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ScienceDirect
Advances in Space Research 58 (2016) 1208–1218
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
www.elsevier.com/locate/asr

Storm-time variation of the horizontal and vertical components of the geomagnetic fields and rate of induction at different latitudes

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Received 22 February 2016; received in revised form 12 June 2016; accepted 13 June 2016
Available online 18 June 2016

Abstract

The paper presents the hourly mean variation of horizontal (H) and vertical (Z) components of the geomagnetic field and the rate of induction $\Delta H/\Delta Z$ at different latitudes during magnetic storm of 20 March 2001 and 1 October 2001. The results of the analysis revealed that at high latitude stations greater than 60°, the reduction in ΔH component was noticed after the noon time while other stations less than 60° experienced reduction of H in the morning time during the geomagnetic storm. Large amplitude of ΔH and ΔZ were exhibited during the daytime over the equatorial zone, the amplitude decreases from mid latitudes to the dip equator during the nighttime. The daytime enhancement of ΔH at AAE, BAN and MBO suggest the presence of a strong eastward directed current which comes under the influence of electrojet. There were strong positive and negative correlations between ring current (DR) and horizontal component of the magnetic field ΔH. The effect of rate of induction is more significant at high latitudes than lower latitudes, during the geomagnetic storm. More enhancement in rate of induction occurred at nighttime than daytime. This result may be from other sources other than the ionosphere that is magnetospheric process significantly contributes toward the variation of induction.

Keywords: Geomagnetic field; Geomagnetic storm; Electromagnetic induction; Ring current; Coronal mass ejection

1. Introduction

The magnetic field of the Earth is influenced by the high plasma speed infused from a coronal mass ejection (CME). The charged particles deposited in the magnetosphere are later released into the upper atmosphere. The charged particles deposited in the high latitudes cause intense current and leads to the enhancement of the electric field and electrical conductivity. These current have an influence on the geomagnetic field observed by magnetometer. During the magnetic storm, the increased solar wind dynamic pressure acting on the magnetosphere and compress the dayside of the magnetosphere, forcing the magnetopause current close to the Earth surface resulted increase in the horizontal component of the geomagnetic field (H).

Literatures have revealed the influence of solar flare effect on the geomagnetic field components at different latitudes (McNish, 1937; Nagata, 1952; Ohshio et al., 1967; Srivastava, 1974; Raja Rao and Rao, 1963; Sastri, 1975; Rangarajan and Rastogi, 1981; Rastogi et al., 1983; Rastogi, 1975, 1996; Tsunomura, 1998) and such influence results into sudden storm commencement. The disturbance storm time variations of the vertical component (Z) of the geomagnetic field exhibit a large decrease during sudden storm commencement at Thiruvananthapuram, Etaiyapuram, Kodaikanal and Annamalainagar. It was observed that this decrease is not the same in time with the decrease

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http://dx.doi.org/10.1016/j.asr.2016.06.017
0273-1177/

in the horizontal component (H) component, which is as a result of the sub-surface channel, where current are induced by the ionospheric current which produced a large decrease in Z (Rastogi, 2001). Day to day variability during the midday and midnight was investigated along Indo-Russian chain stations, using H and disturbance storm time (Dst) index. The relationship between ΔH and Dst index was 0.8 while the slope regression of 1.0 and 0.5 where noticed at daytime and nighttime respectively. It was concluded that the nighttime tail current has influence on the variation of ΔH due to the ring current disturbances (James et al., 2008). Hasegawa (1960) examined the position of the foci of the ionospheric current which have an influence on the day to day variability in solar quiet (Sq). Rastogi (2006) studied the influence of ionospheric current, magnetospheric current and induced current on equatorial electrojet stations over Central Africa, East Brazil and India, using geomagnetic field components of ΔH, ΔY and ΔZ.

The rate of induction refers to the ratios $\Delta Z/\Delta H$ where ΔZ refers to the total amplitude between the extreme in Z field and ΔH is the excess effect in relation to the planetary effect at the magnetic equator. Numerous investigations have been carried out on the responses of induction effect using H and Z components (Price, 1967; Schmucker, 1970; Rabiu and Nagarajan, 2008). The induction at Etaiyapuram is enhanced during strong electrojet current (Rastogi and James, 2001). Also a daily variation of geomagnetic field Z does not show any abnormal effect as a result of induction, but during the storm time the $Dst(Z)$ shows induction effects (Rastogi and James, 2001). Rastogi (2004) studied the response of the induction effect in central and eastern part of South America, induction seems to be absent, but significant induction effect is observed at Peredinia, Sri Lanka, abnormal conductivity distribution. Falayi et al. (2015) used H and Z to examine the response of ionospheric disturbance dynamo and electromagnetic induction during geomagnetic storms. High ratio of $\Delta Z/\Delta H$ is observed at nighttime because of the reduction on the E region conductivity, which allowed F region electric fields to dominate. The aim of this paper is to examine the variation pattern of ΔH, ΔZ and rate of induction during the geomagnetic storm of 20 March 2001 and 1 October 2001, also investigate the correlation coefficient between ring current (DR) and ΔH.

2. Data and method of data analysis

The set of data used in the present work are obtained from International Real-Time Magnetic Observatory Network (INTERMAGNET, 2015), for the study of variation of the magnetic field. It provides one minute values of the northward (X), eastward (Y), vertical (Z) components of the Earth's magnetic field, while horizontal component (H) is computed using Eq. (1)

$$H = \sqrt{(X)^2 + (Y)^2} \tag{1}$$

The variation in H (ΔH) and Z (ΔZ) were obtained by correcting the hourly departure and the midnight baseline values for non-cyclic variation to obtain the hourly ratios of $\Delta Z/\Delta H$ (Rabiu et al., 2007; Bolaji et al., 2013). The geographic and geomagnetic coordinates of these sites are given in Table 1.

The present work focused on the data acquired during the CME of 20 March 2001 and 1 October 2001 were engaged in the study, the CME observed by LASCO-C2 having the following features, the angular width of the CME (full or partial halo); the speed and the height at which this speed can be measured, obtained from: http://cdaw.gsfc.nasa.gov/CME_list.

To identify the corresponding strength of the geomagnetic storm, 1 hourly values of solar wind speed (Vx) gives the amplitude of the solar wind disturbance, the interplanetary magnetic field (Bz) determines the amount of energy that can be transferred to the Earth resulting into geomagnetic activity, upper and lower electrojet (AU and AL) indices, provide better measurement of ground effects of eastward and westward electrojets produced by the enhanced ionospheric current in auroral oval during geomagnetic activity, Kp index is the average of the K values from all contributing observatories and plays a key role

Table 1
List of stations whose data are used together with geographic and geomagnetic coordinates.

Stations	Abbrev	Geographic latitude (°)	Geographic longitude (°)	Geomagnetic latitude (°)	Geomagnetic longitude (°)
Hermanus	HER	−34.43	19.23	−42.39	82.15
Hartebeesthoek	HBK	−25.88	27.71	−36.31	94.72
Mbour	MBO	14.38	343.03	2.06	58.24
Addis Ababa	AAE	9.03	38.77	0.16	110.47
Lerwick	LER	60.13	358.82	58.21	81.65
Eskladimur	ESK	55.32	365.80	52.89	77.76
Sodanklya	SOD	67.06	224.67	69.78	272.23
Nurmijarvi	NUR	60.51	24.66	56.75	102.48
Bangui	BAN	4.33	18.57	−5.27	90.13
L'Aquila	LAQ	42.38	13.32	36.16	87.52
Tamanrasset	TAM	22.79	5.53	9.22	78.37
Hartland	HAR	51.0	335.52	50.96	59.19
Abisko	ABI	68.36	18.82	65.11	102.31

in the magnetospheric and ionospheric modeling (Wing et al., 2005). *Dst* (disturbance storm time) index examined the strength of Earth's ring current and the data were obtained from OMNIWEB (http://omniweb.gsfc.nasa.gov/form/dx1.html).

2.1. Observation

The Figs. 1a and 1b present the time variation of geomagnetic storm of 20 March 2001 and 1 October 2001 solar wind component *Vx*, the component of the IMF *Bz*, *Dst*, *Kp*, *AU*, and *AL* indices.

2.1.1. Case 1. 20 March 2001

This storm originates from solar flare which is caused by coronal mass ejection (CME) associated with magnetic structure interactions and reconfigurations. This CME is a partial halo CME with M 1.6 flare occurred on 20 March 2001. A storm with sudden commencement noted at 1200 UT on 20 March with prolonged periods of southward *Bz* pointing southward with deflections as high as −20 nT (GSM) and *AL* is also disturbed reaching minimum of −1284 nT. The main phase lasted for 6 h between 12:00 UT and 18:00 UT reaching a minimum *Dst* value of −150 nT, as the recovery phase picks up the northward turning at 18:00 UT solar wind speed of 450 km/s. The increase in *Kp* and *AL* indices coincides with *Bz* pointing downward indicating geomagnetic activity enhancement as shown in Fig. 1a.

2.1.2. Case 2. 1 October 2001

Fig. 1b depicts the geomagnetic observation of the storm of 1 October 2001. This storm also originates from CME. The *Bz* plot depressed toward the minimum peak value of −10 nT with *Dst* value of −150 nT between 8:00 UT and 11:00 UT. The solar wind plot signifies a decrease between 539 km/s and 447 km/s at 11:00 UT and *Dst* recover gradually throughout 1 October 2001. *Kp* index peak value used for identification of magnetic storms coincides with rise in *AU* and decrease in *AL* indices. The strength of geomagnetic storm can be examined from solar wind parameters, interplanetary magnetic (*Bz*) and geomagnetic indices. The geomagnetic storm has significant influence on ground magnetic field variations.

2.2. Variations of *H* and *Z* components of geomagnetic field during geomagnetic storms

Fig. 2a and b show the geomagnetic field variations of ΔH obtain from the hourly mean values at different latitudes. During the disturbed event in Fig. 2a shows a significant decrease in *H* component during the main phase of the storm at the noon time across different latitudes. The solar wind parameters such as *Vx* and *Bz* and geomagnetic

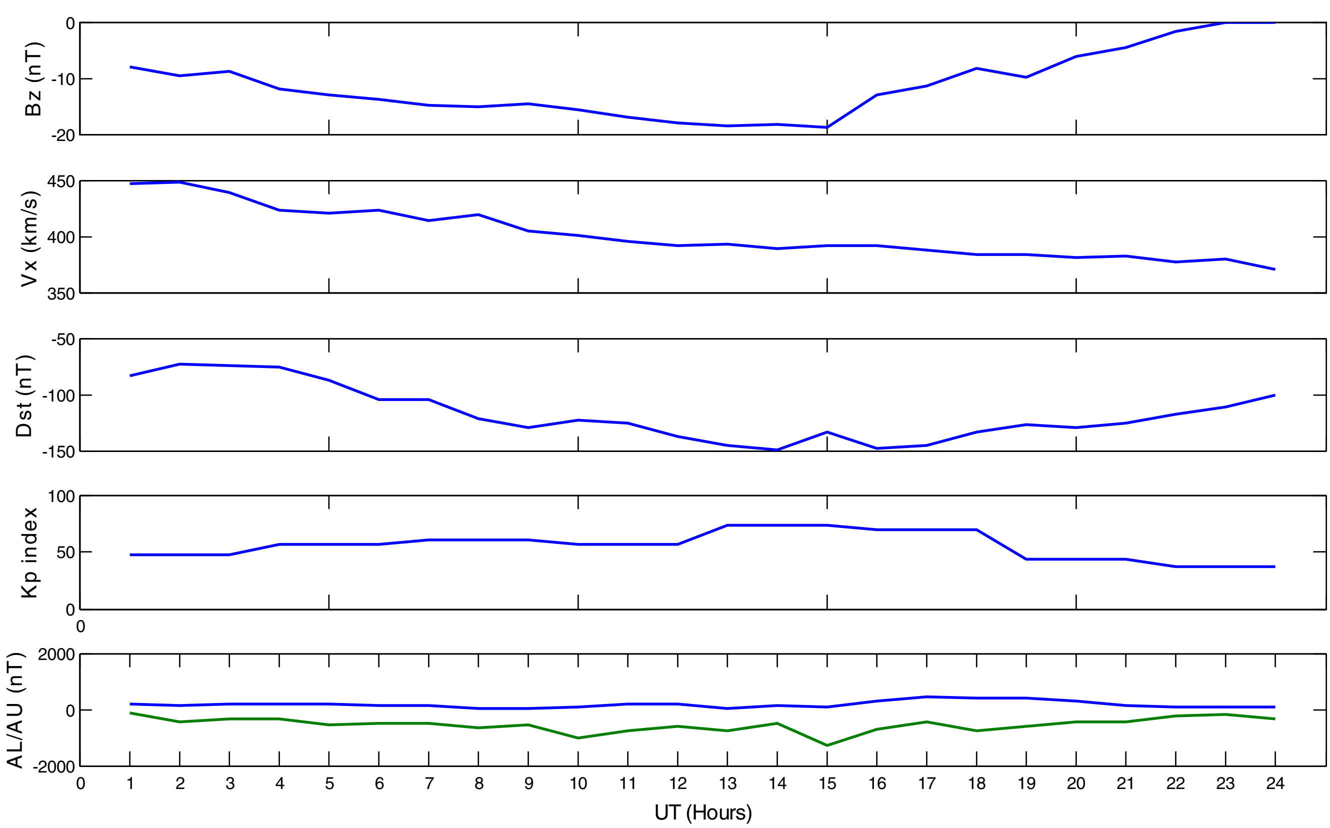

Figure 1a. Interplanetary parameters and geomagnetic indices on 20 March 2001, *Vx*, *Bz*, *Dst* index, *Kp* index, *AU* (blue line) and *AL* (green line) indices (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

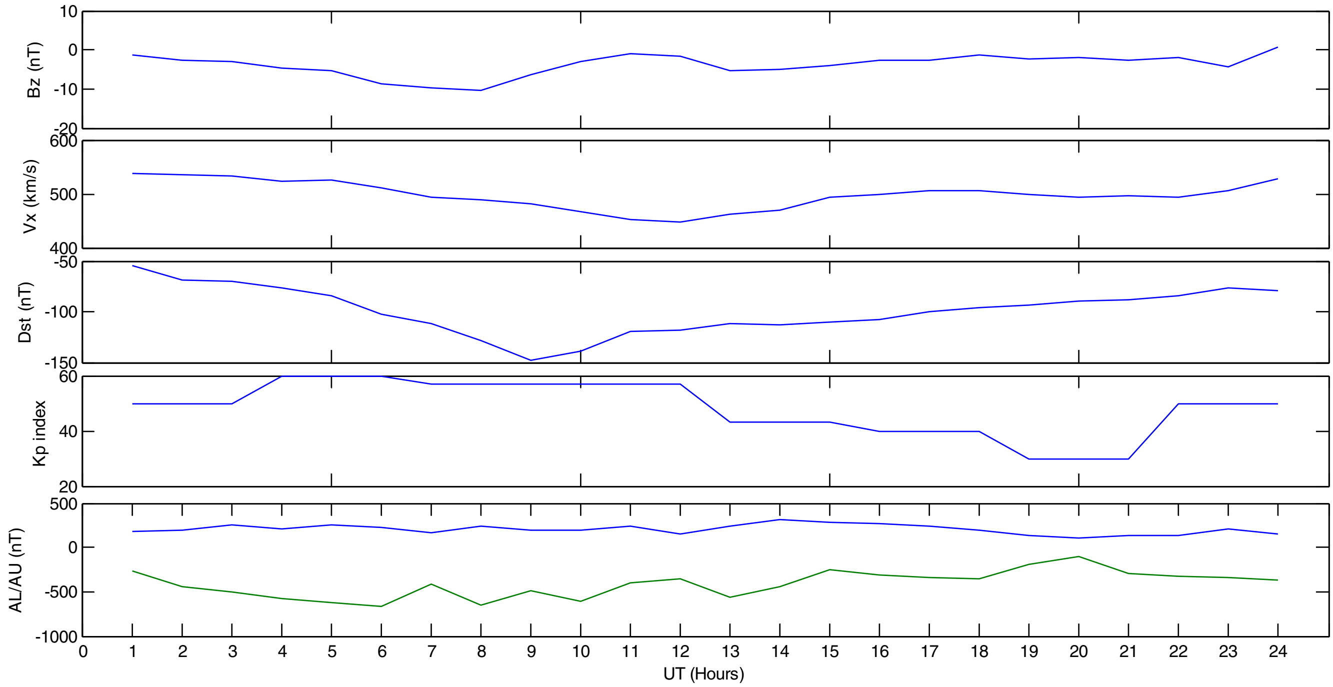

Figure 1b. Interplanetary parameters and geomagnetic indices on 01 October 2001, *Vx*, *Bz*, *Dst* index, *Kp* index, *AU* (blue) and *AL* (green line) indices (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

indices such as *Dst*, *AU* and *AL* show similar fluctuation with geomagnetic field (Fig. 1a). Decrease in the ΔH field at the station during the main phase of the geomagnetic storm is seen to be associated with a decrease in the *Dst* and increase in *Kp* and *Vx*. It was also noted that Fig. 2b shows almost the pattern of variation with Fig. 1b. While the latitudinal variation of ΔZ showed a similar trend to the ΔH component of the geomagnetic field in Fig. 3a and b. During the geomagnetic storm, variation of ΔZ shows a large depression in Z at the selected stations during the middle of the main phase. The large decrease in the ΔH field during the main phase is seen to be associated with a large decrease in the Z field at different latitudes.

2.3. Relationship between ring current and horizontal component of geomagnetic field

The relationship between the *Dst* index and ΔH is examined in Section 2.3. Fukushima and Kamide (1973) refers to *Dst* index as a measure of ring currents flowing in the geomagnetic equatorial plane produced by the geomagnetic disturbance field. ΔH refers to as the variation in the horizontal component of the geomagnetic field. The corrected *Dst* index values for each station was obtained using equation Eq. (2)

$$DR = Dst \text{ index}^{*} \cos(\Phi) \quad (2)$$

where *DR* is ring current and Φ refers to geomagnetic latitude of the station.

Table 2 highlights the regression analysis to test for the relationship between *DR* the ring current and ΔH for the different days of the geomagnetic storm events. The *DR* and ΔH of the stations are well correlated.

Correlations coefficient helps to recognize the relationship between two variables in a single number. We obtain both strong positive and negative correlations between ring current (*DR*) and horizontal component of the magnetic field the ΔH. In this Table 2, a linear correlation between ΔH and *Dst* shows the strength of the geomagnetic storm which strongly depend on the ring current. The correlation is found to be reasonably high except at Addis Ababa on 1 October.

2.4. Variations of electromagnetic induction (dZ/dH) during geomagnetic disturbance

Schmucker (1970) used the geomagnetic field variation from the ratio $\Delta Z/\Delta H$ relation to examine the inductive response of the Earth's interior. Non-uniformities in the electrical conductivity in the upper mantle produced local variation in the Z–H relationship. The non-uniformities of the electrical resistivity within a distance range can be compared with the depth of penetration, these relations can be expressed by using a single transfer function in the frequency-wave number domain. Figs. 4 and 5 show the behavior of $\mathrm{d}Z/\mathrm{d}H$ across the latitudes during the geomagnetic storms on 20 March and 01 October 2001.

2.4.1. Case 1: 20 March 2001

In Fig. 4a at low latitudes: for BAN, the maximum $\Delta Z/\Delta H$ of 0.37 was recorded at the midday while at nighttime the maximum value is 1.2 at 22:00 LT. The maximum rate

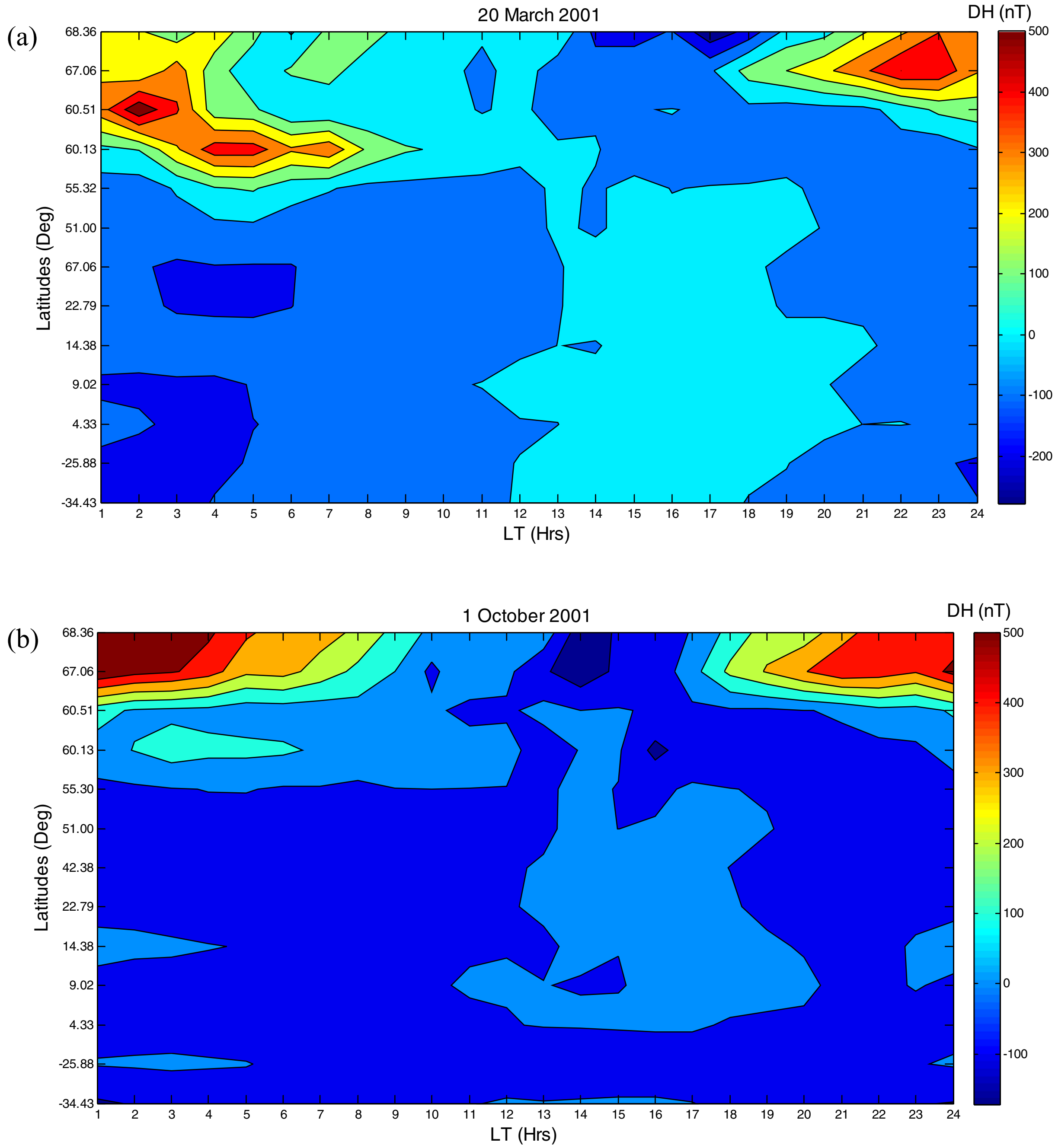

Figure 2. Horizontal component (ΔH) of geomagnetic field across the latitudes on (a) 20 March 2001 and (b) 1 October 2001.

of induction occurred at nighttime at AAE with a value of 1.3 and minimum value of −0.26. At MBO, the enhancement of rate of induction was noticed at the early morning time and nighttime.

At mid latitudes: HER, the variation of the ratio $\Delta Z/\Delta H$ at the midday hours was around 0.71 and increased steadily to 1.8 at the nighttime at round 21:00 LT, later decreases toward the midnight. The rate of induction was also noticed during the post noon at HBK to be 1.4 at 12:00 LT, while at 20:00 LT maximum value recorded was 1.94. Both TAM and LAQ, nighttime occurrences of rate of induction were noticed (see Fig. 4a).

In Fig. 4b, at high latitudes: for HAR, the rate of induction enhancement was noticed at 20:00 LT with a value of 1.87 with a minimum value of −2.6. At ESK, the enhancement of induction was noticed at morning time at 7am with maximum value of 2.4, another post noon peak of $\Delta Z/\Delta H$ was noticed at 16:00 LT with another night increase noticed at 20:00 LT with maximum value of 2.4. Both morning time and nighttime enhancement were noticed on 20 March 2001 at LER with maximum value above 2.5. At NUR, the maximum $\Delta Z/\Delta H$ observed in the early morning time, midday time and another peaks of induction noticed during the nighttime varied between −2.2 and 2.7.

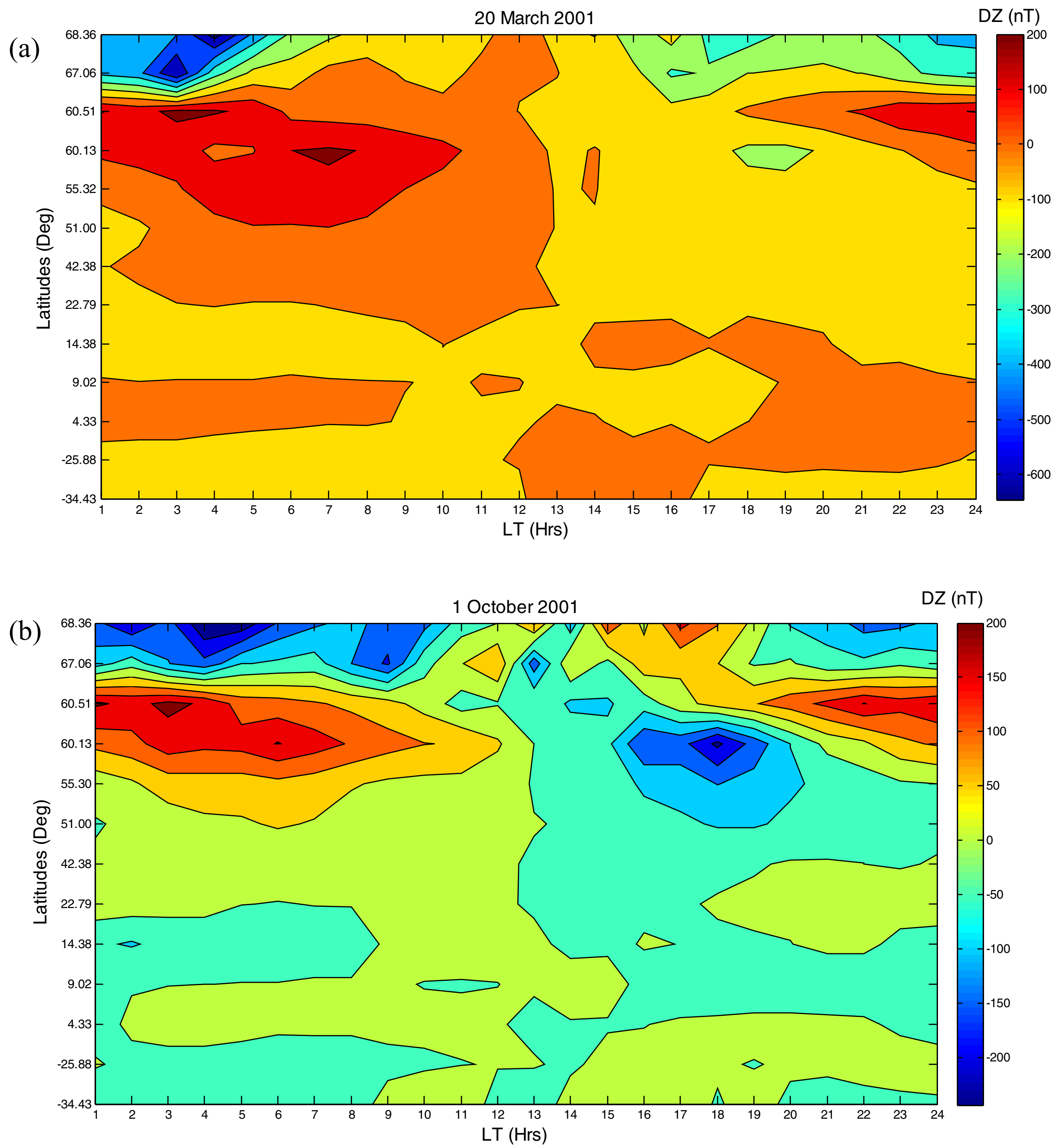

Figure 3. Vertical component (ΔZ) of geomagnetic field across the latitudes on (a) 20 March 2001 and (b) 1 October 2001.

Postnoon increase in rate of induction was noticed with high value of 2.6 and minimum value of −1.7 at morning time, at SOD. The ratio of daytime peaks of $\Delta Z/\Delta H$ at ABI was maximum at 6:00 LT with value of 2.9 and with another peak of 2.9 at 12:00 LT (noontime).

2.4.2. Case 2: 1 October 2001

In Fig. 5a at low latitude: For BAN, maximum and minimum value of dZ/dH varied between −0.9 and 0.6 were observed at nighttime. At AAE, the rate of induction noticed at 13:00 LT with a value of 2.5 and another peak value of dZ/dH was seen at nighttime with a value of 2.7 and minimum value above −2. Early morning enhancement of rate of induction was observed at MBO with maximum value of 1.7.

At mid latitude: For HER, positive enhancement of dZ/dH was noticed at the early morning time, negative enhancement noticed at midday period with another post noontime enhancement. The dZ/dH varied between −2 to 1.9. At HBK, no rate of induction was observed at the daytime while the enhancement noticed at nighttime with a value of 1.7. Both TAM and LAQ shows nighttime

Table 2
Shows correlation coefficient of ΔH and DR at different latitudes on 20 March and 01 October 2001.

Station code	20 March 2001	01 October 2001
AAE	−0.633	−0.353
ABI	−0.647	−0.70
BAN	−0.832	−0.518
ESK	−0.646	0.521
HAR	−0.636	−0.525
HBK	−0.951	0.731
HER	0.952	0.771
LAQ	−0.918	−0.609
LER	−0.659	−0.513
MBO	0.612	0.551
NUR	0.798	0.532
SOD	0.733	0.789
TAM	0.832	−0.518

enhancement rate of induction of 0.4 and 1.4 noticed at 19:00 LT and minimum values of −2.5 and −1 respectively (see Fig. 5a).

In Fig. 5b at high latitudes: Both post midday and nighttime enhancement of ratio dZ/dH was observed at HAR varied between −2.7 and 2.8. At ESK, the ratio dZ/dH varied between −2.5 and 2.6. At LER, positive enhancement of induction was noticed with a maximum occurrence of 0.7 at 24:00 LT and minimum value of −0.8. At NUR with maximum value of 2.7 occurred at noontime, another induction noticed at nighttime 21:00 LT with a value of 2.9 and minimum value of −2.3 was observed. At SOD, the daytime rate of induction was noticed at noontime with value of 2.6 and minimum value of −1.6, while at ABI, the high value of the ratio dZ/dH 0.7 noticed at 13:00 LT with another higher peak at 17:00 LT.

3. Discussion of the results

Figs. 1a and 1b depict the parameter that characterizes the strength of geomagnetic response used in this analysis. The hourly value of solar wind parameters such as the interplanetary magnetic field Bz, solar wind speed Vx, and geomagnetic indices Dst, AU, AL and Kp indices were obtained from OMINIWEB. On 20 March 2001, the interplanetary magnetic field Bz turns southward and compression posture lasted for 6 h and the Dst reach its minimum peak value of −150 nT. While on 1 October 2001 the geomagnetic activity lasted for 3 h between 8:00 and 11:00 UT with southward turning of Bz and minimum value of Dst −150 nT. During the long duration of southward turning of Bz, strongly changed the Earth magnetospheric structure and piercing of the solar energetic particles into the magnetosphere and reduce the size of the region, in which charged particles trapped in the magnetic field surrounding the Earth. When the magnetosphere is compressed by high solar wind dynamic pressure is ring current is enhanced. This is manifested by a decrease in the geomagnetic field and a large decrease in the Dst index.

The horizontal component of the geomagnetic field H gives an estimation of ionospheric current and the effect of current flowing around the Earth. At high latitude stations greater than 60° the reduction in ΔH component was noticed after the noon time than the morning time, this implies that geomagnetic field disturbance is greater in the afternoon. While other stations less than 60° experienced reduction of H in the morning time during the geomagnetic storm of 20 March 2001. The ΔH amplitude in HER and HBK decreases from dawn to the noon time. At low stations high value of ΔH component was noticed during the afternoon period (see Fig. 2a). The same variation pattern of ΔH component on 20 March was also noticed in 1 October 2001 (Fig. 2b). Large enhancement of ΔH was exhibited during the daytime over the equatorial zone, the amplitude decreases from mid latitudes to the dip equator during the nighttime. The daytime enhancement of ΔH at AAE, BAN and MBO suggest the presence of a strong eastward directed current active at this location AAE which comes under the electrojet influence. These increases in H at equatorial electrojet current (EEJ) station are due to intense hall current as a result of dynamo action. Fig. 3a and b show the variation of the ΔZ field at different stations followed the spatial gradient in ΔH field. On 20 March 2001, the ΔZ variations have a positive peak value before noon except ABI and SOD with negative values, ΔZ are minimum during the afternoon hours. On 1 October 2001, the ΔZ variation in some stations is negative (ABI and SOD) and some stations (BAN AAE, and MBO) are close to zero while other stations show positive enhancement of ΔZ variation. The ΔZ variation can be affected as a result of induction effects as suggested by Fukushima (1993).

There are different ways to explain geomagnetic disturbance in the decrease of the ΔH component during the main phase of geomagnetic storms, which is influenced by ring electric current encircling the Earth. Variations in the intensity and distribution of the ring currents, auroral electrojets, and field-aligned currents have an influence on the geomagnetic fields. The auroral electrojets is the horizontal electric currents moving along the E-region around auroral belts and vary widely in amplitude, producing different levels of magnetic activity during the geomagnetic disturbance. The field aligned currents (FACs) is incidence at high latitudes associated with auroral electrojet, these electric currents flowing along the geomagnetic field line create the magnetic disturbance on the ground. Table 2 shows the correlation coefficient between the ring current and ΔH on 20 March 2001 and 1 October 2001 for thirteen stations. Reasonably high correlation coefficients for 20 March 2001 and 1 October 2001 both exhibit strong positive and negative relationship except on 1 October 2001 at Addis Ababa with a correlation coefficient of 0.35. The ring current is responsible for ΔH the variation attributed to the motion of high-energy charged particles coming from the sun into the geomagnetic field. Changes in ΔH and are influenced by the magnetospheric currents such as tail current. The correlation coefficient versus ring current varied as the cosine of the geomagnetic latitude (Φ)

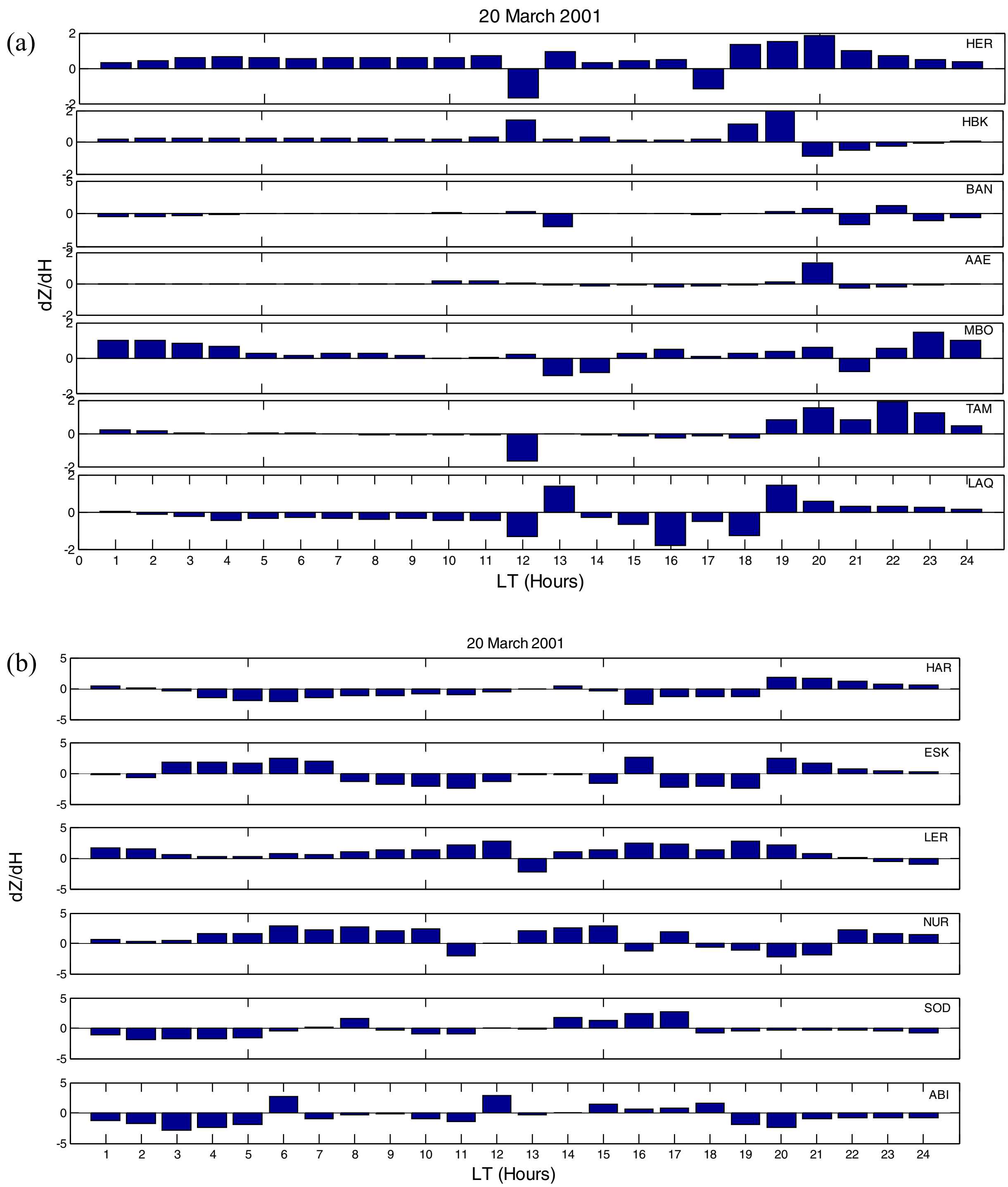

Figure 4. (a and b) Variation of electromagnetic induction $\Delta Z/\Delta H$ at different latitudes on 20 March 2001.

of the station. This implies that they are latitudinal dependent.

Fig. 4a depicts the variability of ratio $\Delta Z/\Delta H$ observed with maximum values of 1.8, 1.9, 1.3, 1.3, 1.5, 1.9 and 1.4 at HER, HBK, BAN, AAE, MBO, TAM and LAQ respectively. While in Fig. 4b at high latitudes the maximum value noticed of 1.9, 2.4, 2.7, 2.9, 2.7 and 2.8 at HAR, ESK, LER, NUR, SOD and ABI respectively. The ratio $\Delta Z/\Delta H$ mostly strong at high latitudes during the geomagnetic storm and less at low latitudes, also the rate of induction increases with latitudes. The maximum value of ratio $\Delta Z/\Delta H$ are 1.9, 1.6, 0.6, 2.7, 1.7, 0.35 and 1.4 at HER, HBK, BAN, AAE, MBO, TAM and LAQ respectively (see Fig. 5a). Also, Fig. 5b shows maximum values of 2.8, 2.6, 2.9, 2.9, 2.6 and 2.9 at HAR, ESK, LER, NUR, SOD and ABI respectively. The effect of rate of

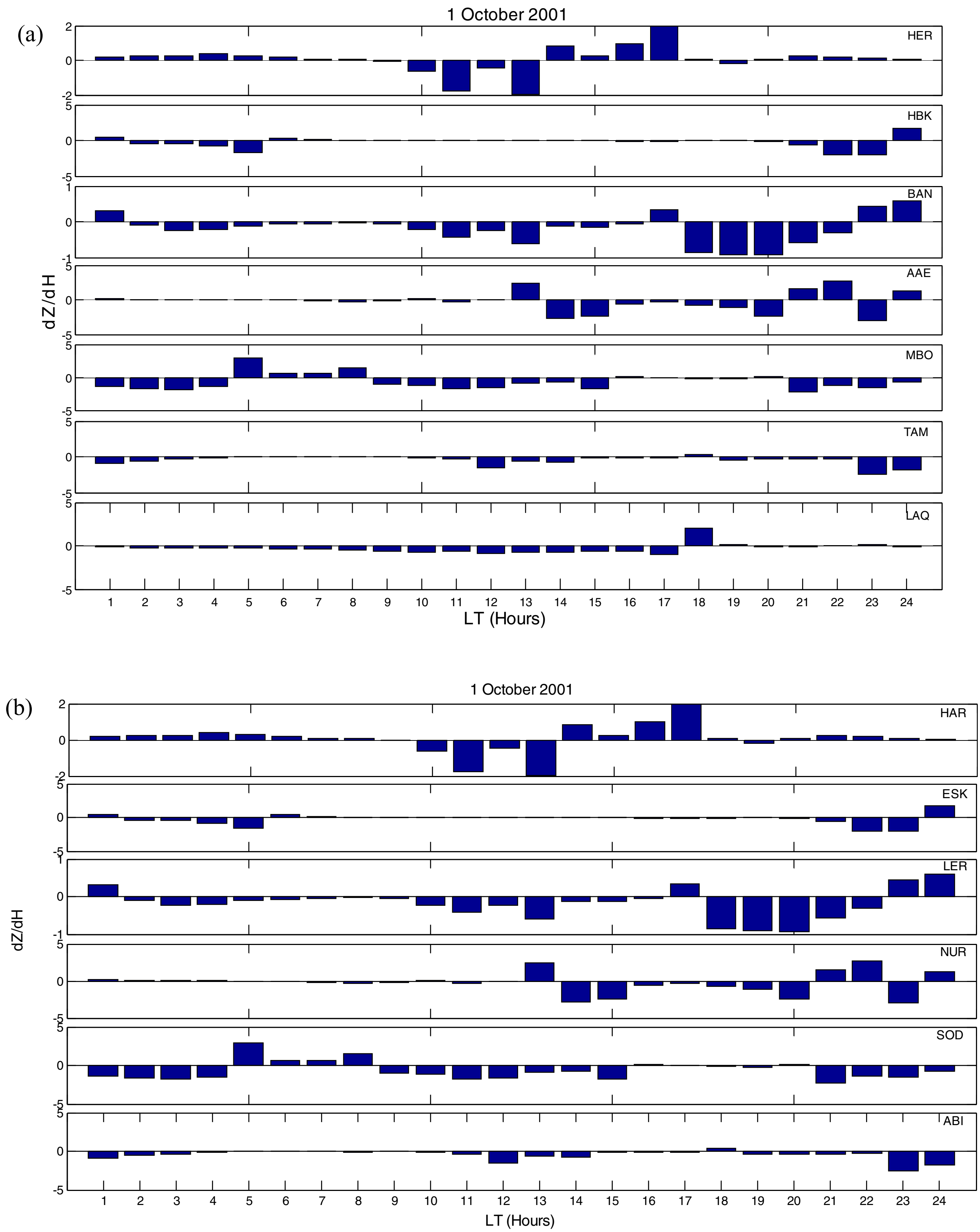

Figure 5. (a and b) Variation of electromagnetic induction $\Delta Z/\Delta H$ at different latitudes on 01 October 2001.

induction is more significant at high latitudes than lower latitudes, during the geomagnetic storm. Nighttime enhancement of rate of induction is more significant than the daytime. The variation of induction noticed at nighttime during the geomagnetic storm may be from sources other than the ionosphere that is magnetospheric process such as the ring current significantly contributes toward the variation of induction. While the daytime enhancement of rate of induction noticed during the geomagnetic storms may be as a result of eastward electric field produced through the wind dynamo mechanism from a charge separation between dawn and dusk suggested by Heelis (2004).

4. Conclusion

The study of ΔH variation, ratio of $\Delta Z/\Delta H$ and interrelationship between the ΔH and the ring current is based on the analyses of geomagnetic field H and Z components from thirteen geomagnetic field stations during the geomagnetic storm of 20 March and 1 October 2001. The following features were drawn.

(i) The reduction in ΔH component was noticed after the noon time than the morning time at high latitude stations greater than 60°, while at stations less than 60° experience reduction of H in the morning time.
(ii) Enhancement of ΔH and ΔZ were observed in the daytime over the equatorial zone, while the amplitude has decreases from mid latitudes to the dip equator during the nighttime.
(iii) The large decrease in the ΔH field during the main phase is seen to be associated with large decrease in the ΔZ field at different latitudes.
(iv) Reasonably high correlation coefficients for 20 March 2001 and 1 October 2001 both exhibit strong positive and negative relationship except on 1 October 2001 at Addis Ababa with low correlation coefficient of 0.35.
(v) The variation of induction noticed at nighttime during the geomagnetic storm may be from sources other than the ionosphere that is magnetospheric process such as the ring current significantly contributes toward the variation of induction.

Acknowledgments

The authors acknowledge INTERMAGNET for providing geomagnetic field data (http://www.intermagnet.org/data), OMINIWEB (http://www.omniweb.gsfc.nasa.gov) staff for providing Vx, Bz, Dst, Kp, AU, and AL indices and coronal mass ejection (CME) http://cdaw.gsfc.nasa.gov/ data used in this research study.

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