, H component is depressed and Z component is enhanced, whereas equatorward of the center of electrojet both H and Z components are depressed (Rostoker et al., 1980; Gupta and Loomer, 1979). For this event depression in H is observed the most prominent at station HOR and the Z variations are grossly opposite between stations BJN and HOR after the onset of substorm as shown in the figure. This observation suggests that the center of substorm electrojet was lying between BJN and HOR.

It should be noted that the first sharp depression in H is observed around 20:58 UT at BJN, which however did not reach higher latitudes. Next surge of westward electrojet depresses the H component dramatically at HOR at 21:12 UT, which is subsequently observed poleward of HOR.

Further, night side low latitude data from ABG observatory has been analyzed to examine signatures of substorms

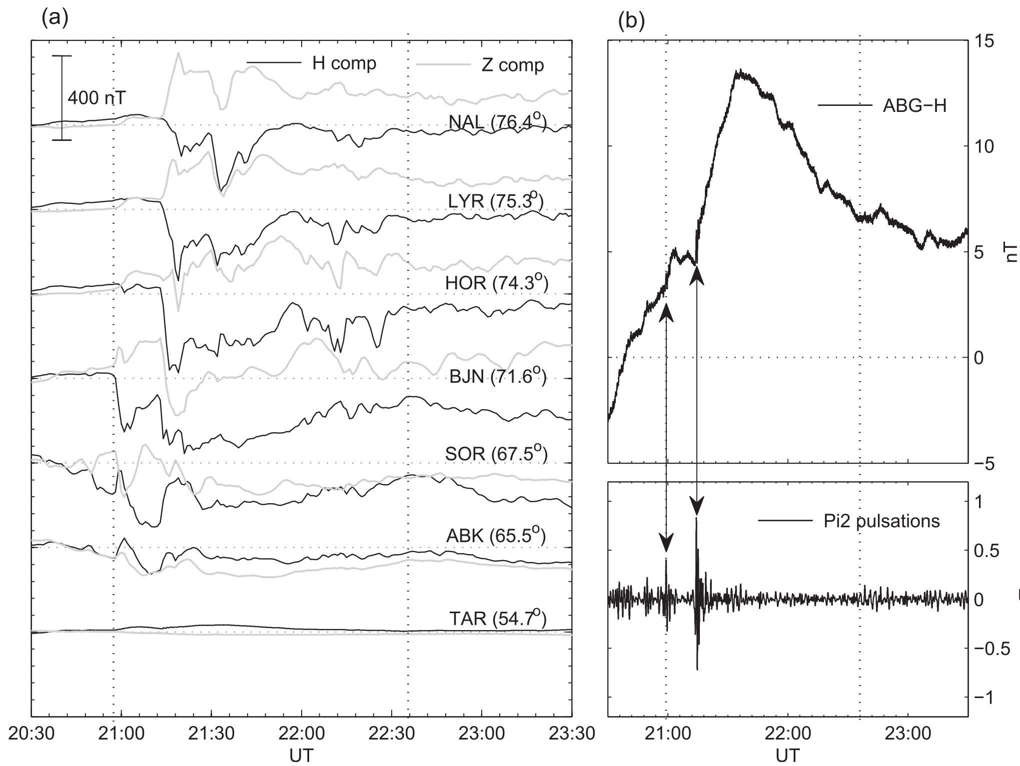

Fig. 3. (a) H and Z component disturbances at closely spaced IMAGE chain stations (~100° magnetic meridian) on the night side of the Earth. Sharp depression in H, first appears at BJN, which maximizes at HOR. Grossly opposite variations in Z component (grey lines) between stations BJN and HOR demarcates the center of westward electrojet for the event. (b) Top panel shows a clear positive bay during the event at low latitude station ABG, which starts with the onset of major Pi2 burst (bandpassed H in frequency range 7–25 mHz) displayed in bottom panel of the figure. Two vertical arrows correspond to the onset of westward surges observed respectively at 20:58 UT and 21:12 UT at very high latitudes.

occurring at very high latitudes. Positive bay in H and Pi2 bursts on the night side low latitude are typical features of a magnetic substorm (Rostoker et al., 1980; Olson, 1999). Low latitude station, ABG (MLT $\simeq$ UT + 5 h) lying in post midnight hours, clearly records positive bay and Pi2 bursts during the event as depicted respectively in top and bottom panels of Fig. 3(b). Two bursts of Pi2's are clearly identified above the background oscillations as marked by two vertical arrows in the figure. First burst of Pi2 corresponds to the westward surge observe around 20:58 UT at BJN, whereas second and more pronounced Pi2 burst corresponds to the surge observed at HOR and poleward ~21:12 UT.

The event of 2 March 2008, discussed above, clearly demonstrates a substorm activity localized poleward of the standard auroral oval, which is supported by auroral breakup (Singh et al., 2011) as well as corresponding low latitude signatures. This substorm event was fairly intense and resulted in around −500 nT depression in H component in both hemispheres (Fig. 2).

3.2. Case 2: event of 1 February 2009

Next, we present a substorm event observed at very high latitudes on 1 February 2009 which can be considered as a weak substorm ($|\Delta H|$ ~150 nT). Shown in Fig. 4 are the interplanetary conditions and geomagnetic disturbances in the time interval 21:00–23:00 UT. Interplanetary observations from ACE satellite, located at $L1$ point, have been delayed by 61 min considering constant travel speed 392 km/s of the solar wind. The components of IMF as well as solar wind velocity, density and pressure are relatively steady in the mentioned duration. Please note that density and pressure data is missing after 22:00 UT. Transient depressions in H component (~ − 150 nT) at very high latitude near-conjugate stations BHA and HOR are clearly observed as marked between a pair of dotted vertical lines. In this case, both AE and ASY indices do not respond to the substorm.

H and Z components at IMAGE stations (Fig. 5a) reveal that onset of westward electrojet was first observed at BJN around 21:30 UT, which reduced in strength within ~20 min. Another surge of electrojet appeared at 21:53 UT depressing the H component to about −150 nT. A systematic delay in arrival of westward travelling surge at stations poleward of BJN is clearly seen in figure. Opposite amplitudes of Z components (grey lines) between stations BJN and HOR confirms that the center of the westward electrojet was lying well above the latitude of the standard auroral oval.

Night side low latitude magnetic data, shown in Fig. 5(b), brings out a clear positive bay in H (upper panel), though the amplitude is fairly small (~2 nT). Filtered H

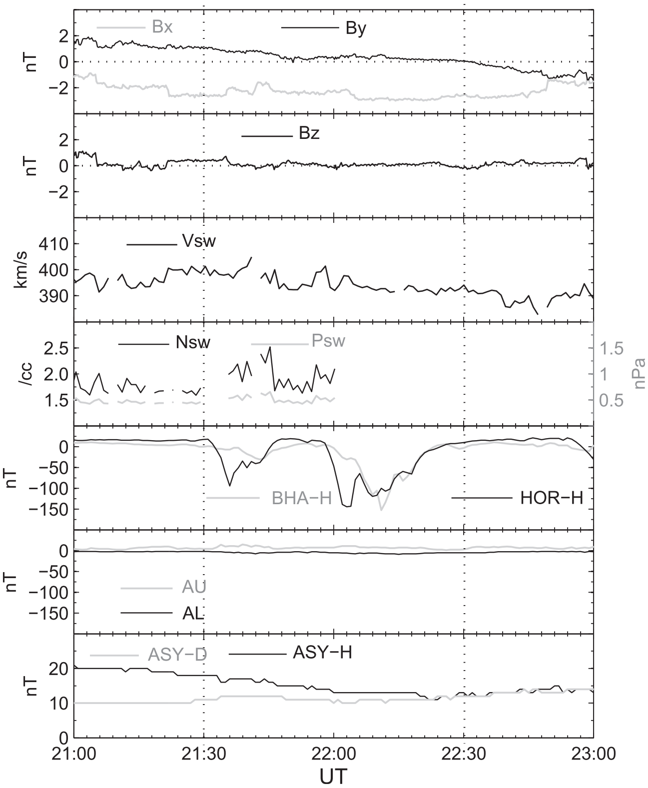

Fig. 4. Same as for Fig. 2 but on 1 February 2009. Interplanetary observations are delayed by 61 min.

data in Pi2 band range (∼7–25 mHz) in the lower panel of the figure shows the Pi2 bursts for both the westward intensifications observed at very high latitudes.

Very high latitude substorm event observed on 1 February 2009 along with the corresponding low latitude signatures clearly suggests that positive bay and Pi2's may be observed on the night side at low latitudes; not only for moderate substorms but for weak substorms also. However, in this case $ASYH/D$ enhancement is not evident.

3.3. Case 3: event of 30 January 2009

In the two substorm events, discussed above, magnetic disturbances in both the hemispheres (almost comparable amplitudes), as well their low latitude signatures, were clearly seen. However, some of the selected events were predominantly localized in one hemisphere. For the sake of completion, we present one such event which was observed at IMAGE chain observatories but did not cast appreciable magnetic disturbance at BHA. For this event, no clear positive bay and Pi2 burst were observed at the night side low latitude station.

Interplanetary conditions and geomagnetic disturbances for the event of 30 January 2009 are shown in Fig. 6. The IMF and solar wind conditions were observed by instruments aboard ACE satellite which was located at $L1$ point. Satellite data has been delayed by 66 min considering

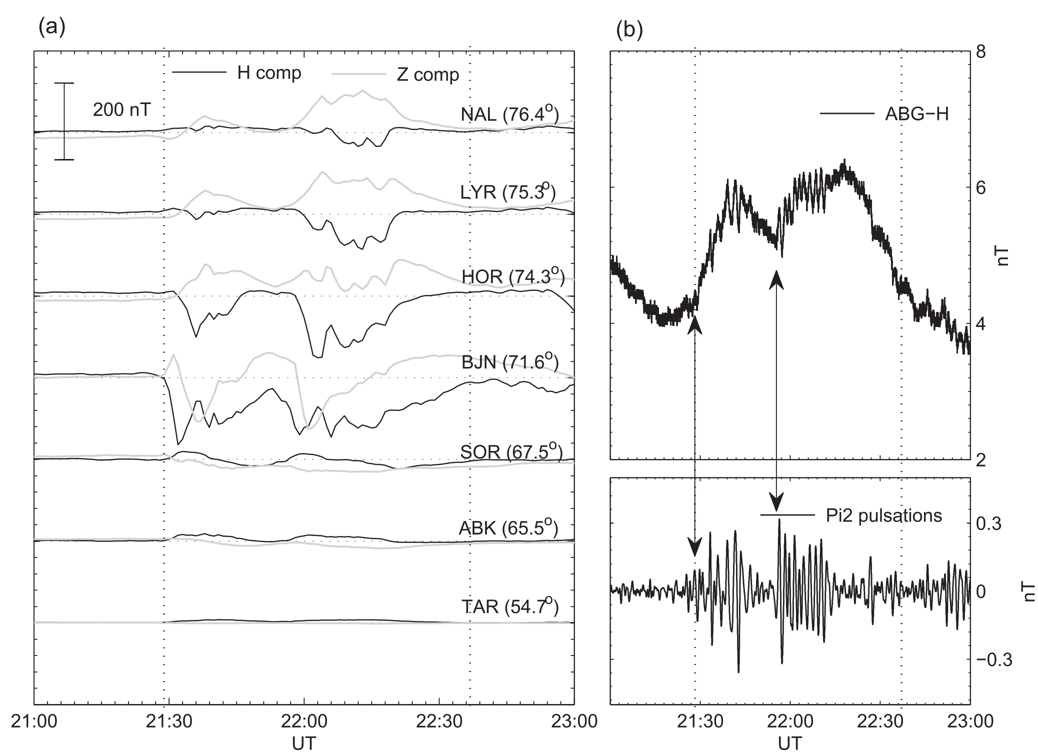

Fig. 5. (a) H and Z component disturbances at IMAGE chain stations on the night side of the Earth for 1 February 2009 event. Opposite variations in Z between stations BJN and HOR demarcates the center of the westward electrojet between BJN and HOR. (b) Positive bay in H (top panel) and Pi2 bursts (bottom panel) during the very high latitude substorm.

constant travel speed 365 km/s of the solar wind. The components of IMF and Vsw are relatively steady during the event, whereas Nsw and Psw data are not available. Transient depression in H component (over -200 nT) at HOR is evident in the figure as indicated between a pair of vertical lines, whereas H component at BHA is almost unaffected. Indices AU, AL and $ASYH/D$ do not show appreciable changes during the event.

Onset of the substorm is first observed at IMAGE chain station BJN at ∼19:35 UT and the disturbance subsequently propagated poleward (Fig. 7(a)). The maximum strength of the westward electrojet is observed at HOR station where H component (black lines) is depressed to ~ -200 nT. No appreciable disturbance is observed in the standard auroral oval. Opposite amplitudes of Z disturbance (grey lines) between stations BJN and LYR in Fig. 7(a) demonstrates the center of the westward electrojet well above the latitude of the standard auroral oval.

H component and filtered H in Pi2 band from night side low latitude station ABG are shown, respectively in upper and lower panels of Fig. 7(b). There is no clear evidence of substorm associated positive bay in H component. Also, no Pi2 burst is identified at the onset of the substorm. However, a pulse was observed during the recovery phase of the substorm.

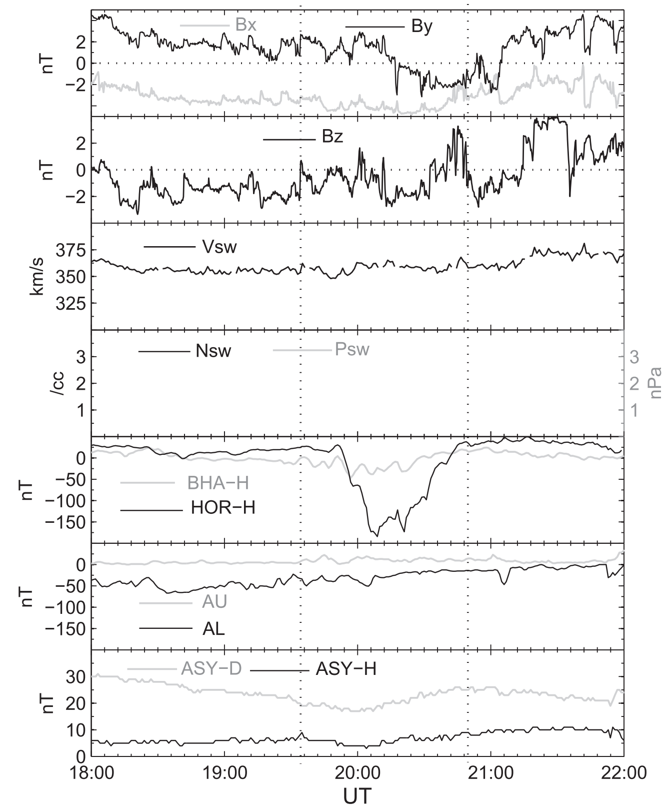

Fig. 6. Same as for Fig. 2 but on 30 January 2009. Interplanetary observations are delayed by 66 min.

4. Statistics of very high latitude substorms

After presenting three different substorm events mainly localized at very high latitudes, general features of 25 identified events are discussed further. The study includes the local time dependence, hemispherical asymmetry, and low latitude signatures of such substorms.

4.1. MLT dependence

Based on large data base of auroral images, it had been reported that substorms tend to occur between 20:00 to 02:00 MLT with maximum occurrence around 23:00 MLT (Milan et al., 2010). However, on occasions onset of substorm are observed even near dusk or dawn. The intensified westward electrojet during substorms travel great distance and the surge can arrive up to dusk hours at auroral latitudes, which consequently depresses the geomagnetic field (Akasofu et al., 1968).

MLT distribution of substorms observed at very high latitudes, has been shown in Fig. 8(a). It is evident from the figure that the majority of substorms (22 out of 25) were observed during 21:00–02:00 MLT. Only one event was observed near dusk, whereas two events were localized near dawn hours. It should be noted that the MLT distribution reported here is the onset of H depression at IMAGE chain stations (Table 1). It is possible that the onset of substorm was at some other local time and we observed the westward surge which arrived later over IMAGE stations.

4.2. Interplanetary dependence

Earlier observations suggest that the polar substorms are predominantly observed near local midnight in very localized region in the winter hemisphere during periods of northward IMF Bz or when the solar wind velocity (Vsw) is high (Gupta and Loomer, 1979; Papitashvili et al., 2002). Interplanetary and solar wind conditions during very high latitude substorms are examined in this study. IMF Bz and solar wind conditions were observed by instruments aboard ACE satellite located at a distance of ∼240 R_E at the Sun–Earth line.

Superposed epoch analysis (SEA) is performed on IMF Bz data by taking onset time of substorms as zero epoch or key time. Grey lines in Fig. 8(b) represent collective IMF Bz variations, two hours before and after substorm onset. It is evident from the figure that substorms, selected in this study, were observed during northward as well as southward IMF Bz conditions. In contradiction to earlier reports (e.g., Gupta and Loomer, 1979; Papitashvili et al., 2002), we note that many selected substorm events had clearly negative Bz.

The solar wind velocity varied significantly from event to event. Fig. 9(a) shows the Vsw distribution for analysed substorm events. The velocities were averaged for individual substorm duration and then divided into bins of 50 km/s. This analysis shows that the majority of substorms

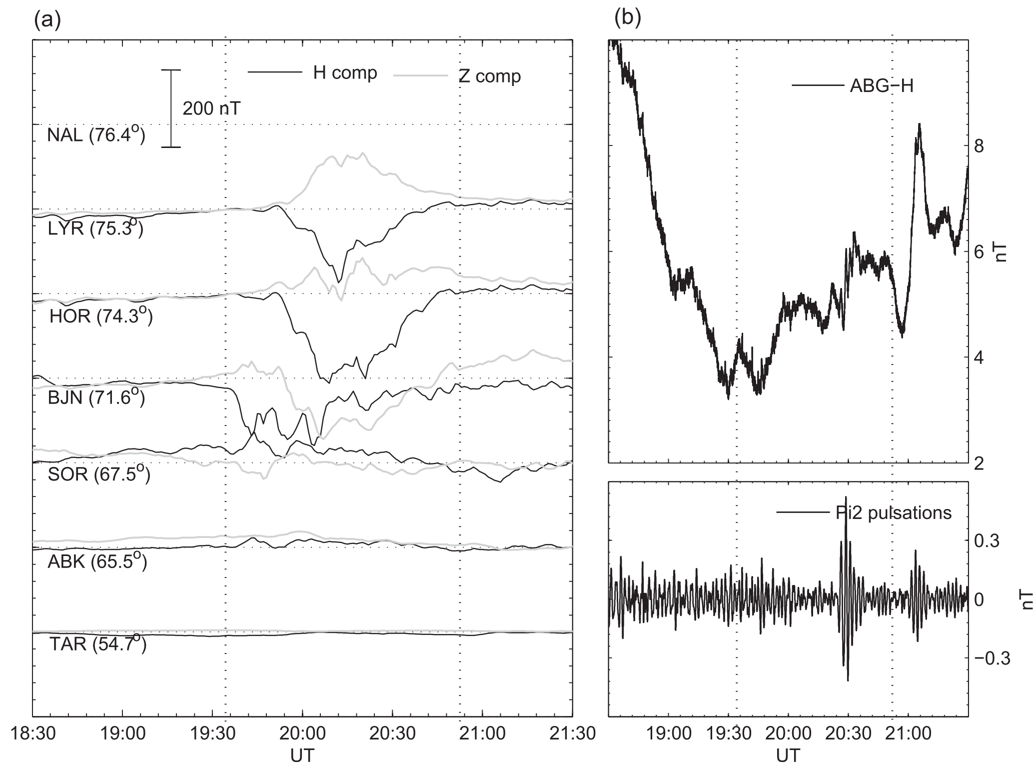

Fig. 7. (a) H and Z component disturbance at IMAGE chain stations for 30 January 2009 event. Onset of the substorm was first observed at BJN. Opposite variations in Z between stations BJN and LYR demarcates the center of the westward electrojet between BJN and LYR. (b) H component (upper panel) and bandpassed H (lower panel) in frequency range 7–25 mHz do not show clear signatures of positive bay in H and Pi2 bursts at onset of substorm.

were observed when solar wind velocity was low or moderate. Only 3 events (out of 25) were observed when the *Vsw* was over 500 km/s.

4.3. Hemispherical asymmetry

During the onset of a geomagnetic substorm the disrupted tail current flows towards the auroral/high latitude ionosphere in both hemispheres, which in turn depresses the geomagnetic field. However, there could be significant asymmetry in observed magnetic field at a pair of near-conjugate stations, either due to uneven diversion of tail current or local ionospheric conditions (Weygand and Zesta, 2008; Newell et al., 1998). Fig. 9(b) shows a comparison between magnitudes of the maximum H depression observed at near-conjugate stations BHA and HOR for selected 25 substorm events. Magnitude of BHA-H is shown on X-axis, whereas the same for HOR-H is plotted on Y-axis.

For events observed during December to February months (shown by asterisks in Fig. 9(b)), there was 24 hr sunlight at BHA and complete dark at HOR, whereas a few hours nighttime conditions were observed at BHA for the substorm cases observed during March (rectangles). At HOR stations nighttime condition continued for events selected in March month. The dashed line demarcates the perfect hemispherical symmetry in H amplitude. Even for the limited number of events, we see a tendency of higher amplitude in the winter (Northern) hemisphere, whereas it appears reversed for the events occurring during equinox month.

4.4. Low latitude implications

Geomagnetic substorms are known to cause substantial field changes at low latitudes, especially on the night side, in terms of positive bay in H and Pi2 pulsations. Lui et al. (1976) suggested that substorms observed at auroral and polar latitudes represent the same physical phenomenon. We expect that the night side low latitude signatures of very high latitude substorms should be similar to those observed in the auroral region. However, in case of weak and localized substorms the low latitude signatures may not be explicit.

Fig. 10 shows the statistics of night side low latitude signatures associated with very high latitude substorms which were not observed in the standard AE indices. 72% of substorms cast their signatures as positive bays in H and Pi2 bursts at the onset. For 8% of the cases positive bays were not clear, nevertheless Pi2 bursts were identified in H component at ABG. For 20% substorm events, neither positive bays nor Pi2 bursts were observed at ABG observatory.

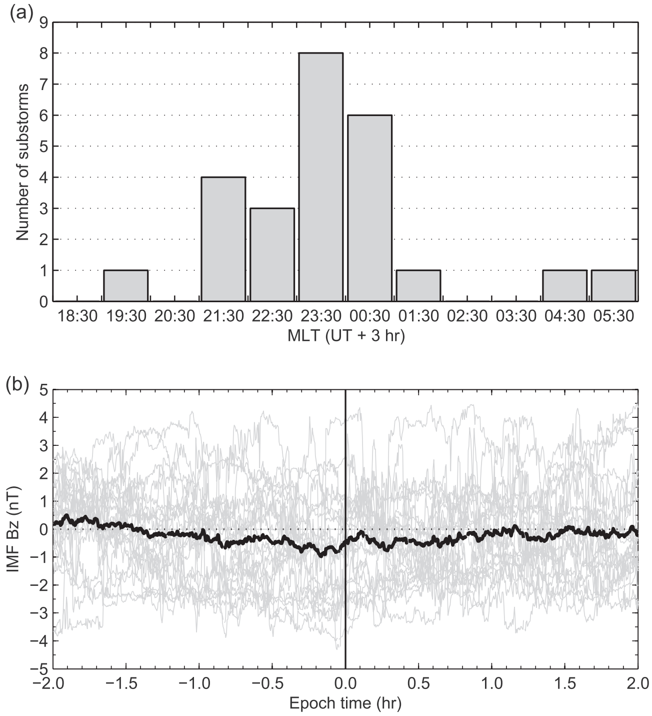

Fig. 8. (a) MLT distribution of onset of *H* depression at IMAGE chain stations for selected 25 very high latitude substorm events. Majority of substorms are observed near magnetic mid night. (b) Superposed epoch analysis of IMF *Bz* condition during high latitude substorms. Grey lines show IMF *Bz* for individual events before and after two hours of substorm onset, whereas thick black line shows average of IMF *Bz*.

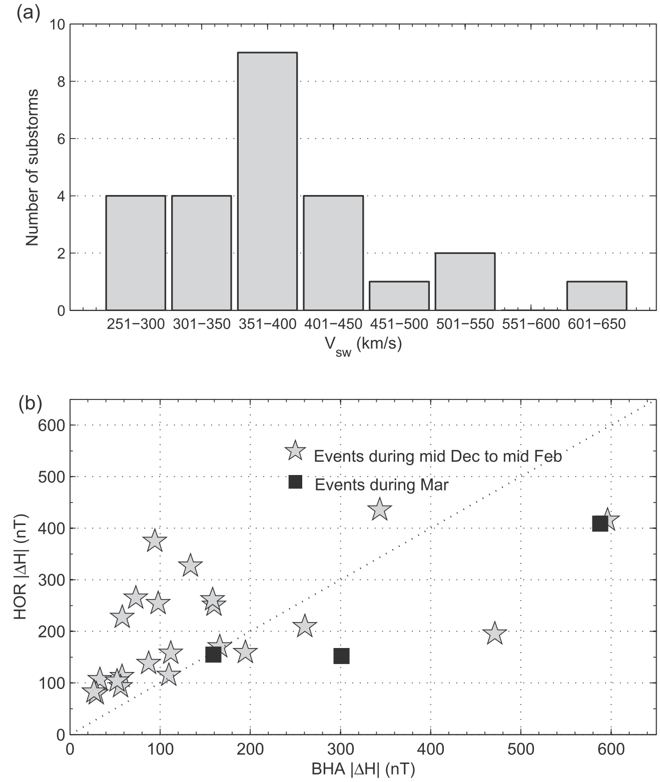

Fig. 9. (a) Solar wind velocity dependence of high latitude substorm events. Majority of substorms were observed under slow or moderate solar wind streams (<500 km/s). (b) Magnitude of maximum *H* depression at station HOR with respect to that observed at near-conjugate station BHA during Antarctic summer and equinox months. The plot shows that there is a tendency of higher amplitude at HOR lying in the winter hemisphere.

5. Discussion

Auroral region, often lying between 60° and 70° geomagnetic latitude, demarcates the open and closed geomagnetic field lines (Feldstein and Starkov, 1970). Maximum amount of energy, derived from solar wind-magnetosphere interaction, is deposited in this region by field-aligned currents (FACs) during a substorm. However, the auroral oval is quite dynamic, expands equatorward and contracts poleward with changing interplanetary conditions and strength of substorm activities (Allen and Kroehl, 1975; Kamide and Akasofu, 1983). During years 2007–10, solar activity was fairly low, which resulted in prolonged quiet magnetospheric conditions. Under such quiet conditions, the auroral oval contracts poleward of 70° magnetic latitude. Substorms occurring during quiet times may not produce appreciable field changes in the standard auroral oval. As a result such substorms are not identified in the standard *AE* indices.

Using magnetic data from a pair of very high latitude (> 74°) near-conjugate stations, we selected 25 weak to fairly intense substorms events (in 100 days duration) which were not identified in the standard *AE* indices. Closely spaced IMAGE chain stations in the same meridian enabled us to estimate the center of westward electrojet for these substorms. For all the selected events, center of the westward electrojet was lying poleward of BJN (latitude

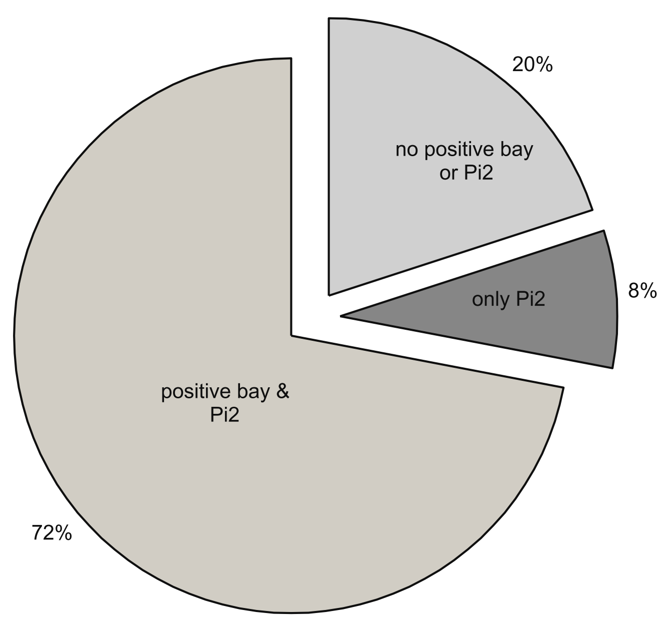

Fig. 10. Statistics for low latitude signatures of very high latitude substorms in terms of positive bay in *H* and Pi2 bursts as observed at ABG.

71.4°). After onset of a substorm the stretched magnetic field lines very rapidly return to dipolar configuration causing the aurora to move poleward, which is followed by westward electrojet (Akasofu, 1964). The westward surge arrives later at stations poleward of onset latitude. Consequently, there is typical delay in the onset of H depression towards higher latitudes as shown in Figs. 3(a) 5(a) and 7(a).

Although this study used smaller data base, we could clearly observe the MLT dependence of very high latitude substorms. Majority of substorms were observed near magnetic mid night (21:00–02:00 MLT). Earlier studies suggested that the polar substorms are predominantly observed in the winter hemisphere during periods of northward IMF Bz or when the solar wind velocity is high (Gupta and Loomer, 1979; Papitashvili et al., 2002). It should be emphasized that for substorms centered around 74° magnetic latitude, we do not find such dependence. This study shows that substorms at very high latitudes were observed during northward as well as southward IMF Bz conditions. Superposed epoch analysis indicates that many substorms occurred when Bz was negative. Moreover, majority of substorms were observed when solar wind velocity was low or moderate (<500 km/s).

Magnetic disturbances at near-conjugate pair stations often varied in tandem. However, there were considerable difference in the amplitudes in the two hemispheres. We found a tendency of higher amplitude in the winter hemisphere than those observed in the summer hemisphere. Earlier reports (e.g., Papitashvili et al., 2002; Weygand and Zesta, 2008) suggests that a substorm initiated at some latitude, propagates poleward; more easily and deeply in dark hemisphere than those in sunlit hemisphere due to significant difference in the ionospheric conductivities.

Differences in the ionospheric conductivity in the two hemispheres could have played an important role for the observed hemispherical asymmetry of amplitudes. During December to February months, very high latitude stations HOR (Northern hemisphere) and BHA (Southern hemisphere) were dark and sunlit, respectively. As a consequence of lower conductivity in Northern (winter) hemisphere, the substorm could have propagated easily to HOR, whereas at BHA in the Southern (summer) hemisphere where ionospheric conductivity was higher, the substorm disturbances might have confined to a narrow latitudinal region and could not leap efficiently to BHA. For equinox month when both stations (BHA and HOR) were in dark, amplitude was found higher in southern hemisphere for 2 out of 3 events. Larger data set would be required to establish the inter-hemispherical characteristics of very high latitude substorms during equinox months.

It should be noted that there is about 1 hr MLT difference between BHA and HOR. This could also lead to hemispherical asymmetry in the amplitude of substorm disturbances in addition to uneven distribution of the tail current in two hemispheres.

A magnetic substorm causes significant magnetic field changes at night side low latitudes. Positive bay in H component, $ASYH/D$ enhancements and Pi2 bursts associated with auroral substorms have been extensively studied for the identification of substorm activities (Rostoker et al., 1980; Iyemori, 1990; Olson, 1999; Clauer and McPherron, 1974). However, low latitude signatures of substorms occurring at very high latitudes, have got less attention despite the fact that there is no physical difference between the substorms initiated at auroral and polar latitudes (Lui et al., 1976). For substorms, selected in this study, we could identify low latitude signatures (positive bay and/or Pi2 pulsations) of 80% events even if AE indices failed to monitor. Since the ASY indices are computed using magnetic data from 5–6 longitudinally distributed stations, there is probability that signatures of weak and localized substorms may not be observed in ASY. However, for some events ASY enhancements were clearly evident, e.g., for the event 2 March 2008.

A new substorm index, Wp is recently introduced by Nosé (2009) as an indicator of substorm onset. The Wp index is based on the Pi2 pulsations observed at globally distributed observatories. For substorms, localized to very high latitudes, Wp index could probably be a better indicator than the popular AE and ASY indices.

6. Concluding remarks

Magnetic disturbance data, collected during four summer Antarctic expeditions (XXVI–XXIX) at Indian Antarctic station Bharati, has been analyzed in conjunction with magnetic data from IMAGE chain and Alibag observatories. Important findings of this study can be summarized as follows:

1. Significant number of substorms during the low solar activity period (year 2007–2010) were observed poleward of the standard auroral oval without giving appreciable clue in frequently used auroral electrojet indices.
2. Substorms initiated at very high latitudes often cause substantial magnetic field changes at night side low latitudes, e.g., positive bays and Pi2 bursts in H component.
3. Strength of substorms Magnetic signatures of very high latitude substorms were often observed more pronounced in the winter hemisphere than those observed in the summer hemisphere probably due to differences in the ionospheric conductivities.
4. Very high latitude substorms (>70° latitude) were observed during northward as well as southward IMF Bz conditions. Fairly large number of substorms, selected in this study, were observed during slightly slow or moderate solar wind speed in contradiction to earlier reports.

The most obvious inference of this study is that inclusion of polar latitude stations to the existing standard AE network will increase the reliability of AE indices for substorm studies. For this study, only Antarctic summer season data was available from Bharati, full year data in the forthcoming expeditions will help us to understand inter-hemispherical characteristics of substorm phenomenon.

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References

Akasofu, S.-I. The development of the auroral substorm. Planet. Space Sci. 12, 273–282, 1964.

Akasofu, S.-I. Polar and magnetospheric substorms, D. Reidel, Dordrecht, Holland, 1968.

Allen, J., Kroehl, H. Spatial and temporal distributions of magnetic effects of auroral electrojets as derived from AE indices. J. Geophys. Res. 80, 3667–3677, 1975.

Clauer, C., McPherron, R.L. Mapping the local time-universal time development of magnetospheric substorms using mid-latitude magnetic observations. J. Geophys. Res. 79, 2811–2820, 1974.

Clauer, C., Kamide, Y. DP 1 and DP 2 current systems for the March 22, 1979 substorms. J. Geophys. Res. 90, 1343–1354, 1985.

Davis, T., Sugiura, M. Auroral electrojet activity index ae and its universal time variations. J. Geophys. Res. 71, 785–801, 1966.

Dobias, P., Wanliss, J.A. Intermittency of storms and substorms: is it related to the critical behaviour? Ann. Geophys. 27, 2011–2018, 2009.

Dungey, J.W. Interplanetary magnetic field and the auroral zones. Phys. Rev. Lett. 6, 47–48, 1961.

Feldstein, Y.I., Starkov, G.V. The auroral oval and the boundary of closed field lines of geomagnetic field. Planet. Space Sci. 18, 501–508, 1970.

Gupta, J.C., Loomer, E.I. Influence on AE index of substorms appearing north of Cambridge Bay. Planet Space Sci. 27, 1019–1025, 1979.

Gustafsson, G., Papitashvili, N.E., Papitashvili, V.O. A revised corrected geomagnetic coordinate system for epochs 1985 and 1990. J. Atmos. Terr. Phys. 54, 1609–1631, 1992.

Iyemori, T. Storm-time magnetospheric currents inferred from mid-latitude geomagnetic field variations. J. Geomag. Geoelectr. 42, 1249–1265, 1990.

Kamide, Y., Akasofu, S.-I. Notes on the auroral electrojet indices. Rev. Geophys. 21, 1647–1656, 1983.

Kisabeth, J., Rostoker, G. The expansive phase of magnetospheric substorms, 1. Development of the auroral electrojets and auroral arc configuration during a substorm. J. Geophys. Res. 79, 972–984, 1974.

Laundal, K.M., Østgaard, N. Asymmetric auroral intensities in the Earth's Northern and Southern hemispheres. Nature 460, 491–493, 2009.

Loomer, E.I., Gupta, J.C. Some characteristics of high-latitude substorms. J. Atmos. Terr. Phys. 42, 645–652, 1980.

Lui, A.T.Y., Akasofu, S.-I., Hones Jr., E., Bame, S., McIlwain, C. Observation of the plasma sheet during a contracted oval substorm in a prolonged quiet period. J. Geophys. Res. 81, 1415–1419, 1976.

Lui, A.T.Y. Comment on "Tail reconnection triggering substorm onset". Science, vol. 324, p. 1391, 2009. http://dx.doi.org/10.1126/science.1167726.

Maclennan, C.G., Lanzerotti, L.J., Akasofu, S.-I., Zaitzev, A.N., Wilkinson, P.J., Wolfe, A., Popov, V. Comparison of electrojet indices from the Northern and Southern hemispheres. J. Geophys. Res. 96, 267–274, 1991.

McPherron, R.L. Substorm related changes in the geomagnetic tail: the growth phase. Planet. Space Sci. 20, 1521–1539, 1972.

McPherron, R.L., Russell, C.T., Kivelson, M.G., Coleman, P. Substorms in space: the correlation between ground and satellite observations of the magnetic field. Radio Sci. 8, 1059–1076, 1973a.

McPherron, R.L., Russell, C.T, Aubry, M.P. 9 Phenomenological model for substorms. J. Geophys. Res. 78, 3131–3149, 1973b.

Meng, C.-I., Akasofu, S.-I. Polar magnetic substorm in conjugate areas. Radio Sci. 3, 751–760, 1968.

Milan, S.E., Grocott, A., Hubert, B. A superposed epoch analysis of auroral evolution during substorms: local time of onset region. J. Geophys. Res. 115, A00I04, http://dx.doi.org/10.1029/2010JA015663, 2010.

Nandy, D., Jaramillo, A.M., Martens, P.C.H. The unusual minimum of sunspot cycle 23 caused by meridional plasma flow variations. Nature 471, 80–82, 2011.

Newell, P.T., Meng, C.-I., Wing, S. Relation to solar activity of intense aurorae in sunlight and darkness. Nature 393, 342–344, 1998.

Newell, P.T., Sotirelis, T., Ruohoniemi, J.M., Carbary, J.F., Liou, K., Skura, J.P., Meng, C.-I., Deehr, C., Wilkinson, D., Rich, F.J. OVATION: oval variation, assessment, tracking, intensity, and online nowcasting. Ann. Geophys. 20, 1039–1047, 2002.

Newell, P.T., Sotirelis, T., Wing, S. Seasonal variations in diffuse, monoenergetic, and broadband aurora. J. Geophys. Res. 115, A03216, http://dx.doi.org/10.1029/2009JA014805, 2010.

Nosé, M., Iyemori, T., Takeda, M. Toh, H., Ookawa, T., Cifuentes-Nava, G., Matzka, J., Love, J.J, McCreadie, H., Tuncer, M.K., Curto, J.J. New substorm index derived from high-resolution gemagnetic field data at low latitude and its comparison with AE and ASY indices. in: Proceedings of XIII IAGA Workshop on Geomagnetic Observatory Instruments, Data Acquisition, and Processing, pp. 202–207, 2009.

Olson, J. Pi2 pulsations and substorm onsets: a review. J. Geophys. Res. 104, 17499–17520, 1999.

Østgaard, N., Mende, S.B., Frey, H.U., Sigwarth, J.B., Aasnes, A., Weygand, J. Auroral conjugacy studies based on global imaging. J. Atmos. Solar-Terr. Phys. 69, 249–255, 2007.

Papitashvili, V.O., Clauer, C.R., Christiansen, F., Kamide, Y., Petrov, V.G. Rasmussen, O., Watermann, J.F. Near-conjugate magnetic substorms at very high latitudes observed by Greenland and Antarctic ground magnetometers and Ørsted satellite. in: R.M. Winglee (Ed.) Proceedings of International Conference on Substorm-6, pp. 110–114, 2002.

Ritter, P., Lühr, H. Near-Earth magnetic signature of magnetospheric substorms and an improved substorm current model. Ann. Geophys. 26, 2781–2793, 2008.

Rostoker, G., Akasofu, S.-I., Foster, J., Greenwald, R., Kamide, Y., Kawasaki, K., Lui, A., McPherron, R.L., Russell, C.T. Magnetospheric substorms – definition and signatures. J. Geophys. Res. 85, 1663–1668, 1980.

Sastri, J.H. Equatorial geomagnetic and ionospheric effects of substorms. Indian J. Radio Space Phys. 31, 309–320, 2002.

Sergeev, V.A., Pellinen, R.J., Pulkkinen, T.I. Steady magnetospheric convection: a review of recent results. Space Sci. Rev. 75, 551–604, 1996.

Shi, Y., Zesta, E., Lyons, L.R., Boudouridis, A., Yumoto, K., Kitamura, K. Effect of solar wind pressure enhancements on storm time ring current asymmetry. J. Geophys. Res. 110, A10205, http://dx.doi.org/10.1029/2005JA011019, 2005.

Singh, A.K., Sinha, A.K., Pathan, B.M., Rawat, R. Solar flare effect on low latitude asymmetric indices. J. Atmos. Solar Terr. Phys. 77, 119–124, http://dx.doi.org/10.1016/j.jastp.2011.12.010, 2012a.

Singh, A.K., Sinha, A.K., Pathan, B.M., Rajaram, R., Rawat, R. Effect of prompt penetration on the low latitude ASY indices. 'under review' J. Atmos. Solar Terr. Phys. 2012b.

Singh, A.K., Jayashree, B., Sinha, A.K., Rawat, R., Pathan, B.M., Dhar, A. Observations of near-conjugate high latitude substorms and their low latitude implications. Current Sci. 101, 1073–1078, 2011.

Stenbaek-Nielsen, H., Davis, T., Glass, N. Relative motion of auroral conjugate points during substorms. J. Geophys. Res. 77, 1844–1858, 1972.

Weygand, J.M., Zesta, E. Comparison of auroral electrojet indices in the Northern and Southern hemispheres. J. Geophys. Res. 113, A08202, http://dx.doi.org/10.1029/2008JA013055, 2008.

Wu, C.-C., Liou, K., Lepping, R.P., Meng, C.-I. Identification of substorms within storms. J. Atmos. Solar-Terr. Phys. 66, 125–132, 2004.