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Auroral electrojets during severely disturbed geomagnetic condition on 24 August 2005

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Abstract

Very intense and highly dynamic eastward and westward currents flowing in the auroral ionosphere are traditionally monitored by the auroral electrojet indices – AU and AL, respectively. In this study we show that on occasions of intense magnetic activity, entire auroral oval could be dominated by the westward flowing currents, which lead to depression not only in AL index but also in supposedly positive AU index. During negative AU intervals, there could be up to $\sim 20\%$ underestimation of the total maximum intensity of the auroral electrojet represented by AE index(defined as $AU - AL$). A detailed investigation of a well-studied extremely intense event of 24 August 2005 has been carried out. Global prevalence of the westward auroral electrojet was clearly observed at the auroral latitudes during the unusually intense substorm ($AL \sim -4000$ nT) on the day. Moreover, along the noon meridian westward electrojet appeared in the auroral region whereas eastward electrojet shifted towards lower latitudes. This paper emphasizes that intense substorms are represented better by AL index than AE index.

Keywords: Storm; Substorm; Auroral electrojets

1. Introduction

Intense electrojets flow in the auroral ionosphere during geomagnetic substorms. The direction and intensity of the auroral electrojets depend on the local times, for example, near the midnight hours strong westward electrojet prevails, whereas comparatively less intense eastward electrojet is often observed on the dusk side (Kamide, 1976). Maximum intensities of the eastward and westward auroral electrojets are represented by the AU and AL indices, respectively (Davis and Sugiura, 1966). The AU/AL index being upper/lower envelop of H component disturbances observed in the auroral region, is positive/negative by definition. The total maximum auroral current intensity is supposed to be represented by a strictly positive AE index, defined as $AE = AU - AL$ (Davis and Sugiura, 1966).

The auroral electrojet (AE) indices (i.e., AU, AL and AE) introduced by Davis and Sugiura (1966) have been extensively used for over several decades in relation to various processes of the solar–terrestrial interaction. These indices (mainly AE or AL index) are widely used to identify various phases of substorms (e.g. Juusola et al. (2011), Singh et al. (2013), etc.). In particular, sudden enhancement (depression) of AE index (AL index) is often related to the onset of a substorm. However, these indices have some limitations in precise monitoring of substorms (see Singh et al. (2012) and references therein). The AU and AL indices are known

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to (i) maximize at different times during the course of a substorm (Kamide et al., 1996), (ii) not always linearly related (Gizler et al., 1976) and (iii) exhibit different diurnal and seasonal variations (Newell et al., 2013; Singh et al., 2013 and references therein). This led Kamide and Rostoker (2004) to question the physical meaning of the AE index which is a sum of two electrojets of fairly different nature (represented by AU and AL) and proposed ceasing the derivation and distribution of the AE index. Note that the AE index ($= AU - AL$) is different from the AE indices which combinedly represent AU, AL and AE. However, recently Newell and Gjerloev (2011) reported that over a period of 2 years the nightside auroral power (even at 1 min cadence) has nearly linear relationship with the AE index (correlation $r = 0.81$) thereby suggesting the fact that the AE index has a clear geophysical meaning.

It has been reported that AU index, which is essentially positive by definition, may attain negative values during intense geomagnetic activity either due to shift of the eastward electrojet towards lower latitudes (Feldstein et al., 2006) or due to the depression produced by intensified ring current at auroral latitudes (Rangarajan, 1989). For the negative AU intervals, the AE index would be smaller than the magnitude of AL index implying that the total maximum intensity of the auroral electrojet is weaker than the westward electrojet itself.

In this study we have briefly examined negative AU intervals during the last solar cycle. A particular event of 24 August 2005, extensively reported in literature (e.g. Mansilla (2013), Keika et al. (2008), Sreeja et al. (2009), etc.), has been studied in detail here. We revisit this event because an intense substorm ($AL \sim -4000$ nT) had occurred during the main phase of a storm on this day and AU index turned negative during the course of the substorm.

The geomagnetic activity indices were taken from the World Data Center (WDC) for geomagnetism, Kyoto. Time-shifted interplanetary magnetic field (IMF) and solar wind parameters to the nose of Earth's bow shock, measured by instruments aboard ACE satellite, were taken from OMNIWeb (http://omniweb.gsfc.nasa.gov/form/omni_min.html).

2. Observation and results

Intensifications of the eastward and westward auroral electrojets are typically observed at different local times during isolated as well storm-time substorms (Kamide et al., 1996; Iyemori and Rao, 1996). Fig. 1 depicts AU and AL indices (at 1 min cadence) characterizing eastward and westward auroral electrojets, respectively during an intense magnetic storm (minimum $SYMH \approx -100$ nT). The storm started on 21 April 2001 when a coronal mass ejection (CME) hit Earth's magnetosphere. The IMF and solar wind conditions have been shown in the top four panels of Fig. 1. $SYMH$ index, depicted in the bottom panel of the figure, clearly shows that the magnetosphere was first compressed due to enhanced solar wind dynamic pressure

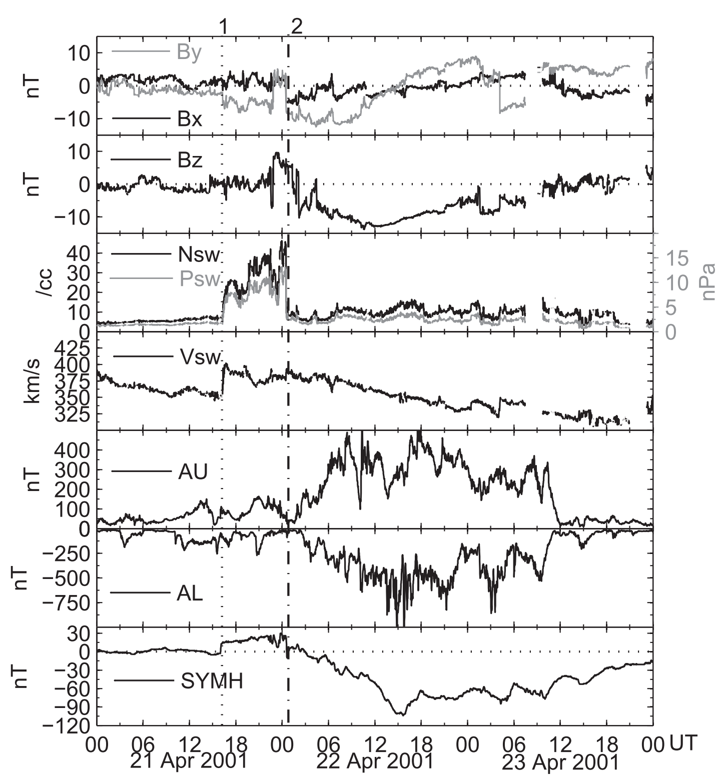

Fig. 1. Components of IMF, solar wind conditions and geomagnetic indices characterizing substorm and storm during 21–23 April 2001. Pair of vertical lines (1 & 2) mark the initial phase of the sotrm, following which the main phase started and the $SYMH$ was profoundly depressed (bottom panel). Highly correlated AU and AL enhancements are evident during the storm (minimum $SYMH \sim -100$ nT).

(marked by vertical line-1) and at later stage the ring current started building up possibly due to the southward turning of the IMF Bz (marked by vertical line-2).

Multiple intensifications in the AU and AL indices are evident during the storm (see fifth and sixth panels from the top in Fig. 1). Although the eastward and the westward auroral electrojets are believed to be driven by different physical processes (Kamide and Rostoker, 2004), in the entire duration shown in Fig. 1, AU and AL indices were simultaneously enhanced and highly anti-correlated ($r = -0.81$). The AE index ($AE = AU - AL$), representing the total maximum intensity of the auroral electrojet would attain, as expected, positive and higher values than AU as well as $|AL|$ index in this case.

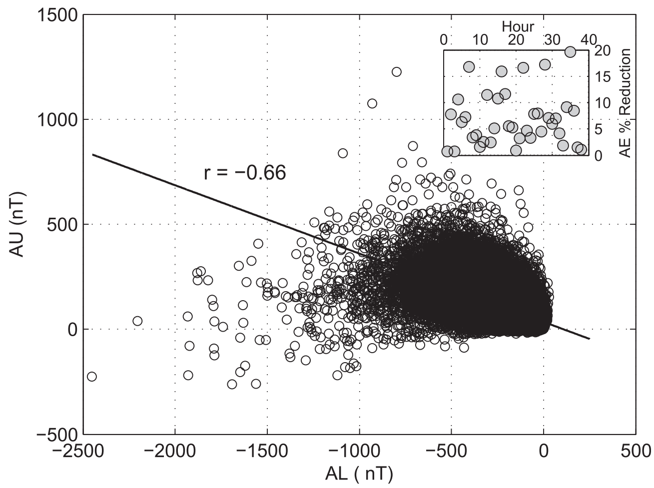

Fig. 2. Scatter plot of hourly AU and AL indices for the complete solar cycle 23. For a few hours (particularly for $AL < -1000$ nT) AU index attains negative values, which leads to underestimation of the magnitude of AE index up to 20% in comparison to AL index as shown in the inset.

We examined the relation between hourly AU and AL indices for the complete solar cycle 23 (years 1996–2008). The hourly averaged data would inevitably suppress the effect of short-lived AU or AL fluctuations. The scatter plot of AL and AU indices, shown in Fig. 2, contains over 10^5 data points. In the selected duration of about 13 years, the scatter of the points suggests that AU is not strongly dependent on AL and this naturally has implications for our understandings on the underlying processes causing these electrojet components.

It is interesting to note in Fig. 2 that for intense substorms ($AL < -1000$ nT), AU values were often less than those observed for substorms having $AL > -1000$ nT. For a few hours, particularly during intense substorms ($AL < -1000$ nT), AU index attains significantly negative values. It could be due to the prevalence of westward electrojet over the entire auroral oval. However, it should be noted that the AU and AL data shown in Fig. 2 are provisional and it is not definite whether minimum required AE stations were available for the computation of indices or not. Unavailability of data from observatories in the dusk hours could additionally result in negative AU values.

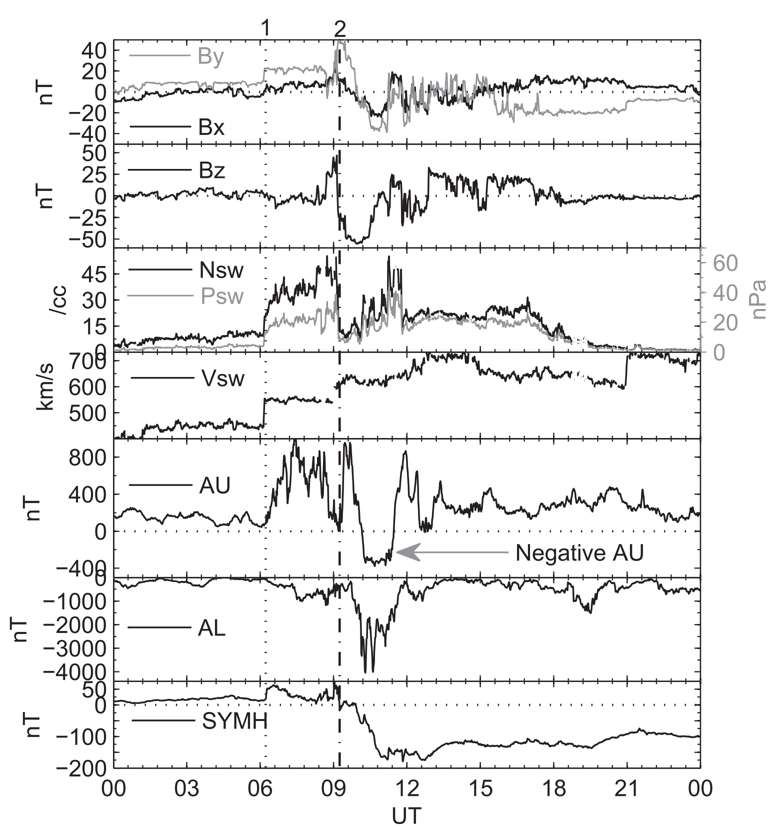

Fig. 3. Same as Fig. 1, but for an intense storm (minimum $SYMH \sim -180$ nT) on 24 August 2005. AU index was fairly depressed (marked by horizontal arrow) during an extremely intense substorm ($AL < -4000$ nT).

2.1. 24 August 2005 event

The near-Earth environment was severely disturbed on 24 August 2005 due to extremely active Sun. Extremely intense geomagnetic activity was driven by a combined effect of two coronal mass ejections (CMEs) erupted from the Sun (Papaioannou et al., 2009). The IMF and solar wind conditions for 24 August 2005 are shown in the top four panels of Fig. 3. *SYMH* index (representing intensity of geomagnetic storms) reached to about −200 nT following the southward turning of IMF *Bz*. During the main phase of the magnetic storm (around 0900–1200 UT), unusually intense westward auroral electrojet ($AL \sim -4000$ nT) was observed. The intensity variation of the eastward auroral electrojets was not consistent with the typical variations, viz. shown above in Fig. 1. Intensity of the eastward electrojet initially increased to about 1000 nT under southward IMF *Bz* condition. However, later the standard *AU* index turned negative (minimum $AU \sim -380$ nT), which suggests that all the standard *AE* observatories (10 for this event) were under the influence of the westward electrojet and the eastward electrojet did not appear at the standard auroral latitudes. The near-Earth environment was severely disturbed on 24 August 2005 due to extremely active Sun. Extremely intense geomagnetic activity was driven by a combined effect of two coronal mass ejections (CMEs) erupted from the Sun (Papaioannou et al., 2009). The IMF and solar wind conditions for 24 August 2005 are shown in the top four panels of

Table 1
List of SuperMAG observatories, their coordinates and MLT.

Station name	Code	Geographic		CGM		MLT at
		lat. (°N)	long. (°E)	lat. (°N)	long. (°E)	1000 UT
Abisko	ABK	68.4	18.8	65.5	101.1	1155
Cape Chelyuskin	CCS	77.7	104.3	72.2	175.8	1652
Barrow	BRW	71.3	203.2	70.1	252.1	2157
College	CMO	64.9	212.2	65.1	264.8	2248
Yellowknife	YKC	62.4	245.6	69.3	301.6	0115
Fort Churchill	FCC	58.8	265.9	68.7	333.0	0320
Post-de-la-Baleine	PBQ	55.3	282.3	65.3	359.1	0506
Narsarsuaq	NAQ	61.2	314.2	66.0	42.6	0801
Leirvogur	LRV	64.2	338.3	64.8	66.5	0936

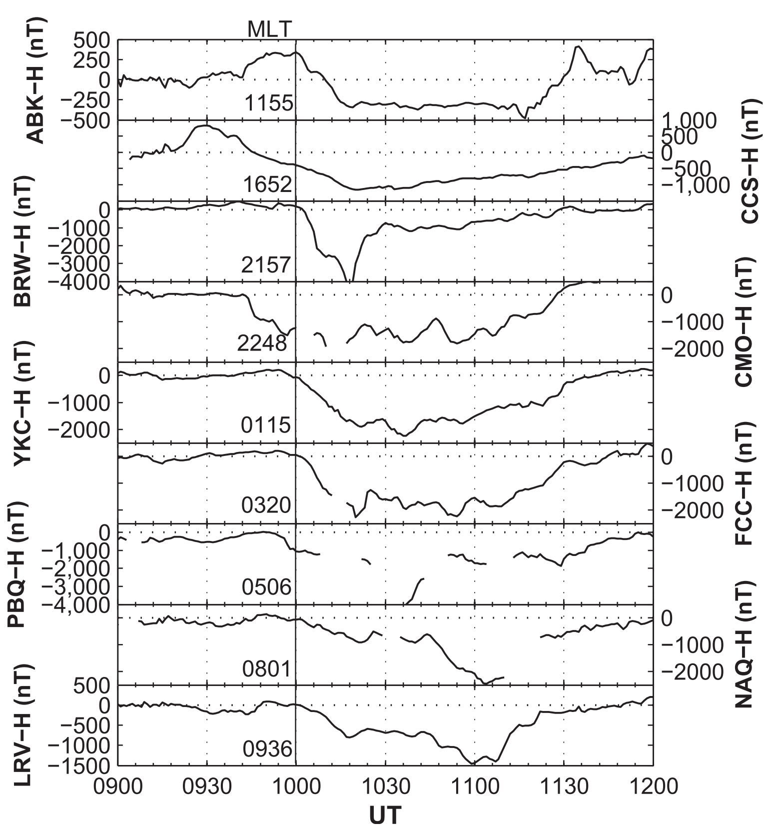

Fig. 4. *H*-components variations at the standard auroral observatories during the interval of negative *AU* shown in Fig. 3. Depression in *H* at all the local times clearly suggest the prevalence of westward electrojet. MLT of each station at 1000 UT has been given in subplots.

Fig. 3. *SYMH* index (representing intensity of geomagnetic storms) reached to about −200 nT following the southward turning of IMF *Bz*. During the main phase of the magnetic storm (around 0900–1200 UT), unusually intense westward auroral electrojet ($AL \sim -4000$ nT) was observed. The intensity variation of the eastward auroral electrojets was not consistent with the typical variations, viz. shown above in Fig. 1. Intensity of the eastward electrojet initially increased to about 1000 nT under southward IMF *Bz* condition. However, later the standard *AU* index turned negative (minimum $AU \sim -380$ nT), which suggests that all the standard *AE* observatories (10 for this event) were under the influence of the westward electrojet and the eastward electrojet did not appear at the standard auroral latitudes.

In order to examine the local time dependence of magnetic field variations at the standard AE observatories,

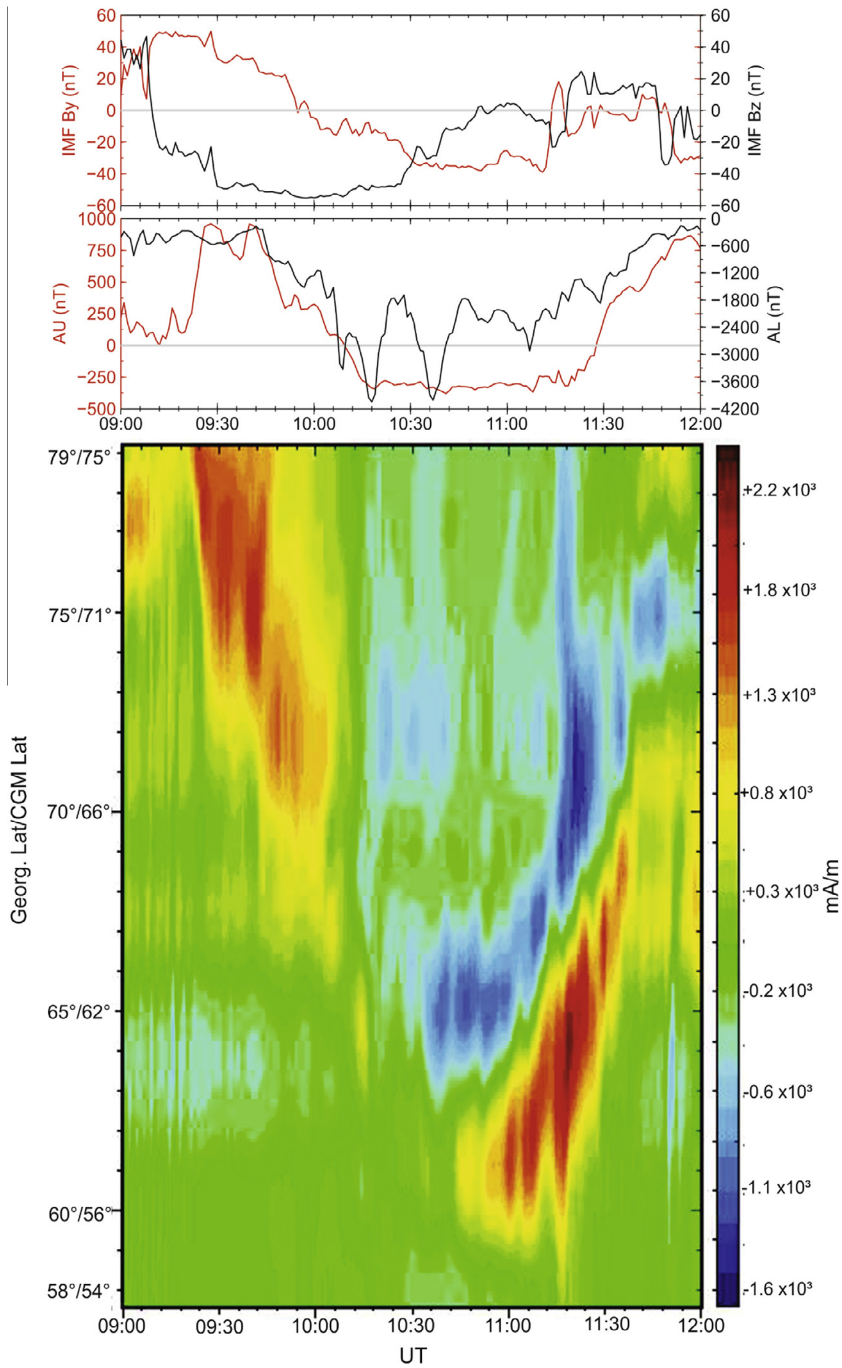

Fig. 5. Top to bottom: *By* and *Bz* components of IMF, *AU* and *AL* indices and ionospheric equivalent currents from sub-auroral to high latitude near noon meridian during 0900–1200 UT on 24 August 2005. *AU* index turns negative during an extremely intense substorm ($AL < -4000$ nT). The eastward electrojet (shown in red color) was first observed at higher latitudes and later shifted to sub-auroral latitudes, whereas at the standard auroral latitude westward electrojet (blue color) prevails during the substorm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

we took data from SuperMAG (Gjerloev, 2012). Details of the observatories and their magnetic local times (MLTs) at the time of the substorm are given in Table 1. For the selected event, *H*-component variations during 0900–1200 UT have been shown in Fig. 4. It may be noted that *y*-scale is different for different stations (Fig. 4).

H-component negative bays were globally observed during the substorm (see Fig. 4). It was most pronounced in the American sector being on the nightside for the event. Two short-lived surges of westward electrojet produced about -4000 nT depression at stations BRW (2157 MLT) and PBQ (0506 MLT) at different UT instances. In the dusk hour (Russian sector), station CCS (1652 MLT) recorded about -1200 nT *H*-component negative bay. Moreover, at ABK located in the noon sector *H*-component negative bay was about -400 nT.

Global disappearance of the eastward auroral electrojet for the event is intriguing. Unavailability of magnetic observatories along the dusk meridian for the event did not allow us to examine the shift of eastward electrojet towards lower latitudes. However, a dense network of IMAGE observatories along the noon meridian did offer such opportunity.

2.2. Ionospheric currents along the noon meridian

Ground magnetic data from closely-spaced IMAGE chain observatories in magnetic latitude range $\sim 54°$N–75°N along 100° magnetic meridian can be used to calculate ionospheric equivalent electrojets (Vanhamäki et al., 2003). The web-based program is available at http://www.geo.fmi.fi/MIRACLE/iono_1D.php. The ionospheric equivalent electrojets represent the time evolution of the eastward and westward equivalent currents along a north–south profile. For the 24 August 2005 event, ionospheric equivalent currents have been shown in Fig. 5. Top panel of the figure shows IMF *By* and *Bz* components and auroral electrojet indices (*AU* and *AL*) are shown in the middle panel. In the bottom panel of Fig. 5, red and blue colors respectively represent mean eastward and westward equivalent currents. On the *Y*-axis the geographic latitude and corresponding CGM latitude of IMAGE stations have been shown.

It is interesting to note that initially the eastward electrojet appeared at higher latitudes (CGM $\sim 75°$N) and later moved to about 70°N following the southward turning of the IMF *Bz*. Furthermore, westward electrojet appeared along the noon meridian at the standard auroral latitudes, whereas eastward electrojet co-existed at the sub-auroral latitudes.

3. Discussion and conclusion

Typically, during a geomagnetic substorm different kind of magnetic field variations (mainly in the *H*-component) are globally observed in the auroral region due to intensification of different currents, e.g. (i) depression near midnight-dawn hours due to the westward electrojet which may, however, expand up to the pre-noon hours (Feldstein et al., 2006; Behera et al., 2014), (ii) enhancement near dusk hours due to the eastward electrojet (Guo et al., 2014 and references therein) and (iii) occasional enhancement or depression near noon due to extension of the polar electrojet towards the auroral latitudes (Feldstein et al., 2006). Positive and negative envelops of *H*-components variations from globally distributed auroral stations (respectively *AU* and *AL* indices) represent the maximum intensities of the eastward and westward auroral electrojets. *AU* and *AL* indices systematically vary during the course of a substorm. However, on the 24 August 2005 exceptionally intense substorm ($AL \sim -4000$ nT) was observed during 1000–1200 UT and the standard *AU* index attained negative values (minimum $AU \sim -380$ nT). It clearly suggests that during the event only westward auroral electrojet was globally observed in the auroral region.

Since data from 10 standard *AE* observatories were available for computation of indices for the 24 August 2005 event, it probably rules out the possibility that negative *AU* index could be artifact of limited number of stations in the standard auroral oval. The equatorial ring current could lead to some depression in the *H*-component at auroral latitudes (Rangarajan, 1989). For the storm event under consideration, on an average the low latitude *H* component was depressed to about -180 nT. The magnetic effect of the ring current subsides as cosine of magnetic latitude in the off-equatorial plane (e.g. Iyemori and Rao (1996)). At 65° magnetic latitude, reduction in *H*-component due to the ring current would be ~ -80 nT, which is far less than observed *AU* depression (~ -380 nT). It suggests that negative *AU* values observed on 24 August 2005 could not be attributed to the intensified ring current.

For the examined event, *H*-component variations from globally distributed standard AE observatories revealed depressed field at all the local times. The most pronounced *H* negative bays (about -4000 nT) were observed on the night and dawn sides. Unusually large depression (~ -1200 nT) in the dusk hour suggests that quite intense westward electrojet extending up to dusk suppressed the effect of expected eastward electrojet. It maybe noted that extreme substorm events, mainly those occurring during storms, need not to be same as isolated substorms (e.g. Hoffman et al. (2010)).

Appreciable change in the size of the polar cap is observed in response to the magnetic activity level (e.g. Milan et al. (2008)). During storm-times, size of the polar cap increases and polar electrojets could migrate to the auroral or even sub-auroral latitudes (Rodger and Cowley, 1986). The direction of dayside polar electrojet mainly depends upon IMF *By*. As a result of enhanced polar electrojet, positive or negative variations in dayside *H*-component are observed for $By > 0$ and $By < 0$ conditions, respectively (Rodger and Cowley, 1986). The westward current leading to ~ -400 nT depression on the noonside (see Fig. 4) could be manifestation of extended polar cap during the event.

On 24 August 2005 time evolution of the eastward and westward equivalent currents along the noon meridian (in Fig. 5) suggests that the eastward electrojet initially appearing at higher latitudes ($\sim 75^\circ$ CGM lat) moved towards the standard auroral latitude. During the extremely intense substorm, westward electrojet appeared along the noon meridian at the standard auroral latitudes due to extending polar electrojet, whereas eastward electrojet clearly co-existed at sub-auroral latitudes.

It should be noted that for intervals when AU attains negative values, computed AE index ($= AU - AL$) will have values lesser (up to $\sim$20%) than the AL. In other words, total maximum intensity of the auroral electrojet will be even less than its westward component thereby suggesting the fact that during extreme geomagnetic activities, AL index could represent substorms better than AE index.

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