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Latitudinal profile of the ionospheric disturbance dynamo magnetic signature: comparison with the DP2 magnetic disturbance

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Abstract. During magnetic storms, the auroral electrojets intensification affects the thermospheric circulation on a global scale. This process which leads to electric field and current disturbance at middle and low latitudes, on the quiet day after the end of a storm, has been attributed to the ionospheric disturbance dynamo (Ddyn). The magnetic field disturbance observed as a result of this process is the reduction of the H component amplitude in the equatorial region which constitutes the main characteristic of the ionospheric disturbance dynamo process, associated with a westward electric current flow. The latitudinal profile of the Ddyn disturbance dynamo magnetic signature exhibits an eastward current at mid latitudes and a westward one at low latitudes with a substantial amplification at the magnetic equator. Such current flow reveals an "anti-Sq" system established between the mid latitudes and the equatorial region and opposes the normal Sq current vortex. However, the localization of the eastward current and consequently the position and the extent of the "anti-Sq" current vortex changes from one storm to another. Indeed, for a strong magnetic storm, the eastward current is well established at mid latitudes about 45° N and for a weak magnetic storm, the eastward current is established toward the high latitudes (about 60° N), near the Joule heating region, resulting in a large "anti-Sq" current cell. The latitudinal profile of the Ddyn disturbance as well as the magnetic disturbance DP2 generated by the mechanism of prompt penetration of the magnetospheric convection electric field in general, show a weak disturbance at the low latitudes with a substantial amplification at the magnetic equator. Due to the intensity of the storm, the magnitude of the DP2 appears higher than the Ddyn over the American and Asian sector contrary to the African sector.

Keywords. Ionosphere (Equatorial ionosphere; Ionosphere-magnetosphere interactions; Ionospheric disturbances)

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1 Introduction

During magnetic storms, two main physical mechanisms of disturbance take place in the ionosphere, at the planetary scale: the direct penetration of magnetospheric convection electric field (Vasyliunas, 1970, 1972) and the ionospheric disturbance dynamo (Blanc and Richmond, 1980). These mechanisms generate significant disturbances of electric fields and currents responsible for the terrestrial magnetic field disturbance in equatorial ionosphere, with different timescales, during and after the magnetic storms. Many theoretical and experimental work, during these last decades, dealt with the direct penetration of the magnetospheric convection electric field from the polar region towards the equatorial latitudes (Wolf, 1970; Pellat and Laval, 1972; Senior and Blanc, 1984; Mazaudier et al., 1984; Spiro et al., 1988; Kobea et al., 2000; Peymirat et al., 2000). In 1980, Blanc and Richmond observed the electric field disturbance, after the end of a storm, due to the dynamo action of storm thermospheric winds generated by auroral Joule heating, during the active phases of the storm and first proposed the ionospheric disturbance dynamo mechanism to explain this phenomenon (Fejer et al., 1983; Sastri, 1988; Fambitakoye et al., 1990; Mazaudier and Venkateswaran, 1990; Fejer and Scherliess, 1995; Fejer, 2002). The limited number of studies related to the disturbance dynamo mechanism, from the time of the work of Blanc and Richmond (1980) to those of Le Huy and Amory-Mazaudier (2005), confirm the complexity of the attempt to isolate ionospheric disturbed dynamo events. Although storm time ionospheric electric fields and currents have been investigated extensively, there are still some fundamental difficulties in understanding their signatures and driving mechanisms (Fejer et al., 1990). The characteristics of disturbance dynamo electric fields have not been fully determined. In general, it has not been possible to separate the contributions of the direct penetration and disturbance dynamo processes (Fejer and Scherliess, 1995). The recent studies on the Ddyn disturbance marked some progresses in the understanding of its mechanism including the definition of the criteria of identifying such events (Richmond et al., 2003; Sastri et al., 2003; Le Huy and Amory-Mazaudier, 2005). A comparison between latitudinal variations of the Ddyn disturbance and the direct penetration mechanisms has not been established yet. Such comparison could contribute to the subject of highlighting the specific features of both types of disturbances of polar origin which strongly affect the equatorial ionosphere.

At present, we still need more morphological analysis of the Ddyn disturbance mechanism (Fejer, 2002) and such a task requires case identification. Most ionospheric disturbance dynamo studies have been dedicated to the disturbed electric field, the neutral wind characterization and simulation with models (Blanc and Richmond, 1980; Spiro et al., 1988; Fejer et al., 1990; Richmond et al., 2003; Huang et al., 2005), but only few of them are interested in identifying disturbance dynamo cases from magnetic data analysis. In this report, we used 1-min digital magnetometer data recorded at high, middle and equatorial latitudes to select Ddyn events through case studies. We carry out a comparative study of the dayside latitudinal profiles of the Ddyn disturbance magnetic signature (Le Huy and Amory-Mazaudier, 2005) and the magnetic disturbance due to the ionospheric currents generated by the magnetospheric convection electric field (Nishida et al., 1966; Nishida, 1968).

Section 2 describes the ionospheric disturbance dynamo process. Section 3 is devoted to the selection criteria for periods of observation and the data reduction. Section 4 presents the analysis of data and the results are summarized in Sect. 5 with the identification of ionospheric disturbance dynamo events. Section 6 deals with the analysis of the ionospheric disturbance dynamo latitudinal variations. In Sect. 7, we compare these variations with the latitudinal profile of DP2 magnetic fluctuations which occurred during the magnetic storms of 20 April 1993 (Kikuchi et al., 1996) and 27 May 1993 (Kobea et al., 2000) over the African and American sector and 6 November 2001 (Kikuchi et al., 2008) over the Asian sector. Section 8 is the summary and the conclusion.

2 Ionospheric disturbance dynamo process

During the active phases of storms, the auroral electrojets are intensified by fields aligned currents. Subsequently, the auroral electrojets currents transfer thermal energy to the neutral gas via Joule heating and impulses through the ion-neutral momentum transfer. This process sets up gravity waves and equatorward thermospheric winds (Hadley cell between the poles and the equator) at F-region altitudes (Testud and Vasseur, 1969; Richmond and Robble, 1979). These winds extend from auroral zone to mid and low latitudes (Mazaudier et al., 1985) with a small return flow at the E-region altitudes around the equator (below about 120 km altitude). At mid latitudes, through the Coriolis force action due to the Earth rotational movement, the equatorward thermospheric meridional flow gives rise to a westward zonal flow which drives a part of the ionized fluid. The westward zonal movement of ionized particles, in combinaison with the downward component of the Earth's magnetic field, produce an equatorward Pedersen current ($\boldsymbol{J}_P=\sigma_P \boldsymbol{V}\times\boldsymbol{B}$) (by the action of the Lorentz force). In turn, the Pedersen current accumulates positive charges at the equator (and electrons towards the poles) until a poleward electric field is established, opposing the Pedersen current flow. This poleward electric field gives rise to a large eastward Hall current ($\boldsymbol{J}_H=\sigma_H(\boldsymbol{E}\times\boldsymbol{B}/B^2)$) and a poleward Pedersen current. This physical process is called "ionospheric disturbance dynamo" by Blanc and Richmond (1980) and denoted by the symbol Ddyn (Le Huy and Amory-Mazaudier, 2005).

At mid latitudes, the equatorward Pedersen current driven by the winds is opposed to the poleward Pedersen current generated by the electric field. The result is the eastward Hall currents flow located at 45° magnetic latitude in a 20° wide strip within which the largest densities are produced. These currents are interrupted at the dawn and dusk terminators where the ionospheric conductivities have large longitudinal gradients. The interrupted currents set up polarization charges at the terminators and give rise to an electric field directed from dusk-to-dawn. There is consequently a large divergence of the east-west currents at dawn and dusk which requires a closure of these currents on the highly conducting dayside through the adjacent latitudinal regions. These currents achieve closure through two separate vortices: the polar vortex realized via the higher latitudes and the equatorial vortex realized via the lower latitudes where it constitutes a striking feature of the currents maps: a sort of "reversed Sq" current vortex flowing clockwise on the dayside with a focus close to noon at about 25° magnetic latitude. Both vortices have westward currents associated with them in polar and equatorial region respectively. Hence, at the equatorial region, the westward currents flow is opposed to the normal eastward equatorial electrojet currents.

3 Criteria of selection and data reduction

The selection criteria of observation periods were defined by Le Huy and Amory-Mazaudier (2005). These periods mainly correspond to the daytime in order to determine the dynamo action in the conducting E-region. Indeed, the generation of electric fields by the ionospheric disturbance dynamo process occurs mainly below 150 km, where the daytime electric conductivities are more significant (Mazaudier et al., 1987). These periods are subsequent to a magnetic storm related to a Joule heating in the auroral zone. The periods of observation show a weak auroral activity (intense generally in the main phase of the storm), thus there is no penetration of magnetospheric convection electric field from high latitude to the equator.

To investigate the Ddyn events, we first analyze the variations of the solar wind speed component, V_x, following the Sun Earth axis, the B_z component of the interplanetary magnetic field (IMF), the D_{st}, AU, AL indices and the horizontal component of the terrestrial magnetic field H. Note that the speed component V_x gives an estimate of the amplitude of the solar wind disturbance. When the B_z component is southward, the interplanetary magnetic field lines and those of the terrestrial magnetic field become "antiparallel" and can merge, involving a transfer of energy, particles and impulses from solar wind towards the magnetosphere. This process is at the origin of the auroral electrojet intensification. The D_{st} index gives an estimate of the sum of magnetospheric currents and depicts the different phases of magnetospheric disturbances (Akasofu, 1964). In fact, it illustrates the influence of the Chapman Ferraro currents (DCF) during the compression phase of the storm, the ring current (D_R) and the tail current (DT) during the main phase and the ring current during the recovery phase. The AU and AL indices are used to evaluate the auroral electrojets currents amplitude in the ionosphere. The H component of the terrestrial magnetic field gives an estimate of the equatorial electrojet current intensity.

Following the Biot and Savart's laws, the Earth's magnetic field integrates the effects of all currents flowing in the Earth's environment. The expression of the H component is:

$$H = S_R + D \tag{1}$$

where S_R is the daily regular variation of the Earth's magnetic field due to the regular electric current associated with winds driven by the solar heating and D the disturbed variation due to the electric currents generated by the various disturbance mechanisms. The irregular component D of the magnetic field is expressed with various components of current (Cole, 1966; Fukushima and Kamide, 1973) following the relation:

$$D = D_R + DCF + DT + DP + DG \tag{2}$$

where DP represents the magnetic effects of the ionospheric electric current systems flow in the E-region and generated by the main disturbance processes: the direct penetration of the magnetospheric convection electric field and the ionospheric disturbance dynamo; DG stands for the effects of the magnetotelluric inducting currents which are negligible.

The periods of observation are magnetically quiet owing to the weak auroral activity; these periods are subsequent to the very active phases of the storm and correspond to the recovery phase. Under these conditions, only the ring current is in action in the magnetosphere involving the magnetic disturbance D_R evaluated by the following equation derived from D_{st} index which gives a good approximation of the symmetric ring current during the observation periods:

$$D_R = D_{st} \times \cos(L) \tag{3}$$

Table 1. Geophysical context of the periods of study.

Periods	Days	ΣK_p (nT)	Remarks
No 1	10 June 1993	21−	Disturbed day
	11 June 1993	17	Quiet day
	21 June 1993	2+	Reference quiet day
No 2	18 September 1993	8	Reference quiet day
	20 September 1993	24+	Disturbed day
	21 September 1993	18+	Quiet day

where L is the geomagnetic latitude of the station. The H component expression becomes:

$$H = S_R + D_{st} \times \cos(L) + DP \tag{4}$$

We may infer the magnetic disturbance DP as follows:

$$DP = H - D_{st} \times \cos(L) - S_R \tag{5}$$

The H component variations during these periods of observation, in the equatorial zone, are compared with those of quiet reference days in order to highlight the influence of the disturbance dynamo mechanism. Indeed, the main characteristic associated with the disturbance dynamo observed on the magnetic data (Cole, 1966; Sastri, 1988; Fambitakoye et al., 1990; Le Huy and Amory-Mazaudier, 2005) is the reduction of the H component amplitude at the magnetic equator due to the circulation of a disturbed westward electric current opposing the regular equatorial electrojet eastward flow.

4 Periods of observation

We analyze two selected events: period No 1 (10, 11 June 1993) and period No 2 (20, 21 September 1993). Table 1 gives the geophysical context of these periods. The magnetometer data were recorded during the IEEY campaign measurement from the equator to high latitudes along the 5° West meridian profile over the Europe-Africa sector. In addition, we used data from stations spanning the longitude range 250° E–320° E and 100° E–160° E over the American and Asian sector. Table 2 indicates the position of these stations.

4.1 Variations of the solar wind parameters and the magnetic indices

Figures 1 and 2 show the plots of the speed component V_x, the interplanetary magnetic field (IMF) component B_z, the indices of the auroral electrojet AU, AL and the D_{st} index for the No 1 and No 2 periods. The D_{st} index variations (Figs. 1c and 2c) characterize the beginning of the magnetic storms in the first days of these periods. The subsequent days

Table 2. Positions of the magnetic stations.

		Geographic coordinates		Magnetic coordinates		
Code	Name	Latitude	Longitude	Latitude	longitude	LT
	Europe-Africa sector					UT
BJN	Bjornoya	74.50	19.20	71.00	109.10	+1
LER	Lerwick	60.13	358.82	62.37	89.19	+0
ESK	Eskdalemuir	55.32	356.80	58.30	83.56	+0
CLF	Chambon-La-Forêt	48.03	2.26	49.84	85.06	+1
TAM	Tamanrasset	22.79	5.53	24.66	80.31	+1
TOM	Tombouctou	16.73	357.00	6.36	71.15	+0
MOP	Mopti	14.51	355.91	3.85	69.90	+0
SAN	San	13.24	355.12	2.45	68.98	+0
KOU	Koutiala	12.36	354.55	1.49	68.32	+0
SIK	Sikasso	11.34	354.30	0.37	67.96	+0
NIE	Niellé	10.20	354.36	−0.89	67.88	+0
KOR	Korhogo	9.34	354.57	−1.84	67.98	+0
TSU	Tsmeb	−19.20	17.58	−18.77	83.51	+2
HBK	Hartebeesthoek	−25.88	−27.13	-26.82	91.86	+2
HER	Hermanus	−34.42	19.23	−33.98	81.35	+2
	American sector					
PBQ	Poste-De-La-Baleine	55.28	282.26	65.46	348.61	−5
OTT	Ottawa	45.40	284.55	55.63	352.76	−5
FRD	Fredericksburg	38.20	282.63	48.40	350.03	−5
DLR	Del Rio	29.49	259.08	38.30	324.61	−6
SJG	San Juan	18.11	293.85	28.31	3.99	−4
HUA	Huancayo	−12.05	284.67	−0.70	354.59	−5
VSS	Vassouras	−22.40	316.35	−12.09	24.63	−3
AIA	Argentine Island	−65.25	295.73	−55.06	3.92	+0
	Asian sector					
IRT	Irkutsk	52.27	104.27	41.93	175.20	+8
MMB	Memembetsu	43.91	144.19	35.35	209.13	+9
KAK	Kakioka	36.23	140.19	27.37	206.70	+9
HTY	Hatizyo	33.07	139.82	24.20	208.78	+10
CBI	Chichijima	27.10	142.18	18.47	209.59	+9
LNP	Lunping	25.00	121.17	14.99	192.14	+8
GUA	Guam	13.59	144.87	5.30	213.67	+10
BCL	Baclieu	9.28	105.73	1.33	175.59	+7
TND	Tondano	1.29	124.92	−8.53	196.89	+9
KDU	Kakadu	−12.69	132.47	−21.99	203.72	+9.5
CTA	Charters Towers	−20.09	146.26	−28.01	219.26	+10
ASP	Alice Springs	−23.76	133.88	−32.91	206.35	+9
GNA	Gnagara	−31,78	115.95	−40.93	186.70	+8
CNB	Cambera	−35.32	149.39	−42.71	225.56	+10
MCQ	Macquarie Island	−54.50	158.95	−60.06	243.84	+11

are magnetically quiet and coincided with the recovery phase of the storms.

During the night from 10 to 11 June 1993, in the time interval 20:00–03:00 UT, the variations of the V_x component (Fig. 1a) and of the B_z component (Fig. 1b) show an increase of the solar wind speed towards the Earth of about 110 km/s associated with a southward B_z component of the interplanetary magnetic field (IMF). The auroral activity becomes weak thereafter in the time interval 04:00–16:00 UT on 11 June, during the recovery phase of the storm.

In the period No 2, the variations of the parameters V_x, B_z, D_{st}, AU and AL show the same characteristics as previously, between 09:00 UT on 20 September and 02:00 UT on 21 September 1993: V_x increases approximately of 50 km/s (Fig. 2a), the B_z component is mainly southward (Fig. 2b), the D_{st} index decreases (Fig. 2c) and the AU and AL indices

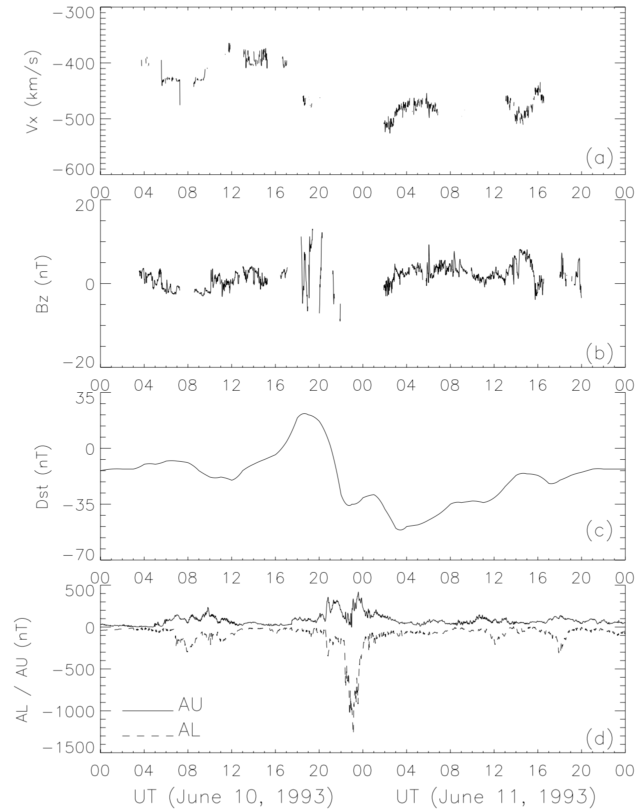

Fig. 1. Variation of the interplanetary parameters and the magnetic indices for the period No 1. From top to bottom: **(a)** component V_x of the solar wind speed, **(b)** the B_z component of the interplanetary magnetic field, **(c)** the D_{st} index and **(d)** the AU and AL indices.

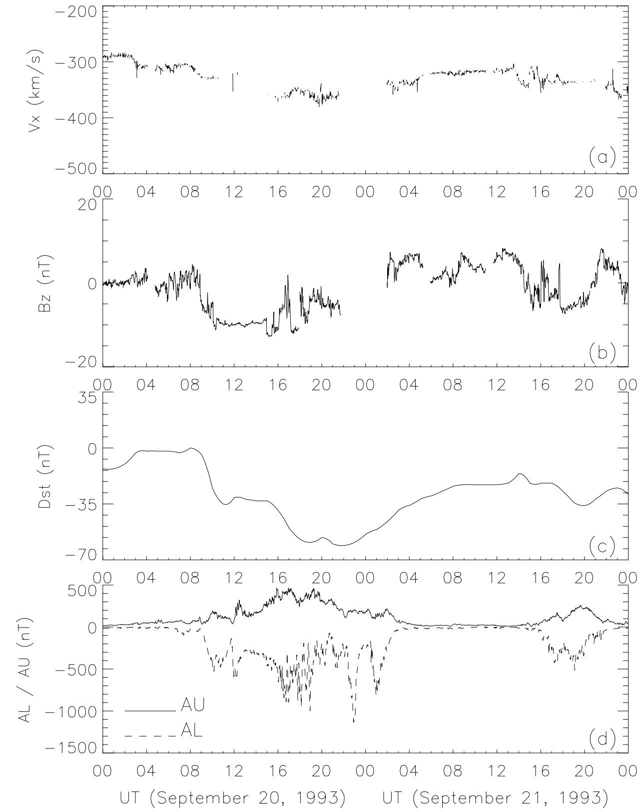

Fig. 2. Idem as Fig. 1, for the period No 2.

intensify (Fig. 2d). From 03:00 UT to 15:00 UT, on 21 September, during the recovery phase of the storm, the B_z component reversed to become northward and the AU and AL indices become almost nil. Note that the gaps in the data exactly during the storm period for V_x and B_z traces in Figs. 1 and 2 make the amplitude estimation difficult. However, the two limits of the the time interval for B_z traces 22:00–02:00 UT for Fig. 1 (−09 nT at 22:00 UT and −2.5 nT at 02:00 UT) and Fig. 2 (−2.5 nT at 22:00 UT and 0 nT at 02:00 UT) suggest negative deflections nearly coherently with the end of the main phase and the beginning of the recovery phase associated with the intensification of auroral activities (−1200 nT peak amplitude for AL at 23:00 UT for both Figs. 1 and 2). This suggestion is corroborated by studies that have shown a strong positive correlation between the southward IMF component (B_z) and a variety of geomagnetic and auroral activity indices (Arnoldy, 1971; Foster et al., 1971; Rostoker et al., 1972; Burch, 1974; Garrett et al., 1974; Murayama and Hakamada, 1975).

4.2 Variations of the magnetic field in the equatorial region

Figure 3b shows the plot of the H component on 10 and 11 June 1993 (solid line) (period No 1) compared with those of the reference quiet day levels (dashed line), over the African sector (UT=LT). On 11 June 1993, during the time interval 06:00–16:00 UT, we clearly observe an attenuation of the H component amplitude in all the stations as an evidence of the decrease of the auroral activity. The attenuation is more significant in Sikasso station (MLAT: 0.37° N), the nearest station to the magnetic equator. The variations of DP disturbance (Fig. 3c) exhibit a southward disturbance in all the stations (more noticeable in Sikasso), in the same time interval. Note that concerning the plots of the Ddyn latitudinal variations (Figs. 3 to 10), the number 12 written in these figures represents the local noon and the negative as well as positive deviations are shaded.

On 21 September 1993 (period No 2), during the time interval 09:00–15:00 UT, the variations of H (Fig. 4b) and DP component (Fig. 4c) exhibit the same characteristics as the preceding case. We observe an attenuation of the H component amplitude compared with the reference quiet day levels and a southward DP disturbance, simultaneously with the

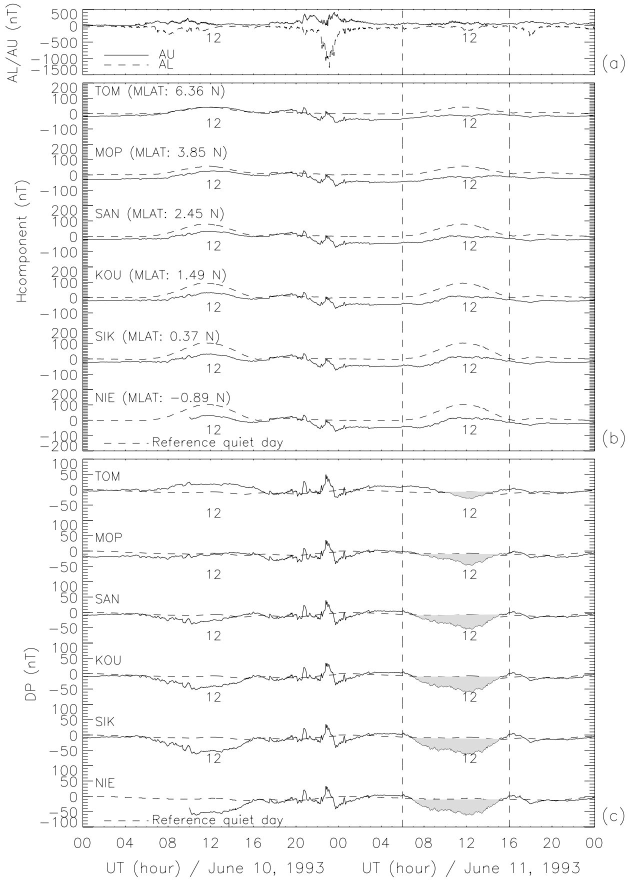

Fig. 3. Variation of the H component of the Earth's magnetic field observed in the African equatorial stations (middle panel) and the corresponding disturbance DP (bottom panel), on 10, 11 June 1993 (solid line). The plots in dashed line indicate the variations of the reference quiet day. On the top panel, the variations of the AU and AL indices are represented. The local time is the same as the universal time in these stations and local noon is indicated on the plots.

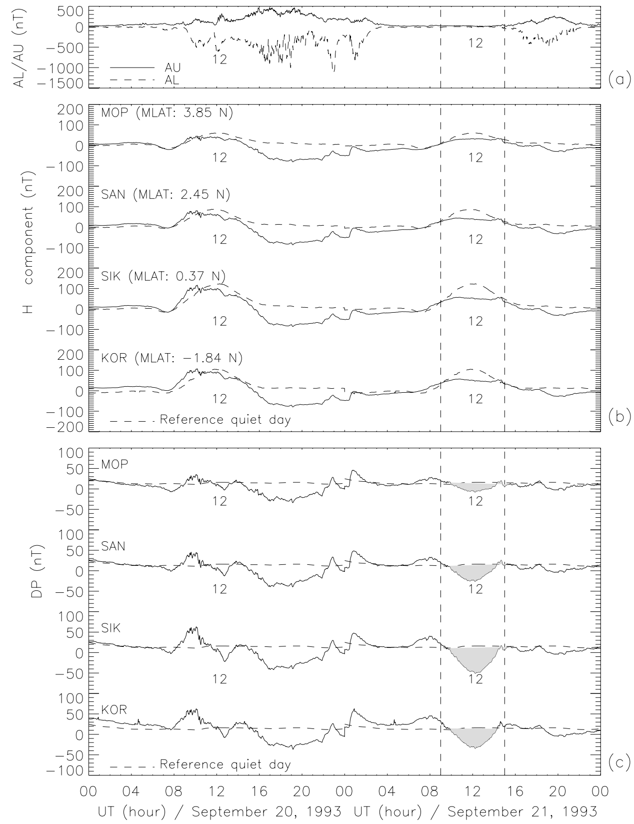

Fig. 4. Idem as Fig. 3, for the magnetic storm on 20, 21 September 1993.

decrease of the auroral activity. The reduction of the H component amplitude is important in Sikasso, indicating a more intense DP disturbance.

5 Results and cases identification

Note that the observation periods have been selected according to the previously defined criteria. We have also taken into account the solar wind and the geomagnetic activity indices analysis; these periods extend over the time interval 06:00–16:00 UT on 11 June 1993 (for period No 1) and 09:00–15:00 UT on 21 September 1993 (for period No 2). During the main phase of the storms the disturbed days prior to these periods of observation, the speed of the solar wind (toward the Earth) intensifies, the B_z component is southward and the D_{st} index undergoes a decrease due to the intensification of the westward ring current supported by a flow of the hot particles towards the equatorial plane of the magnetosphere near the Earth. The AU and AL indices also increase in response to the Joule heating in the auroral zone generated by the auroral electrojets which became very intense. The periods of observation correspond to the subsequent quiet days, when the recovery process sets up and the auroral activity becomes weak. Thus, only the mechanism of the ionospheric disturbance dynamo is in action in the ionosphere (Le Huy and Amory-Mazaudier, 2005). The substantial reduction of the H component for each of these periods with respect to the reference quiet day levels is indicative of a westward currents flow. These currents superimpose the eastward equatorial electrojet and cause its attenuation. The southward variation of the DP disturbance in all the equatorial stations consistently with the attenuation of the equatorial electrojet constitutes an evidence of a westward electric current which superimposes the regular eastward equatorial electrojet currents. The attenuation of the equatorial electrojet concurrently with the decrease of the auroral activity, the quiet day after the magnetic storm, illustrates the signature of the Ddyn disturbance process at the equator according to the

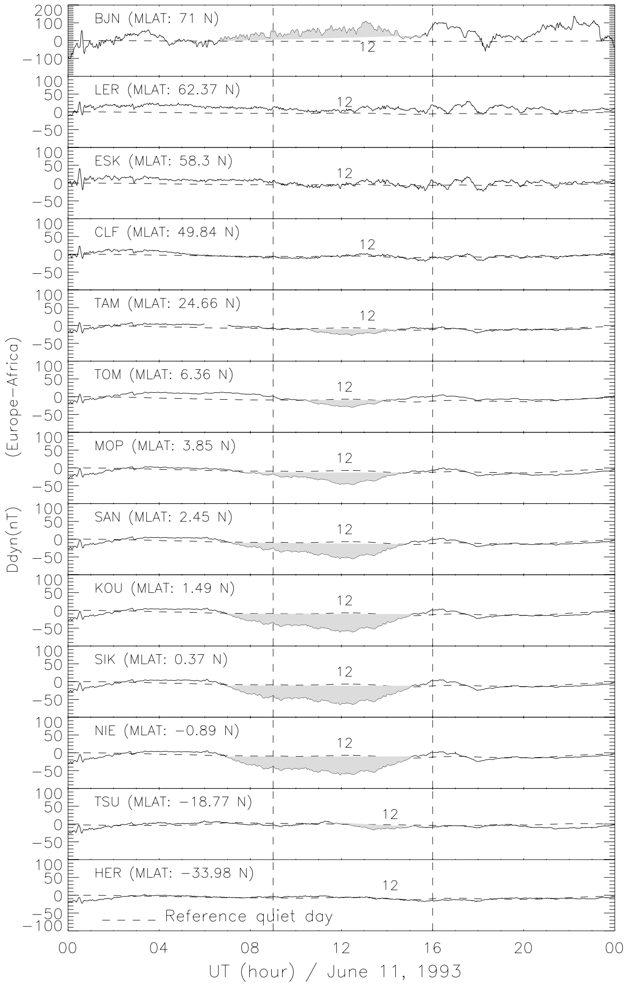

Fig. 5. Latitudinal variation of the Ddyn disturbance in the Africa-Europe sector, from high latitudes to the equator in the two hemispheres, on 11 June 1993. In this sector the maximum disturbance is observed during daytime around 12:00 LT as indicated on the plots.

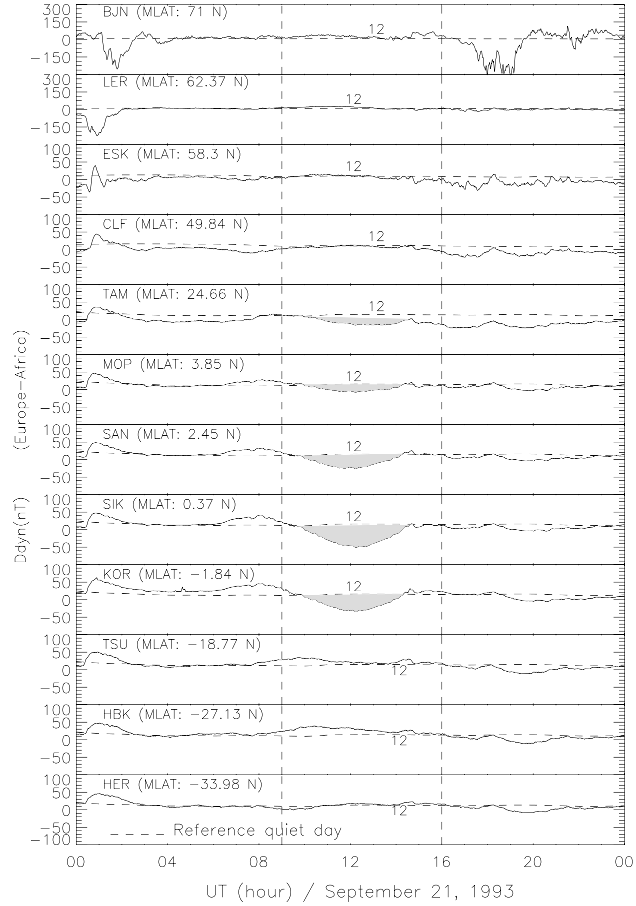

Fig. 6. Idem as Fig. 5, on 21 September 1993.

predictions of Blanc and Richmond (1980). Hence, the disturbance of the magnetic field during the periods of observation would be due to the only mechanism of the ionospheric disturbance dynamo; in other words, the DP disturbance depicts the magnetic signature of the Ddyn disturbance.

6 Latitudinal variations of the Ddyn disturbance

Figures 5 and 6 show the latitudinal variations of the Ddyn disturbance over the Europe-Africa sector, from high to low latitudes, in both hemispheres, respectively on 11 June 1993 (period No 1) and on 21 September 1993 (period No 2). The latitudinal profile of period No 1 (11 June 1993) and period No 2 (21 September 1993) over the Europe-Africa sector exhibit southward increasing Ddyn from MOP to NIE (Fig. 5) or KOR stations (Fig. 6) during the daytime (09:00–16:00 UT) with a maximum amplitude at local noon. This southward increase is due to disturbed westward current flow at the equator opposite to the regular eastward equatorial electrojet. The Ddyn deviation is quasi inexistent in mid latitude stations CLF (49, 84° N MLAT) and HER (−33, 98° N MLAT). However, the Ddyn deviation increases northward notably at BJN (71° N MLAT) in the Northern Hemisphere denoting eastward equivalent current flow which closes via the equator through the previously observed westward current. As a result, the absence of the Ddyn deviation at mid latitude during daytime is indicative of the focus of a large "anti-Sq" current cell established over the African sector in Northern Hemisphere. Figure 6 (period No 2) exhibits the same pattern of equivalent current flow in the time interval 09:00–16:00 UT. The eastward equivalent current flow latitude strip might be higher than 45° N as in the previous case (Fig. 5); the closure via the low latitude and the equator is realized through the westward current illustrated by the Ddyn southward deviation. These observations reveal an establishment of a large "anti-Sq" cell of equivalent currents. In the Southern Hemisphere, from the magnetic equator (SIK

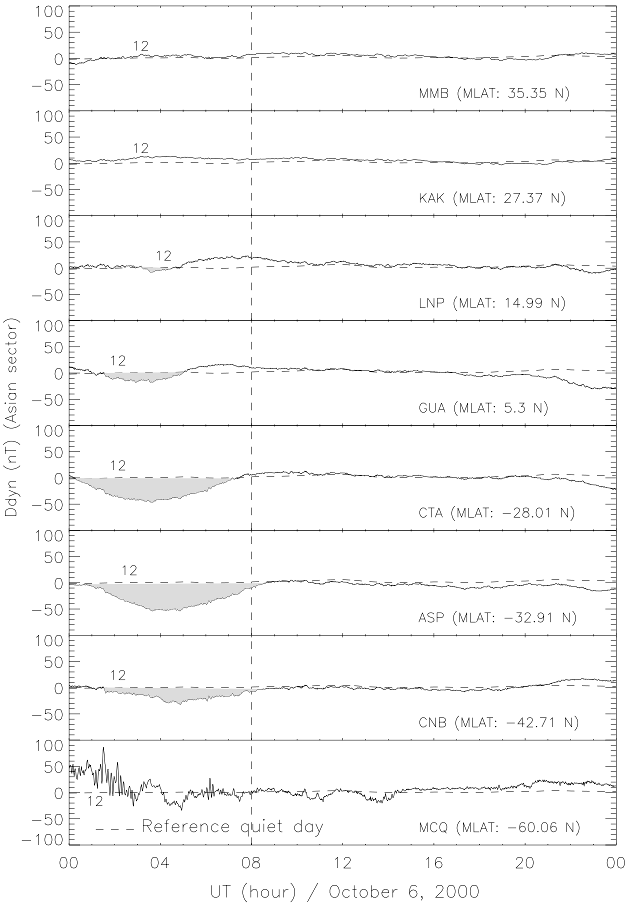

Fig. 7. Latitudinal variation of the Ddyn disturbance in the Asian sector, on 6 October 2000.

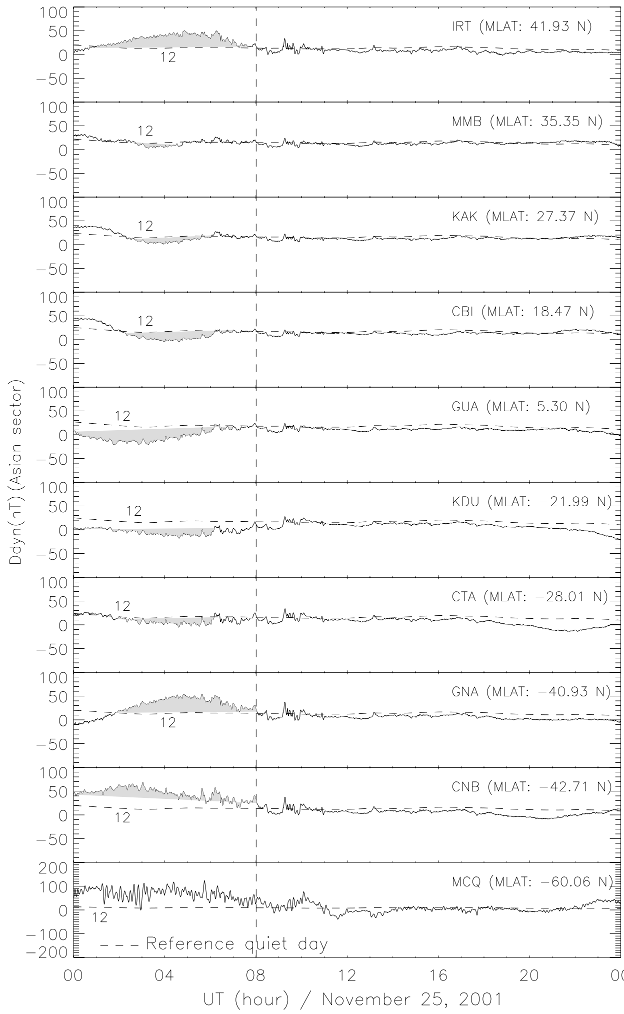

Fig. 8. Idem as Fig. 7, on 25 November 2001.

station) towards the high latitudes, after the KOR station, the disturbance is not observed any more; this is an illustration of the dissymmetry of the Ddyn disturbance relative to the magnetic equator. Due to the lack of data over the Asian and American sectors during the above investigated periods, we are not able to draw a conclusion with regard to these sectors. In view of this, we shall use the Ddyn disturbance cases identified by Le Huy and Amory-Mazaudier (2005) during the following periods of storm: 5, 6 October 2000; 31 March–1 April 2001 and 24, 25 November 2001. Figures 7, 8, 9 and 10 show the variations of the Ddyn disturbance over the Asian and American sectors. The variations of the Ddyn disturbance on 6 October 2000 (Fig. 7), over the Asian sector, clearly show the equatorial signature of the Ddyn disturbance at GUA station, in the equatorial region. CTA, ASP and CNB stations at mid latitudes in the Southern Hemisphere illustrate a southward variation of the Ddyn disturbance.The Ddyn variations in BCL station where the disturbance is maximum (Le Huy and Amory-Mazaudier, 2005) is not available. The disturbance intensity decreases as we move away from these regions towards the poles.

On 25 November 2001, in the time interval 00:00–08:00 UT, the Ddyn disturbance over the Asian sector (Fig. 8) is observed in GUA, in the equatorial zone (maximum in BCL, not shown) and decreases in intensity towards the poles in both hemispheres. At low latitudes, in the Northern Hemisphere in KAK (MLAT: 27.37° N) and MMB (MLAT: 35.35° N) and in the Southern Hemisphere at CTA (MLAT: −28.01° N), the Ddyn disturbance becomes very weak. However, at mid latitudes, in both hemispheres, namely at IRT (MLAT: 41.93° N) in the Northern Hemisphere and GNA (MLAT: −40.93° N) in the Southern Hemisphere, we note a northward deviation of the Ddyn disturbance featuring an eastward current flow in the vicinity of 40°–45° MLAT in both hemispheres. The low latitude Ddyn weakening observed at KAK and CTA in the vicinity of 25° N–30° N MLATprior to the Ddyn northward increase at the adjacent stations (IRT and GNA) in both hemispheres is typical of the "reversed Sq" current vortex pattern in each

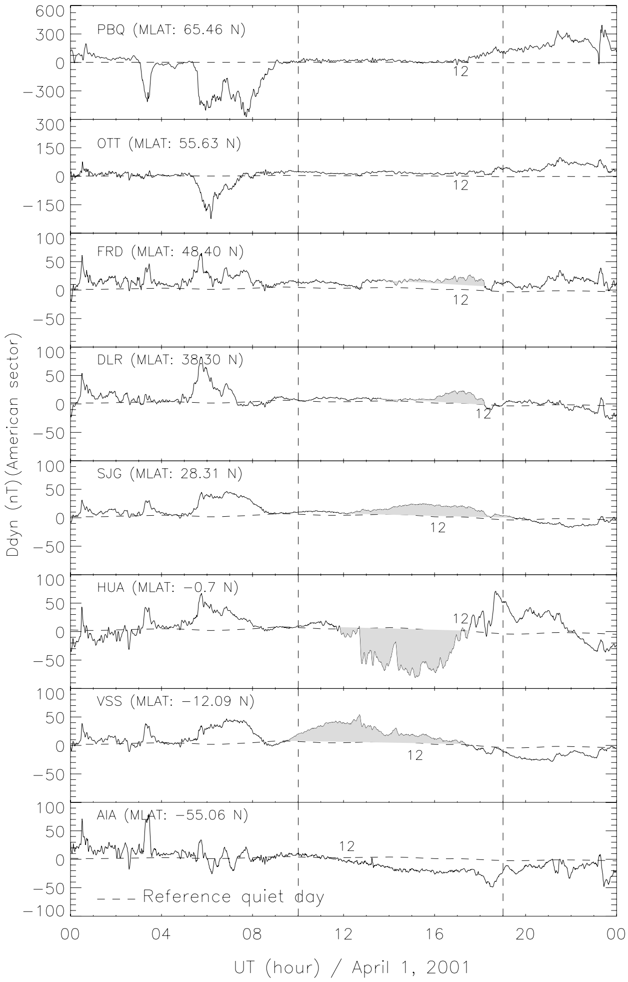

Fig. 9. Latitudinal variation of the Ddyn disturbance in the American sector, on 1 April 2001.

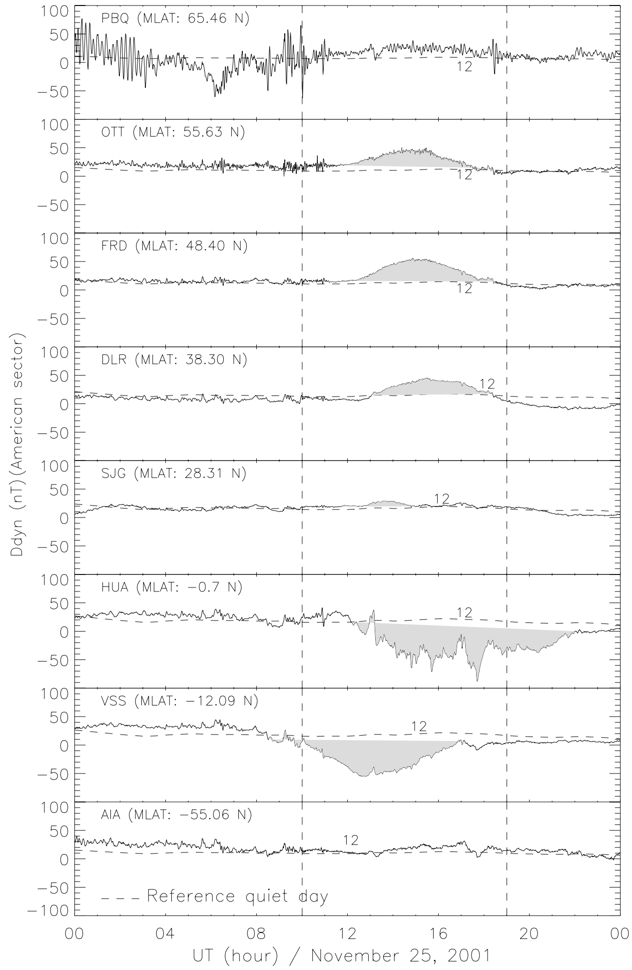

Fig. 10. Idem as Fig. 9, on 25 November 2001.

hemisphere at the lower latitudes with their focuses around 25° MLAT in support of Blanc and Richmond (1980) theory. Both vortices are adjacent to the magnetic equator.

On 1 April 2001 (Fig. 9), similar pattern with “reversed Sq” currents cell in each hemisphere in the lower latitudes can be easily retrieved over the American sector from the plots of Ddyn, when we focus on the time interval 10:00–19:00 UT. In fact, we note a small northward variationof Ddyn at mid and low latitudes (DLR: 38.30° N MLAT; VSS: −12.09° N MLAT), in both hemispheres with a negative peak amplitude in HUA station (−0.7° N MLAT) characteristic of the westward equivalent currents flow in the vicinity of the magnetic equator. Moreover, we notice that the adjacent VSS station undergoes a northward Ddyn deviation suggesting an equivalent current return flow.

On 25 November 2001 over the American sector (Fig. 10), the disturbance is very weak at the low latitudes station SJG (28, 31° N MLAT) whereas at mid latitudes in the Northern Hemisphere, the Ddyn deviation is growing bigger northward (FRD: 48, 40° N and OTT: 55, 63° N MLAT). Contrary to this evolution, the Southern Hemisphere station HUA and VSS exhibit a southward Ddyn deviation. At mid latitudes, in AIA station, the disturbance is quasi non-existent. We may infer from these observations the existence of a large equivalent current cell that establishes approximately between OTT and VSS with a focus around 20°–25° N MLAT. The southward Ddyn deviation at the equator (HUA and VSS stations) is typical of the westward current flow which results in the closure of the eastward equivalent currents flow in the vicinity of 50° N MLAT (OTT and FRD stations) where the Ddyn reached a maximum northward deviation.

7 Latitudinal profile of Ddyn disturbance and comparison with DP2

Figures 11 and 12 show the plots of the Ddyn latitudinal profiles (dotted line). The Ddyn profile plots of Fig. 11 are

Table 3. Characteristics of the magnetic storms and currents induced at mid latitudes in the Northern Hemisphere and the equatorial region.

Periods Beginning of the storm	Beginning and End of the auroral activity Duration	Maximum of AU (≥1000 nT) and hour	Maximum of AL (≥1000 nT) and hour	Current generated by the disturbed dynamo: Latitudes range of westward current. Latitude of eastward current (Northern).
10, 11 June 1993 Beginning: 10 June at 10:00 UT	Beginning: June 10, at 20:00 UT End: 11 June at 04:00 UT Duration: 7 h	No value	1283 nT on 10 June at 23:08 UT	Westward current: [45° N–30° S] Eastward current: maximum at 60° N
20, 21 September 1993 Beginning: September 20, at 08:00 UT	Beginning: 20 September at 09:00 UT End: September 21, at 03:00 UT Duration: 18 h	No value	1000 nT on 20 September at 18:57 UT. 1135 nT on 20 September at 22:56 UT.	Westward current: [45° N–20° S] Eastward current: maximum at 65° N
5, 6 October 2000 Beginning: October 5, at 03:27 UT	Beginning: 5 October at 03:27 TU End: 5 October at 22:00 UT Duration: 18 h	No value	2000 nT on 5 October at 07:00 UT. 3000 nT on 5 October at 12:00 UT.	Westward current: [10° N–60° S] Eastward current: maximum at 20° N
31 March 1 April 2001 Beginning: March 31, at 00:53 UT	Beginning: March 31, at 01:00 UT End: 31 March at 22:00 UT Duration: 21 h	No value	2000 nT on 31 March at 17:00 UT	Westward current: [25° N–10° S] Eastward current: maximum at 45° N
24, 25 November 2001 Beginning: November 24, at 05:57 UT	Beginning: November 24, at 05:57 UT End: November 24 at 18:00 UT Duration: 11 h	1500 nT at 07:00 UT, 1500 nT at 12:00 UT, 1000 nT at 14:00 UT on 24 November	1000 nT at 06:00 UT, at 07:00 UT, and at 11:00 UT. 3100 nT at 14:00 UT on 24 November	Westward current: America: [30° N–50° S] Asia: [35° N–30° S] Eastward current: America: maximum at 50° N Asia: maximum at 45° N
20 April 1993 Beginning: 20 April at 02:00 UT	Beginning: 20 April at 02:00 UT End: 20 April at 20:00 UT Duration: 18 h	No value	No value	No disturbed dynamo current
26, 27 May 1993 Beginning: 26 May at 20:00 UT	Beginning: 27 May at 04:00 UT End: 27 May at 09:00 UT Duration: 5 h	No value	No value	No disturbed dynamo current
5, 6 November 1993 Beginning: 5 November at 11:00 UT	Beginning: 5 November at 14:57 UT End: 7 November at 08:00 UT Duration: 41 h	1218 nT on 6 November at 02:04 UT	1069 nT on 5 November at 23:16 UT. 2338 nT on 6 November at 02:04 UT.	No disturbed dynamo current

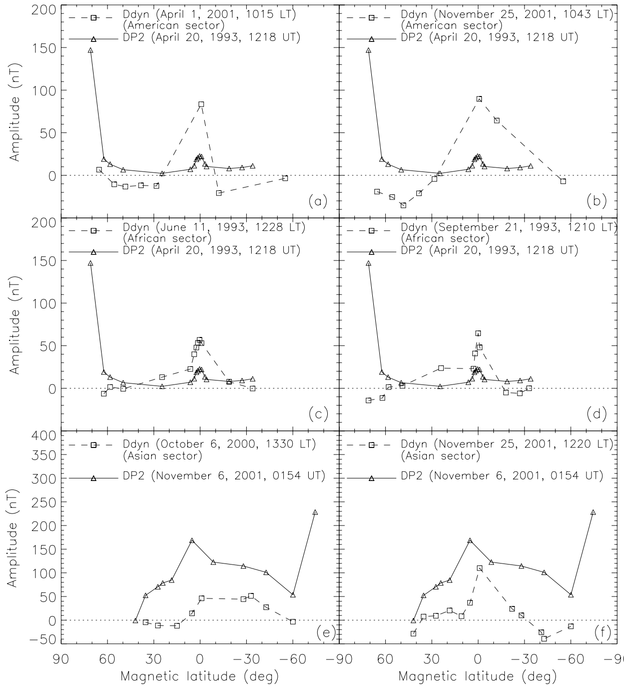

Fig. 11. Latitudinal profiles of the Ddyn disturbance compared with the latitudinal profile of the DP2 disturbance on 20 April 1993 at 12:18 UT and 6 November 2001 at 01:54 UT.

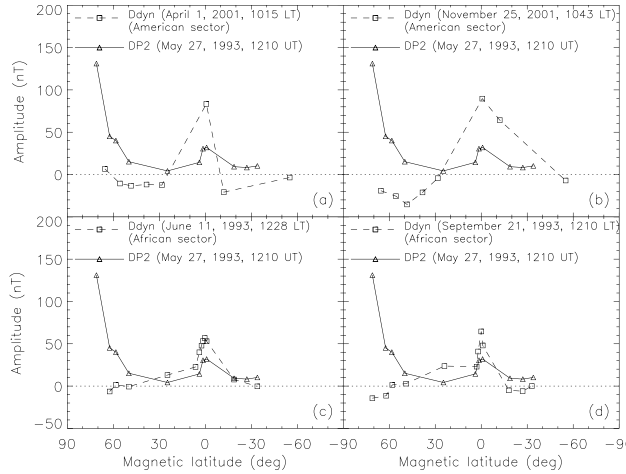

Fig. 12. Latitudinal profiles of the magnetic disturbance Ddyn compared with the latitudinal profile of the DP2 disturbance on 27 May 1993 at 12:10 UT.

related to the events of the periods No 1 (11 June 1993 at 12:28 LT) and No 2 (21 September 1993 at 12:10 LT) over the Europe-Africa sector and also to events identified by Le Huy and Amory-Mazaudier (2005) over the American and Asian sectors (6 October 2000 at 13:30 LT; 1 April 2001 at 10:15 LT and 25 November 2001 at 12:20 LT). We compare these profiles with those of the magnetic disturbance of polar origin DP2 generated by the magnetospheric convection electric field of the direct penetration process (Figs. 11 and 12, solid lines). These DP2 latitudinal profiles have been selected from investigated events on 20 April 1993 (Kikuchi et al., 1996); 27 May 1993 (Kobea et al., 2000) and 6 November 2001 (Kikuchi et al., 2008). Note that over the Asian sector, the DP2 event of 6 November 2001 occurs during daytime, that is 11:54 LT (LT=UT+10); therefore, it can be compared with the Ddyn event of 25 November 2001 at 12:20 LT. The Ddyn disturbance amplitude is obtained by removing the reference quiet day levels from the disturbed day values so that a positive amplitude corresponds to a southward deviation of the Ddyn disturbance and conversely. The Ddyn profiles (Fig. 11a–f) exhibit a positive amplitude at lower latitudes in both hemispheres during the daytime, with a peak positive amplitude at the magnetic equator regardless of the longitude sector and periods of the events occurrence. The Ddyn disturbance positive amplitude in this zone corresponds to a westward current flow along a latitude strip in the vicinity of the equator, in agreement with the predictions of Blanc and Richmond (1980). This Ddyn disturbance amplification at the magnetic equator is due to the Cowling conductivity effect which is significant in the equatorial electrojet region during the daytime. In fact, the westward zonal current flows in a latitude strip around the magnetic equator, ranging from 25° N to 10° S on 1 April 2001 (Fig. 11a, top left panel) at 10:15 LT, from 30° N to 50° S on 25 November 2001 at 10:43 LT (Fig. 11b, top right panel), over the American sector; in Africa, it ranges from 45° N to 35° S on 11 June 1993 at 12:28 LT (Fig. 11c) and from 55° N to 20° S on 21 September 1993 at 12:10 LT (Fig. 11d); over the Asian sector, it ranges from 10° N to 55° S on 6 October 2000 at 13:30 LT (Fig. 11e) and from 35° N to 30° S on 25 November 2001 at 12:20 LT (Fig. 11f). It is clear that the zone of influence of the westward disturbed currents generated by the meridional electric field at low latitudes differs from one storm to another on the one hand, and from one sector of longitude to another, on the other hand. To be accurate, this latitude strip may widen or narrow, it may also shift a bit northward or southward. Such characteristics summarized in Table 3 could be associated with the storms. Indeed, over the American sector, the Ddyn negative amplitude in the latitude range of 60°–30° N MLAT (Fig. 11a) and 70°–30° N MLAT (Fig. 11b) indicate an eastward equivalent current in accordance with the circulation of a large eastward Hall current in 20° wide latitude strip located around 45° N as suggested by Blanc and Richmond (1980) model. Similar eastward currents can be noticed in the latitude range of 40°–10° N (Fig. 11e) over the Asian sector. The latitudinal extension of the "anti-Sq" system of current generated by the Ddyn disturbance differs from the Northern to the Southern Hemisphere exhibiting a dissymmetry of the ionospheric disturbance dynamo signature with respect to the equator. From Table 3, it is noteworthy that the storm of 24–25 November 2001 exhibits the greatest amplitudes for the indices AU (1500 nT) and AL (3100 nT) with a duration of 11 h of auroral activity. The "anti-Sq" system current position is in agreement with the predictions of Blanc and Richmond (1980) model: an intense eastward current at 45° N latitude and a westward current at low latitudes. The same observations hold for the storm of 31 March–1 April 2001 with a relatively significant peak amplitude of AL (2000 nT) (no value of AU higher than 1000 nT) and an auroral activity which lasts 21 h: an eastward current around 45° N and a westward current at low latitudes. The storms of 10–11 June 1993 and 20–21 September 1993 are less intense than the previously investigated ones (the maximum value of AL fluctuates around 1000 nT and there is no value of AU higher than 1000 nT) and respectively lasts 7 and 18 h. The eastward current during these storms is observed around 60° N. The storm of 5–6 October 2000 is as intense as the storm of 24–25 November 2001 and the auroral activity lasted longer (18 h). The eastward current is around 20° N and the westward current flows in a latitude range from the magnetic equator to 60° S.

These observations suggest that for a very significant auroral activity with a long duration, the eastward current generated by the disturbance dynamo is established towards the mid and low latitudes, far from the zone of Joule heating (situated between 64° N and 74° N for a severe magnetic storm (Blanc and Richmond, 1980) while a relatively less significant auroral activity induces an eastward current flow close to the heating zone. This is in agreement with the probably more intense flow of meridional wind far from the Joule heating zone as a result of a severe storm which leads to a significant dynamo action at mid and low latitude. However, a moderate storm generates more intense winds flow towards the zone of Joule heating which is able to lead to a dynamo action at high latitudes.

In Figs. 11 and 12, we compare the profiles of the DP2 and Ddyn disturbances. The striking features of both types of disturbances consist in the significant amplification and the similarities exhibited in the equatorial zone. However, the amplitude of the Ddyn disturbance is higher than the DP2 ones over the American and African sector; it remained lower than the DP2 over the Asian sector. These differences in the amplitude can be explained by the more intense and long lasting storm of 6 November 2001 (Table 3) that generated the DP2 disturbance compared to that of 20 April 1993 and 27 May 1993 ones over the American and African sector. Indeed, the highest AU and AL indices peak amplitudes for the DP2 related storms reached respectively 1218 nT and 2338 nT on 6 November 2001. With regard to the DP2 event of 20 April 1993 at 12:18 UT recorded at the Brazilian stations, Fig. 11a and b indicates a weaker peak amplitude at the equator owing to the relatively low conductivity around 07:18 LT, namely at Huancayo station (LT=UT−5). However, it is of interest to note that the maximum electrojet strength is generally obtained at Huancayo somewhat earlier than noon (Mariott et al., 1979); consequently, the ionospheric conductivity is not negligible at this local time (07:18 LT) and the DP2 event may be compared with a morning sector event on 25 November 2001 at 10:43 LT. Likewise, the Ddyn events of 1 April 2001 at 10:15 LT and 25 November 2001 at 10:43 LT over the American sector (Fig. 12a and b) are comparable with the DP2 event of 27 May 1993 that occurred at 07:10 LT.

Gaps in data at stations in both hemispheres at high latitudes (Figs. 11a, e and 12a) for the DP2 events did not allow complete plots. However, there are traits in the behavior which tentatively suggest a rough symmetry with respect to the equator.

8 Summary and conclusions

From the analysis of the main features of the disturbance dynamo and its comparison with the DP2 disturbance, the various results can be summed up as follow:

1. At low latitudes and the magnetic equator, the Ddyn disturbance is southward, associated with a westward disturbance of the equatorial electrojet current in agreement with recent simulations of the TIEGCM model (Richmond et al., 2003; Huang et al., 2005).

2. The Ddyn disturbance is maximum at the magnetic equator, probably due to the daytime significant Cowling conductivity effect at the equatorial electrojet altitude.

3. At mid latitudes in the Northern Hemisphere, the latitudinal profile of Ddyn disturbance shows the circulation of an eastward current at 45° N for a severe magnetic storm in agreement with the model of Blanc and Richmond (1980) whereas it is established around 60° N (near the heating zone) for a moderate magnetic storm. Both currents close via the low latitude and the equator through an "anti-Sq" cell.

4. An eastward current is observed at low latitudes for a severe magnetic storm with a longer auroral activity. The westward current flow observed at the magnetic equator extends to the mid latitudes in the Southern Hemisphere.

5. The magnetic signature of the Ddyn disturbance in the Northern Hemisphere is often different (in term of latitudinal extension) from that of the Southern Hemisphere; as a result of these observations, the Ddyn signature exhibits a dissymmetry with respect to the magnetic equator.

6. The latitudinal profiles of the Ddyn and DP2 disturbances exhibit similar behaviors with a weak amplitude

at mid and low latitudes and a remarkable amplification at the magnetic equator due to the Cowling conductivity effect.

7. Depending on the intensity of the storms, the Ddyn disturbance peak amplitude at the equator is higher than the DP2 and vice-versa. The DP2 signature appears tentatively symmetric with respect to the equator.

Efforts must be concentrated on the ionospheric disturbance dynamo magnetic signature at mid latitudes in order to better understand the circulation of the various currents generated during magnetic storms.

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References

Akasofu, S. I.: A source of energy for geomagnetic storms and auroras, Planet. Space Sci., 12, 81–833, 1964.

Arnoldy, R. L.: Signature in the interplanetary medium for substorms, J. Geophys. Res., 76, 5189–5201, 1971.

Blanc, M. and Richmond, A. D.: The ionospheric disturbance dynamo, J. Geophys. Res., 85, 1669–1686, 1980.

Burch, J. L.: Observations of interactions between interplanetary and geomagnetic fields, Rev. Geophys. Space Phys., 12, 363–378, 1974.

Cole, K. D.: Magnetic storms and associated phenomena, Space. Sci. Rev., 5, 699–770, 1966.

Fambitakoye, O., Menvielle, M., and Mazaudier, C.: Global disturbance of the transient magnetic field associated with thermospheric storm winds on March 23, 1979, J. Geophys. Res., 95, 209–218, 1990.

Fejer, B. G.: Low latitude storm time ionospheric electrodynamics, J. Atmos. Solar Terr. Phys., 64, 1401–1408, 2002.

Fejer, B. G. and Scherliess, L.: Time dependent response of equatorial ionospheric electric fields to magnetospheric disturbances, Geophys. Res. Lett., 22, 851–854, 1995.

Fejer, B. G., Larsen, M. F., and Farley, D. T.: Equatorial disturbance dynamo electric fields, Geophys. Res. Lett., 10, 537–540, 1983.

Fejer, B. G., Spiro, R. W., Wolf, R. A., and Foster, J. C.: Latitudinal variations of perturbation electric field during magnetic disturbed periods 1986, SUNDIAL observations and model results, Ann. Geophys., 8, 441–454, 1990.

Fukushima, N. and Kamide, Y.: Partial ring current models for worldwide geomagnetic disturbances, Rev. Geophys. Space Phys., 11, 795–853, 1973.

Foster, J. C., Fairfield, D. H., Ogilvie, K. W., and Rosenberg, T. J.: Relationship of interplanetary parameters and occurrence of magnetospheric substorms, J. Geophys. Res., 76, 6971–6975, 1971.

Garrett, H. B., Dessler, A. J., and Hill, T. W.: Influence of solar-wind variability on geomagnetic activity, J. Geophys. Res., 79, 4603–4610, 1974.

Huang, C. M., Richmond, A. D., and Chen, M.-Q.: Theoretical effects of geomagnetic activity in low-latitude ionospheric electric fields, J. Geophys. Res., 110, A05312, doi:10.1029/2004JA010994, 2005.

Kikuchi, T., Lühr, H., Kitamura, T., Saka, O., and Schlegel, K.: Direct penetration of the polar électric field to the equator during a DP2 event as detected by the auroral and equatorial magnetometer chains and the EISCAT radar, J. Geophys. Res., 101, 17161–17173, 1996.

Kikuchi, T., Hashimoto, K. K., and Nozaki, K.: Penetration of magnetospheric electric fields to the equator during a geomagnetic storm, J. Geophys. Res., 113, A06214, doi:10.1029/2007JA012628, 2008.

Kobea, A. T., Richmond, A. D., Emery, B. A., Peymirat, C., Lühr, H., Moretto, T., Hairston, M., and Amory-Mazaudier, C.: Electrodynamic Coupling of High and low latitudes Observations on May 27, 1993, J. Geophys. Res., 105(A10), 22979–22989, 2000.

Le-Huy, M. and Amory-Mazaudier, C.: Magnetic signature of the ionospheric disturbance dynamo at equatorial latitudes: "Ddyn", J. Geophys. Res., 10, 10301–10314, 2005.

Mariott, R. T., Richmond, A. D., and Venkateswaran, S. V.: The quiet time equatorial electrojet and counter electrojet, J. Geomag. Geoelectr., 31, 311–340, 1979.

Mazaudier, C., Blanc, M., Nielsen, E., and Min Yun Zi: Latitudinal profile of the magnetospheric convection electric field at ionospheric altitudes from a chain of magnetic radar data, J. Geophys. Res., 89(A1), 375–381, 1984.

Mazaudier, C., Bernard, R., and Venkateswaran, S. V.: Saint-Santin Observation of lower thermospheric storms, J. Geophys. Res., 90(A3), 2885–2895, 1985.

Mazaudier, C., Richmond, A., and Brinkman, D.: On thermospheric winds produced by auroral heating during magnetic storms and associated dynamo electric fields, Ann. Geophys., 5A, 443–448, 1987.

Mazaudier, C. and Venkateswaran, S. V.: Delayed ionospheric effects of the geomagnetic storms on March 22, 1979, studied by the sixth coordinated data analysis workshop (CDAW-6), Ann. Geophys., 8, 511–518, 1990.

Murayama, T. and Hakamada, K.: Effects of solar wind parameters on the development of magnetospheric substorms, Planet. Space Sci., 23, 75–91, 1975.

Nishida, A.: Geomagnetic DP2 fluctuations and associated magnetospheric phenomena, J. Geophys. Res., 73, 1795–1803, 1968.

Nishida, A., Iwasaki, N., and Nagata, T.: The origin of fluctuations in the equatorial electrojet: A new type of geomagnetic variations, Ann. Geophys., 22, 478–485, 1966.

Pellat, R. and Laval, G.: Remarks on the steady time dependant mathematical, convection models, in: Critical Problems of Magnetospheric Physics, edited by: Diyer, E. R., Inter-Union Commission on Solar Terrestrial Physics, Washington, D.C., 1972.

Peymirat, C., Richmond, A. D., and Kobea, A. T.: Electrodynamic coupling of high and low latitudes: simulations of shielding and overshielding effects, J. Geophys. Res., 105, 22991–23003, 2000.

Richmond, A. and Roble, R. G.: Dynamic effects of aurora generated gravity waves on the mid-latitude ionosphere, J. Atmos.

Terr. Phys., 41, 841–852, 1979.

Richmond, A., Peymirat, C., and Roble, R. G.: Long-lasting disturbances in the equatorial ionospheric electric field simulated with a coupled magnetosphere-ionosphere-thermosphere model, J. Geophys. Res., 108(A3), 1118, doi:10.1029/2002JA009758, 2003.

Rostoker, G., Lam, H.-L., and Hume, W., D.: Response time of the magnetosphere to the interplanetary electric field, Can. J. Phys., 50, 544–547, 1972.

Sastri, H.: Equatorial electric field of ionospheric disturbance dynamo origin, Ann. Geophys., 6, 635–642, 1988.

Sastri, H., Sridharan, R., and Tarun Kumar Pant: Equatorial Ionosphere-Thermosphere System During Geomagnetic Storm, Ann. Geophys., 142, 185–203, 2003.

Senior, C. and Blanc, M.: On the control of magnetospheric convection by the spatial distribution of ionospheric conductivities, J. Geophys. Res., 89, 261–284, 1984.

Spiro, R. W., Wolf, R. A., and Fejer, B. G.: Penetration of high-latitude-electric-field effects to low latitudes during SUNDIAL 1984, Ann. Geophys., 6, 39–50, 1988, http://www.ann-geophys.net/6/39/1988/.

Testud, J. and Vasseur, G.: Ondes de gravité dans la thermosphère, Ann. Geophys., 25, 525–546, 1969.

Vasyliunas, V. M.: Mathematical models of magnetospheric convection and its coupling to the ionosphere, in: Particules and Fields in the Magnetosphere, edited by: Mc Cormac, M., D. Reidel, Norwell Mass, 60–71, 1970.

Vasyliunas, V. M.: The interrelationship of magnetospheric processes, in: Earth's Magnetosphere Processes, edited by: Mc Cormac, M., D. Reidel, Norwell Mass, 29–38, 1972.

Wolf, R.: Effects of ionospheric conductivity on convective plasma flow in the magnetosphere, J. Geophys. Res., 75, 4677–4698, 1970.