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Solar activity dependence of two types of east-west geomagnetic disturbances at mid latitudes

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Abstract: It has been suggested that auroral electrojets are of two types, and each of them is associated with a different current system: the wedge current system and a current system related with magnetospheric convection. In this paper, solar cycle dependences of two different current systems were examined. Each of the two current systems is associated with a different field-aligned current system, which generates a different pattern of geomagnetic disturbances at mid latitudes. In order to examine solar cycle dependences of the two current systems, we investigated those of mid-latitude geomagnetic disturbances. The results suggests that the two current systems have different solar cycle dependences. The activity of the current system associated with convection has a good correlation with D_{st} activity, and it tends to be enhanced around a solar maximum. On the other hand, the wedge current system is enhanced in the late declining phase of the solar cycle. It was also suggested that relative contributions of the two current systems to auroral electrojet activity has a solar cycle dependence. The contribution of the wedge current system to auroral electrojet activity is rather small around a solar maximum, while it becomes considerable around a solar minimum.

key words: solar cycle, magnetic disturbances, magnetic storm, substorm

1. Introduction

Field-aligned currents have a significant effect on geomagnetic disturbances at mid latitudes. For example, it is thought that asymmetrical disturbances at mid latitudes are mainly caused by field-aligned currents (*e.g.*, Nakano and Iyemori, 2003a). In particular, east-west geomagnetic disturbances ΔD at mid latitudes are mainly attributed to field-aligned currents (*e.g.*, Sun *et al.*, 1984). Since field-aligned currents are closely associated with geomagnetic activities at auroral region, east-west geomagnetic disturbances at mid latitudes show a good correlation with intensity of auroral electrojets (*e.g.*, Nakano *et al.*, 2002).

It has been suggested that auroral electrojets are generally divided into two components (Troshichev *et al.*, 1974; Rostoker *et al.*, 1987; Kamide and Kokubun, 1996). One is a westward electrojet around midnight which develops at substorm expansions, and it corresponds to the wedge current system (Clauer and McPherron, 1974). The other is electrojets which develop when the interplanetary magnetic field (IMF) is directed southward. Since the two different electrojets are associated with different field-aligned current systems, two different geomagnetic variations are accordingly observed at mid latitudes. At a substorm expansion, a wedge current signature is observed; that is, an eastward/westward disturbance in the pre-midnight and a westward/eastward disturbance in the post-midnight in the northern/southern hemisphere are observed (Clauer and McPherron, 1974). On the other hand, when the IMF is directed southward and magnetospheric convection is developed, an eastward/westward disturbance in the northern/southern hemisphere centered around the midnight or the post-midnight is observed (*e.g.*, Clauer and Kamide, 1985; Nakano and Iyemori, 2003b).

Geomagnetic disturbances are closely related with solar activity. Therefore it is expected that the two auroral current systems depend on the solar cycle. However, different magnetospheric phenomena do not necessarily have the same dependence on solar activity. For example, it has been pointed out that storms and substorms have different dependences on the solar cycle (Vennerstrøm and Friis-Christensen, 1996). Thus the two auroral current systems may have different dependences on the solar cycle. However, the solar activity dependence of each of the two different current systems has not been investigated.

The purpose of this paper is to examine the solar activity dependence of each of the two current systems. Recently, Nakano and Iyemori (2003b) have introduced two parameters, which roughly monitors the two different current systems. The two parameters are derived from east-west components of geomagnetic data obtained at mid-latitude observatories. The solar activity dependence of each of the two parameters must reflect on that of each of the two different current systems. In this paper, the solar activity dependences of the two parameters were investigated, and the solar activity dependences of the two current systems were discussed.

2. Parameterization

In this paper, we analyzed the east-west component of geomagnetic data obtained at mid-latitude observatories listed in Table 1. As mentioned above, the east-west geomagnetic disturbances at mid latitudes are mainly attributed to field-aligned currents. In order to avoid a mixing of the effect from the ring current, we used the eastward component in the dipole coordinate system in this paper according to Iyemori (1990). From the data, we derived a local-time profile of the east-west geomagnetic variations at mid latitudes. The local-time profile reflects the local-time structure of field-aligned currents. From the local-time profile, we derived two parameters, which roughly monitors the two different current systems. The method is same as that of Nakano and Iyemori (2003b) except that the set of observatories used in this study is different. Here we describe the outline of the method.

Table. 1. List of mid-latitude geomagnetic observatories used in this paper.

	Geographic (deg.)		Dipole (deg.)		Std. dev.
	Lat. (N)	Long. (E)	Lat. (N)	Long. (E)	of ΔD (nT)
Fresno (FRN)	37.1	240.3	43.7	304.5	9.58
Boulder (BOU)	40.1	254.8	48.7	319.8	13.22
Fredericksburg (FRD)	38.2	282.6	48.8	352.9	11.50
Chambon-La-Foret (CLF)	48.0	2.3	49.9	85.8	12.34
Martin De Vivies (AMS)	−37.8	77.6	−46.8	143.6	11.28
Memambetsu (MMB)	43.9	144.2	34.9	210.8	8.19
Honolulu (HON)	21.32	202.00	21.60	269.45	4.42

We subtracted the S_q-field for each observatory for each month from the original data to obtain a eastward disturbance field, ΔD. The S_q-field was estimated from data of quiet days (in UT) for each month. As the quiet days, we have selected the days when high latitude geomagnetic disturbances (*AE* and K_p activity) are nearly or completely absent over a whole day. The averaged daily variation of the quiet days for each month for each observatory was fitted by 12 terms Fourier series. These Fourier series were used as the S_q-field and the geomagnetic main field.

We derived a magnetic local time (MLT) profile of east-west geomagnetic disturbances, ΔD, for each minute at the mid-latitude observatories by linear interpolation. In deriving the MLT profile of ΔD, we inverted the sign of ΔD at southern hemisphere observatory (AMS) because magnetic effects of field-aligned currents on the east-west component in the southern hemisphere must be opposite to those in the northern hemisphere. In order to eliminate latitudinal and longitudinal dependences, ΔD for each observatory was normalized such that its standard deviation within 2100–0300 MLT from 1987 to 2001 is 10.0 nT before deriving the MLT profile. (The actual standard deviation of ΔD for each observatory is displayed in Table 1.)

The top panel of Fig. 1 indicates a UT variation of the MLT profile of ΔD at mid latitudes during a storm on 13 October 2000. The ordinate denotes MLT, and the abscissa denotes UT. Positive represented by red-yellow denote eastward/westward disturbances in the northern/southern hemisphere, which correspond to the effect of upward field-aligned currents, and negative represented by blue-cyan denote westward/eastward disturbances in the northern/southern hemisphere, which correspond to the effect of downward field-aligned currents. The location (MLT) of each observatory is indicated by a solid line superposed on the panel. This figure also shows the *SYM-H* index (second panel), the *ASY-D* and *ASY-H* indices (third panel) (Iyemori, 1990) are also displayed. The *SYM-H* index is a geomagnetic index which essentially represents the D_{st} field with a 1-min resolution. The sign of the *ASY-H* index is inverted in plotting it. The QL *AE* indices and the z-component of the IMF (in GSM coordinates) B_z obtained by the ACE satellite are shown in the fourth panel and the fifth panel, respectively. Parameters ψ and ζ displayed in the bottom panel will be explained later. For convenience of comparison with geomagnetic variations, the IMF measured by the ACE is plotted time delayed at the Earth location. The delay time from the ACE position to the Earth location is assumed to be 50 min in this paper. Figure 2 indicates a UT variation of the MLT profile of ΔD during a substorm on 21 January 1999. The data appended in this figure are the same as those of Fig. 1.

As shown in the top panel of Fig. 1, a positive ΔD disturbance at mid latitudes was seen on the nightside from about 0100 UT to about 0300 UT and from about 0400 UT to about 0600 UT on 13 October 2000 (top panel). This positive disturbance means that upward field-aligned currents developed on the nightside. Such a disturbance is basically seen during southward IMF conditions (*e.g.*, Clauer and Kamide, 1985; Nakano and Iyemori, 2003b). On the other hand, Fig. 2 shows that a wedge current signature appeared at mid latitudes around 1100 UT on 21 January 1999; that is, positive and negative disturbances are observed in the pre-midnight and post-midnight, respectively (Clauer and McPherron, 1974). These two types of disturbances are commonly seen at mid latitudes.

From the MLT profile of ΔD, we derive two parameters: ψ and ζ. A parameter ψ is defined as the average value of the MLT profile of ΔD within $2100 \leq MLT < 0300$, and it

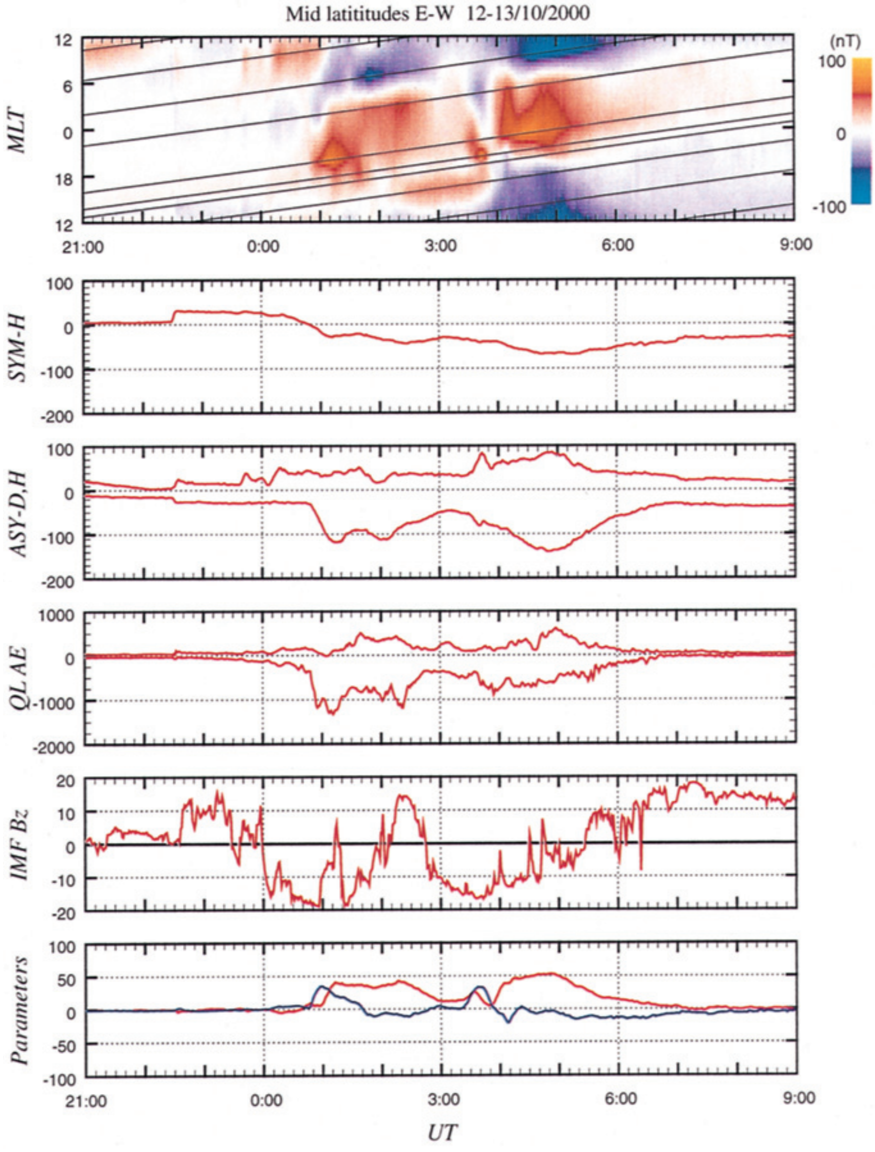

Fig. 1. *Overview plot for a weak storm on 13 October 2000. The top panel shows ΔD at mid-latitudes in the MLT-UT plane. Positive variations (red-yellow) denote eastward/westward disturbances in the northern/southern hemisphere, and negative variations (blue-cyan) denote westward/eastward disturbances in the northern/southern hemisphere. The location of each observatory used here is indicated by a solid line superposed on the panel. In this figure, the SYM-H index (second panel), the ASY-D, H indices (third panel), the QL AE indices (fourth panel), and the z-component (in GSM coordinates) of the IMF B_z are also displayed. In addition, ψ and ξ defined in the text are also shown in the bottom panel with the red and blue lines, respectively.*

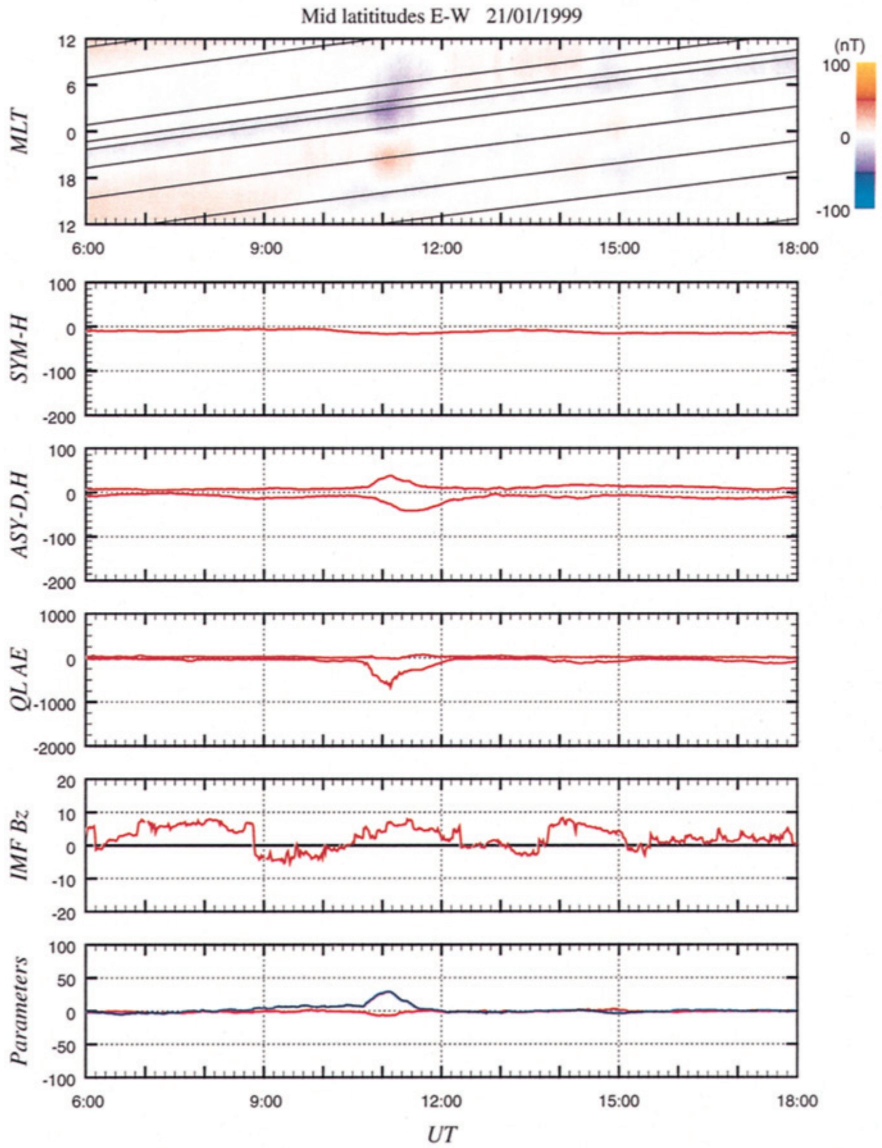

Fig. 2. Overview plot for a substorm on 21 January 1999 in the same format as Fig. 1.

generally represents upward currents centered around the midnight as seen in Fig. 1, which are accompanied with southward IMF. Another parameter ζ is defined as the average of the MLT profile of ΔD within $2100 \leq MLT < 0000$ with subtraction of the average of that within $0000 \leq MLT < 0300$. Positive ζ indicates that ΔD in the pre-midnight are larger than those in the post-midnight. The ζ substantially represents whether Region 1 sense currents or Region 2 sense currents are relatively intensified. The development of Region 1 sense currents enhances ζ, and the development of Region 2 sense currents depresses ζ. Since a current wedge around the midnight, which is in a Region 1 sense, would enhance ζ, we can regard the ζ as a rough proxy of wedge current intensity. We must note that the ζ can not always detect development of current wedges. If the local-time where a current wedge develops is located far from the midnight, the current wedge can not enhance the ζ. In addition, the seven observatories, which are distributed sparsely, may not detect either or both of the upward and downward currents which consist in the current wedge. However, the ζ can be used as a rough proxy of current wedge activity, as far as it is used for statistical analyses. In the bottom panels of Fig. 1 and 2, the variations of ψ and ζ are plotted with red and blue lines, respectively. ψ was enhanced from about 0100 UT to about 0300 UT and from about 0400 UT to about 0600 UT on 13 October 2000 according that the positive ΔD disturbance was seen on the nightside (Fig. 1). ζ was enhanced around 1100 UT on 21 January 1999 according that the current wedge signature was observed (Fig. 2). Figure 1 also indicates that ζ was enhanced around 0100 and 0340 UT on 13 October 2000 and that ψ develops after the brief enhancements of ζ, which means the development of the current wedge. The upward currents centered around the midnight usually develops after substorm onsets, although it principally depends on southward IMF. This point is further discussed another paper (Nakano and Iyemori, 2003b).

3. Analysis

In order to examine long term variations of ψ and ζ, we calculated minutes of $\psi > 20$ and of $\zeta > 20$ per day for each month for the period from 1987 to 2001, and we used them as proxies of activities of ψ and ζ, respectively. The minutes of $\psi > 20$ per day for a month is defined as a product of probability for $\psi > 20$ in the month and minutes of one day (*i.e.*, 1440). The probability of $\psi > 20$ for each month can be calculated by dividing number of data when $\psi > 20$ by total number of available ψ values in the month.

In Fig. 3, the minutes of $\psi > 20$ per day for each month are shown with dotted lines in the top panel. In the middle panel, monthly averages of the D_{st} index are displayed. Solid lines in the top and the middle panel indicate 1-year running average values. The monthly sunspot number variation is also appended in the bottom panel of this figure for reference. The ψ activity well correlated with D_{st} activity. Both the ψ activity and the D_{st} activity have two peaks in a solar cycle (1989 and 1991), although the ψ activity was more high at the latter peak than at the former while the D_{st} activity at the latter peak was as high as at the former. The good correlation between the ψ activity and the D_{st} activity is natural because both are accompanied with southward IMF (Nakano and Iyemori, 2003b). The ψ activity also roughly correlated with the solar activity. In the solar minimum (1996), the ψ activity was reduced to a minimum. When solar activity is high, however, the relation between the ψ and the solar activity was rather complicated. The peak of the ψ activity was delayed behind the solar activity. In addition, the ψ activity dipped in the late of 1990. These features were seen in the variation of the averaged D_{st} as well.

In Fig. 4, the minutes of $\zeta > 20$ per day for each month are shown with dotted lines in the top panel. A solid line indicates 1-year running average values as well as in the top and the middle panel of Fig. 3. The monthly sunspot number values are also displayed in the bottom panel again. The relation between the ζ activity and the solar activity was different from that between the ψ activity and the solar activity. The peak of the ζ activity was in

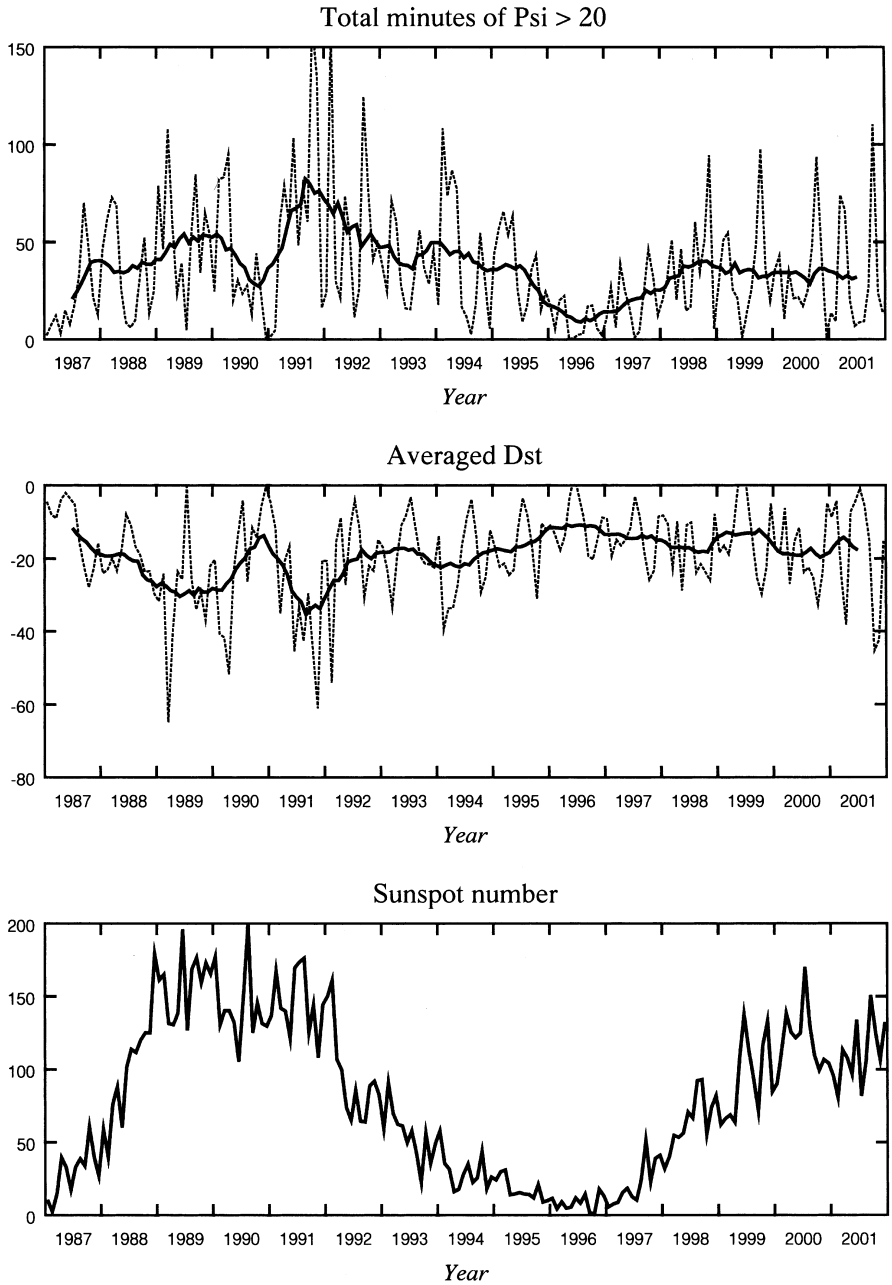

Fig. 3. The minutes of $\psi > 20$ per day for each month from 1987 to 2001 (top panel). Monthly averages of the D_{st} index (middle panel) and the sunspot number (bottom panel) for each month are also displayed for reference. In the top and middle panels, 1-year running average values are superposed with solid lines.

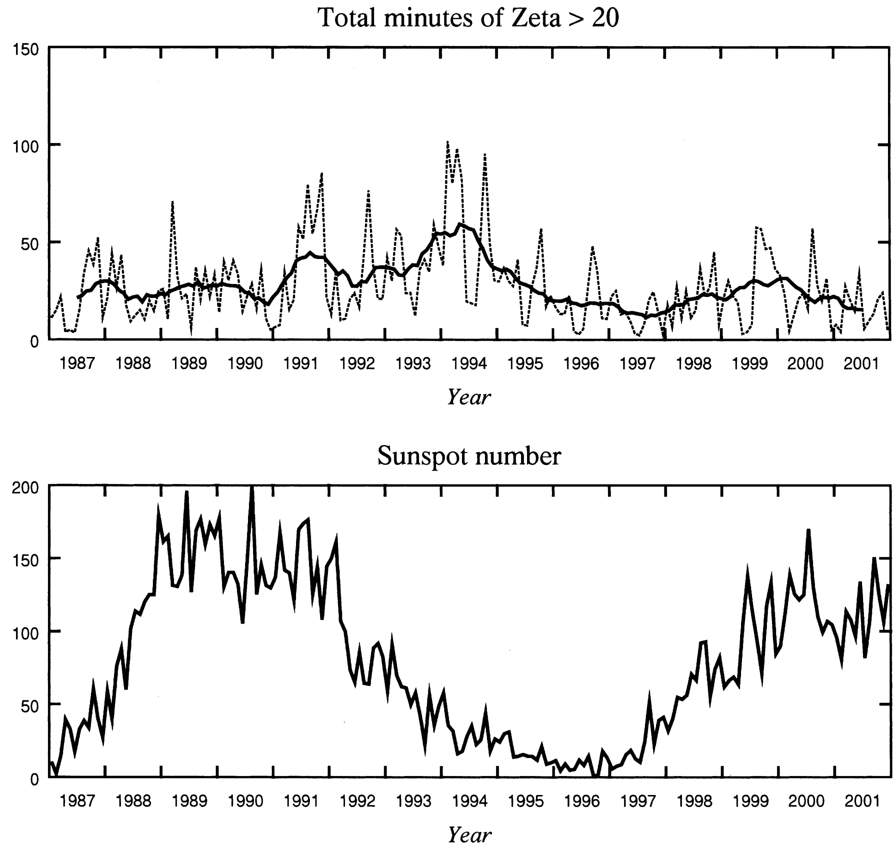

Fig. 4. The minutes of $\zeta > 20$ per day for each month from 1987 to 2001 (top panel). The monthly values of the sunspot number are also displayed as well as in Fig. 3 (bottom panel). In the top panel, 1-year running average values are superposed with a solid line again.

1994 when solar activity was decaying. Around the solar maximum, the ζ activity was only slightly enhanced.

Vennerstrøm and Friis-Christensen (1996) have suggested that geomagnetic activity has three peaks during one solar cycle. The first peak appears slightly prior to a sunspot maximum. In the first peak, the ring current activity is high while the high-latitude geomagnetic activity is not enhanced. In the second peak, which comes after a sunspot maximum, both the ring current activity and the high-latitude activity are enhanced. In the third peak, which appears in the late declining phase of the solar cycle, the high-latitude activity are enhanced while the ring current is not so activated.

The three peaks of geomagnetic activity may be seen in the result of this study as well, although our study examined only one solar cycle. In the first peak (around 1989), the D_{st} activity and the ψ activity were high, and the D_{st} was more activated than the ψ. In the second peak (around 1991), both the D_{st} activity and the ψ activity were high again, and the ζ was slightly activated. In the third peak (around 1994), the ζ activity became high while the

D_{st} activity was not so enhanced. Since ψ and ζ correspond to the high-latitude geomagnetic activity, the result of this study indicates that the high-latitude geomagnetic activity was mainly enhanced in the second and third peaks as well as the result by Vennerstrøm and Friis-Christensen. However, this study suggests that the high-latitude geomagnetic activity was associated with different current systems between in the second peak and in the third peak. The second peak in the high-latitude geomagnetic activity was mainly attributed to the ψ activity; that is, the development of geomagnetic activity at high latitudes were mainly attributed to magnetospheric convection, which is caused by southward IMF. The third peak in the high-latitude geomagnetic activity was mainly attributed to the ζ activity; that is, the development of geomagnetic activity at high latitudes were mainly caused by the development of the wedge current systems.

This fact suggests that the high-latitude geomagnetic activity is associated with different current systems between around the solar maximum and around the late declining phase of the solar cycle. In order to compare the contributions of the two different current systems to the high-latitude geomagnetic activity, we examined relation between ψ and the *AE* index and that between ζ and the *AE* index. Figure 5 indicates correlation coefficients between ψ and *AE* and those between ζ and *AE*. In general, the correlation between ψ and *AE* is higher than that between ζ and *AE*. This indicates that *AE* activity is mainly attributed to the current system which is associated with magnetospheric convection. Although the correlation between ψ and *AE* varies little, the correlation between ζ and *AE* became gradually higher from 1990 to 1994. Around the solar maximum (from 1990 to 1992), the correlation between ζ and *AE* was low. In the declining phase (1993 and 1994), ζ came to have a correlation with *AE*. This may indicate that a contribution of the wedge current system to *AE* activity has a solar cycle dependence. The wedge current system hardly contributes to *AE* activity around the solar maximum, while the wedge current system comes to have a considerable contribution to *AE* activity after the solar maximum.

Unfortunately, the Provisional *AE* index is not available for most of periods from 1987 to 2001 when we can obtain ψ and ζ values. In order to investigate long term variation of relative contribution of the two current systems to the high-latitude geomagnetic activity, we compared ψ and ζ with the *ASY-H* index (Iyemori, 1990). The *ASY-H* index indicates

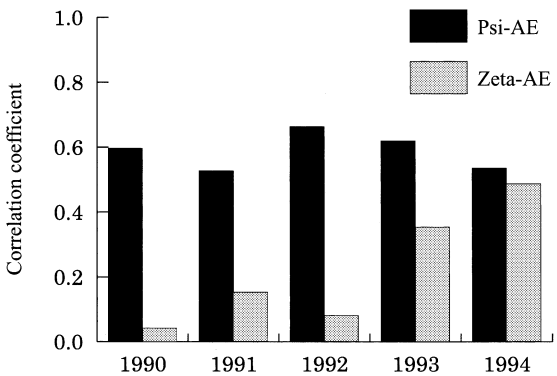

Fig. 5. Correlation coefficients between ψ and AE and those between ζ and AE for each year from 1990 to 1994.

asymmetrical geomagnetic north-south disturbances at mid latitudes. Since the asymmetrical disturbances at mid latitudes are associated with the high-latitude geomagnetic activity (*e.g.*, Crooker and McPherron, 1972; see also, Nakano and Iyemori, 2003a), we can use the *ASY-H* as a proxy of the high-latitude geomagnetic activity. Figure 6 indicates correlation coefficients between ψ and *ASY-H* and those between ζ and *ASY-H*. In general, ψ is positively correlated with *ASY-H* as well as *AE*, and the correlation coefficient varies little. Correlation between ζ and *ASY-H* is likely to have a solar cycle dependence. Around the solar maximum, the correlation between ζ and *ASY-H* was near zero. From the declining phase to the developing phase of the solar cycle, ζ have a certain correlation with *ASY-H*. Thus it is suggested that a contribution of the wedge current system to the high-latitude geomagnetic activity has a solar cycle dependence.

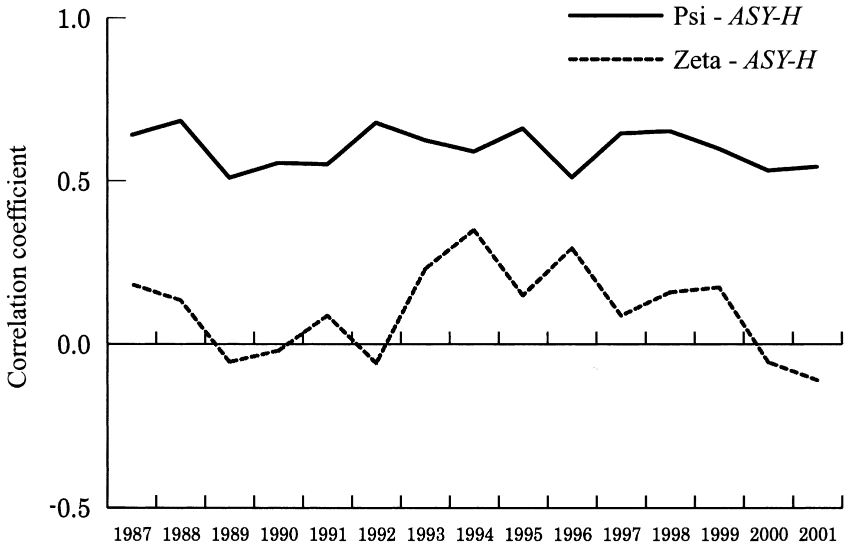

Fig. 6. Correlation coefficients between ψ and ASY-H and those between ζ and ASY-H for each year from 1987 to 2001.

4. Summary and discussions

In this paper, we derived two parameters (ψ and ζ), which roughly monitors the two different current systems, according to Nakano and Iyemori (2003b), and long term variations of the two parameters were investigated during the period from 1987 to 2001. The ψ generally represents intensity of the current system which is associated with magnetospheric convection. The ζ generally represents intensity of the wedge current system at substorm expansion. The result suggested that the two current systems have different solar cycle dependences. One current system, which is associated with convection, closely correlates with the D_{st} activity, and it roughly correlates with the sunspot number. The other current system, the wedge current system, does not have any clear correlation with the sunspot number. However, it is enhanced in the late declining phase of the solar cycle.

The long-term variations of solar wind parameters have been examined by many authors (*e.g.*, King, 1991). Around solar maxima, the IMF intensities become larger than around solar minima. The convection electric field in the magnetosphere and the ionosphere is dependent on the IMF intensities, although it is dependent on the IMF orientation as well (*e.g.*, Boyle *et al.*, 1997). Therefore it is natural that the solar wind condition more favorable for the development of the current system associated with convection in solar maxima. On the other hand, it is suggested that high speed solar wind streams frequently occur in the declining phase of the solar cycle. Thus the result of this study might suggest that high solar wind speed conditions are favorable for the development of the wedge current system. However, our result is not a conclusive evidence of the relationship between the development of current wedge and solar wind speed. It is necessary to compare the occurrence frequency of current wedge developments with various solar wind parameters to clarify the origin of the solar cycle dependence of current wedge developments in the future.

Since the two current systems have different solar cycle dependences, relative contributions of the two current systems to auroral electrojet activity has a solar cycle dependence. Around the solar maximum, the contribution of the wedge current system is rather small, and auroral electrojet activity is mostly attributed to convection. On the contrary, the contribution of the wedge current system becomes considerable around the solar minimum. This fact may explain the result by Nakai and Kamide (1999) who have indicated that the relation between the AL index and the D_{st} index becomes closer in the solar maximum than in the solar minimum, because geomagnetic storms is associated with the convection.

The wedge current system appears at substorm expansions. It is well known that a substorm expansion is accompanied with a Pi2 pulsation. If the current wedge and the Pi2 pulsation are generated through the same process, the current wedge activity and the Pi2 pulsation activity should have the same solar cycle dependence. However, it is suggested that occurrence frequency of the Pi2 pulsations inversely correlated with solar activity (Saito and Matsushita, 1968), while the result of this study has suggested that the current wedge activity reaches a peak in the declining phase of the solar cycle. Possibly most of the current wedges are so weak that ζ can hardly exceed 20. Otherwise most of Pi2 pulsations around a solar minimum might not be accompanied with any current wedge activations.

This study examined geomagnetic variations for only one solar cycle. Therefore we can not actually say whether the suggestion provided by the result of this study is universally valid for other solar cycles. We must make a similar analysis for other solar cycles in the future to confirm whether the suggestion is generally valid or not.

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