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Response of the Geomagnetic Activity Indices to the Solar Wind Parameters

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Abstract

This study attempts to show how the geomagnetic indices, AU, AL and Dst, respond to the interplanetary parameters, more specifically, the solar wind electric field VBz during southward interplanetary magnetic field (IMF) period. The AU index does not seem to respond linearly to the variation of southward IMF. Only a noticeable correlation between the AU and VBz is shown during summer, when the ionospheric conductivity associated with the solar EUV radiation is high. It is highly likely that the effect of electric field on the eastward electrojet intensification is only noticeable whenever the ionospheric conductivity is significantly enhanced during summer. Thus, one should be very cautious in employing the AU as a convection index during other seasons. The AL index shows a significantly high correlation with VBz regardless of season. Considering that the auroral electrojet is the combined result of electric field and ionospheric conductivity, the intensification of these two quantities seems to occur concurrently during southward IMF period. This suggests that the AL index behaves more like a convection index rather than a substorm index as far as hourly mean AL index is concerned. Contrary to the AU index, the AL index does not register the maximum value during summer for a given level of VBz. It has something to do with the findings that discrete auroras are suppressed in sunlight hemisphere (Newell et al. 1996), thus reducing the ionospheric conductivity during summer. As expected, the Dst index tends to become more negative as VBz gets intensified. However, the Dst index (nT) is less than or equal to 15 VBz (mV/m) + 50 ($Bz < 0$). It indicates that VBz determines the lower limit of the storm size, while another factor(s), possibly substorm, seems to get further involved in intensifying storms. Although it has not been examined in this study, the duration of southward IMF would also be a factor to be considered in determining the size of a storm.

Keywords: AU, AL, Dst indices, solar wind electric field

1. Introduction

Since their introduction to the community, the geomagnetic activity indices, AU, AL, AE and Dst have played various roles in many aspects of the solar-terrestrial physics. In spite of their usefulness in providing a proxy for geomagnetic activity level, several researchers (e.g., Rostoker 1972, Allen & Kroehl 1975) have raised questions about their accuracy and limitations. Some of the limitations are from either the data availability or the simplified scheme of deriving them (Kamide 1988).

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Recently Ahn et al. (2000a,b) reported that the limitations are further associated with seasonal variations and unrealistic location of magnetic stations from which those indices are derived.

The auroral electrojet indices AU, AL and AE have been widely used as measures of the auroral electrojet intensity and magnetospheric substorm activity. Rostoker(1972) argued that the eastward electrojet (described by AU index) is driven by a quasi-steady convection in the magnetosphere, while the main part of the westward electrojet described by the AL index arises from both substorm and convection. Since the intensification of the auroral electrojets is the result of the electric field and ionospheric conductivity enhancements, the relative importance of the two quantities to the electrojets has been extensively discussed (Ahn et al. 1999).

Since the center of the eastward electrojet is located in the dusk sector (Allen & Kroehl 1975) where the ionospheric conductivity associated with auroral activity is insignificant (Ahn et al. 1999), it is likely that the electric field variation is reflected on the AU. Thus, it has been tacitly assumed that the AU is a convection index reflecting the "directly driven" process of the solar wind and magnetospheric coupling. On the other hand, Allen & Kroehl (1975) noted that the AL index is most often derived from the records of AE stations located around 0315 MLT, where auroral particle precipitation contributes largely to the ionospheric conductivity (Ahn et al. 1999), indicating that the AL index closely reflects substorm activity. This is the reason why the AL index has been used as a substorm index.

Unfortunately, a rigorous test for whether the AU and AL indices can be used as the magnetospheric convection and substorm indices, respectively, has not been carried out mainly because of the unavailability of reliable solar wind data. With the deployment of WIND and ACE satellites, it has finally been possible to monitor uninterrupted solar wind, thus providing us with a unique opportunity to compare various geomagnetic indices with the solar wind parameters. We are going to examine how the geomagnetic indices, AU and AL indices respond to the variation of the interplanetary magnetic field (IMF), more specifically, the solar wind electric field, VBz, defined by the product of the solar wind velocity and the IMF Bz component. When the IMF Bz shows southward component, the sign of the solar wind electric field becomes negative. The comparison between the indices and the solar wind electric field would shed light on the roles of the magnetospheric convection and substorm activity upon those indices.

Also compared with VBz is the Dst index. According to Akasofu (1968), a geomagnetic storm is built by the successive occurrence of intense substorms, while Kamide (1992) and McPherron (1997) argued that a magnetic storm is caused by the enhanced magnetospheric convection during a prolonged period of southward IMF. It is further argued that substorms occur coincidentally during the main phase of magnetic storms, suggesting that they do not contribute to the ring current intensification. From the ionospheric outflow observed by AMPE/CCE and also by CRRES, however, Daglis et al. (1994, 1996) suggested the importance of substorm occurrence during the storm time ring current development. Thus, the comparison between the Dst index and VBz could provide us with an opportunity to test the long-standing debate on the storm-substorm relationship.

2. Data

For this study hourly mean indices during the period from 1998 to 2002 are utilized. Unfortunately, the AU and AL indices are Quick Look Preliminary ones that were derived from sometimes eight or less AE stations instead of 12. Thus, it is likely that the final conclusion derived from this study can be slightly modified when the final indices are available. The Dst index used in this study covered the years from 1998 to 2003. The dynamic pressure effect of the solar wind has been removed from the Dst index (Burton et al. 1975). All indices are provided by the World Data Center

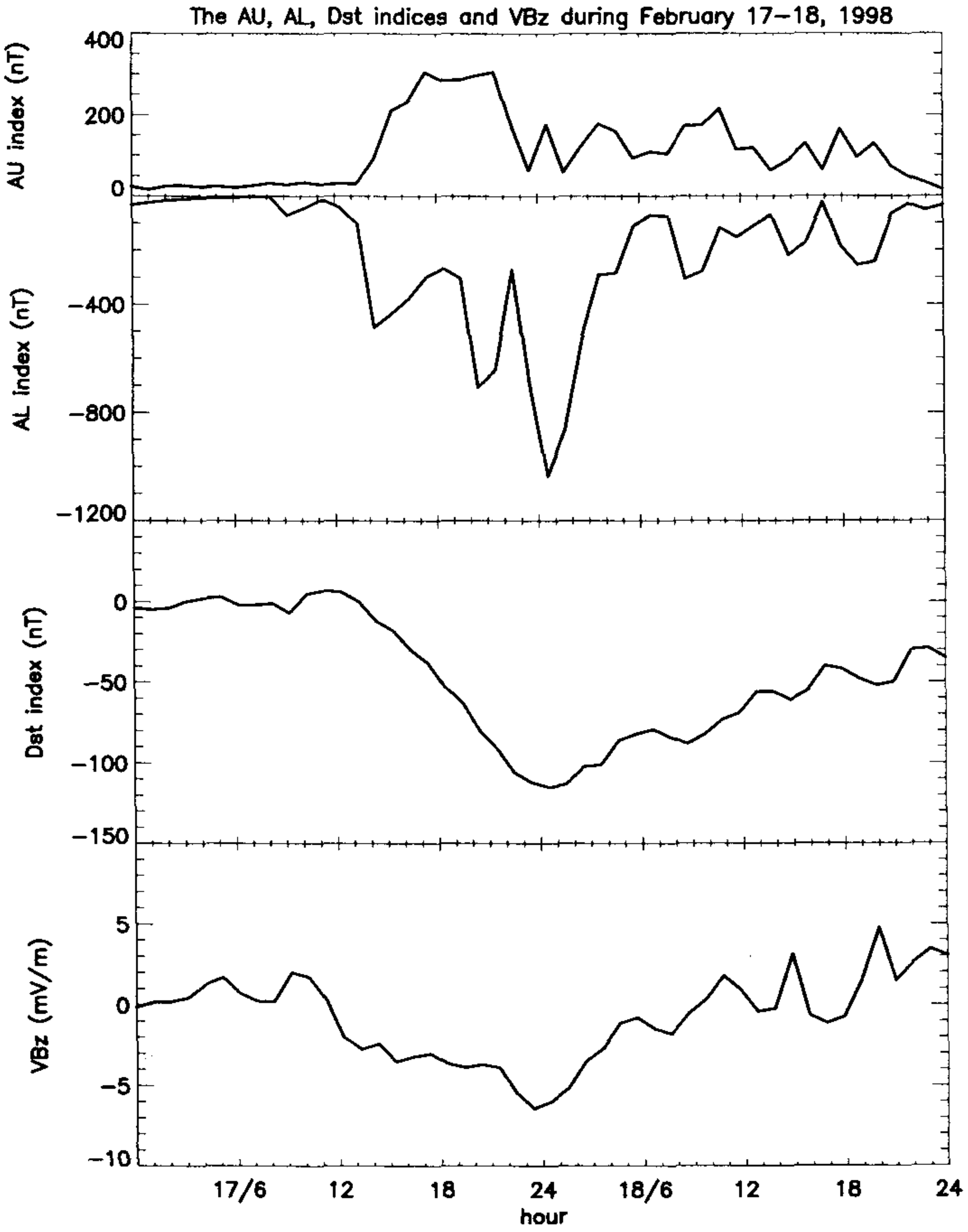

Figure 1. The AU, AL, Dst and VBz variations during February 17-18, 1998.

for Geomagnetism at Kyoto University. The interplanetary parameters during the same period were measured by ACE satellite.

To investigate the response of geomagnetic activity indices to the variation of solar wind, one has to take into account the exact response time of the magnetosphere to the solar wind variation. Before comparing the two quantities, we first allowed one hour-long propagation time of the solar wind from the ACE satellite located in the L1 point to the magnetopause. Many researches have attempted to determine the response time by estimating the cross-correlation between the interplanetary parameters and the activity indices. According to Kamide (1988), the peak correlation coefficient between the eastward electrojet and the solar wind parameters is about 0.7 when allowing about 30 minutes of lag time, while the peak coefficient for the westward electrojet is about 0.85 with lag time of about 65 minutes. On the other hand, Gonzalez & Echer (2005) noted that the magnetosphere/ring current response-time to solar wind forcing is about one to four hours. So we have attempted to employ various lag times in this study, for example zero (no delay), one, two, and even three hours. However, it is noted that the correlation coefficient between those indices and the solar wind parameters does

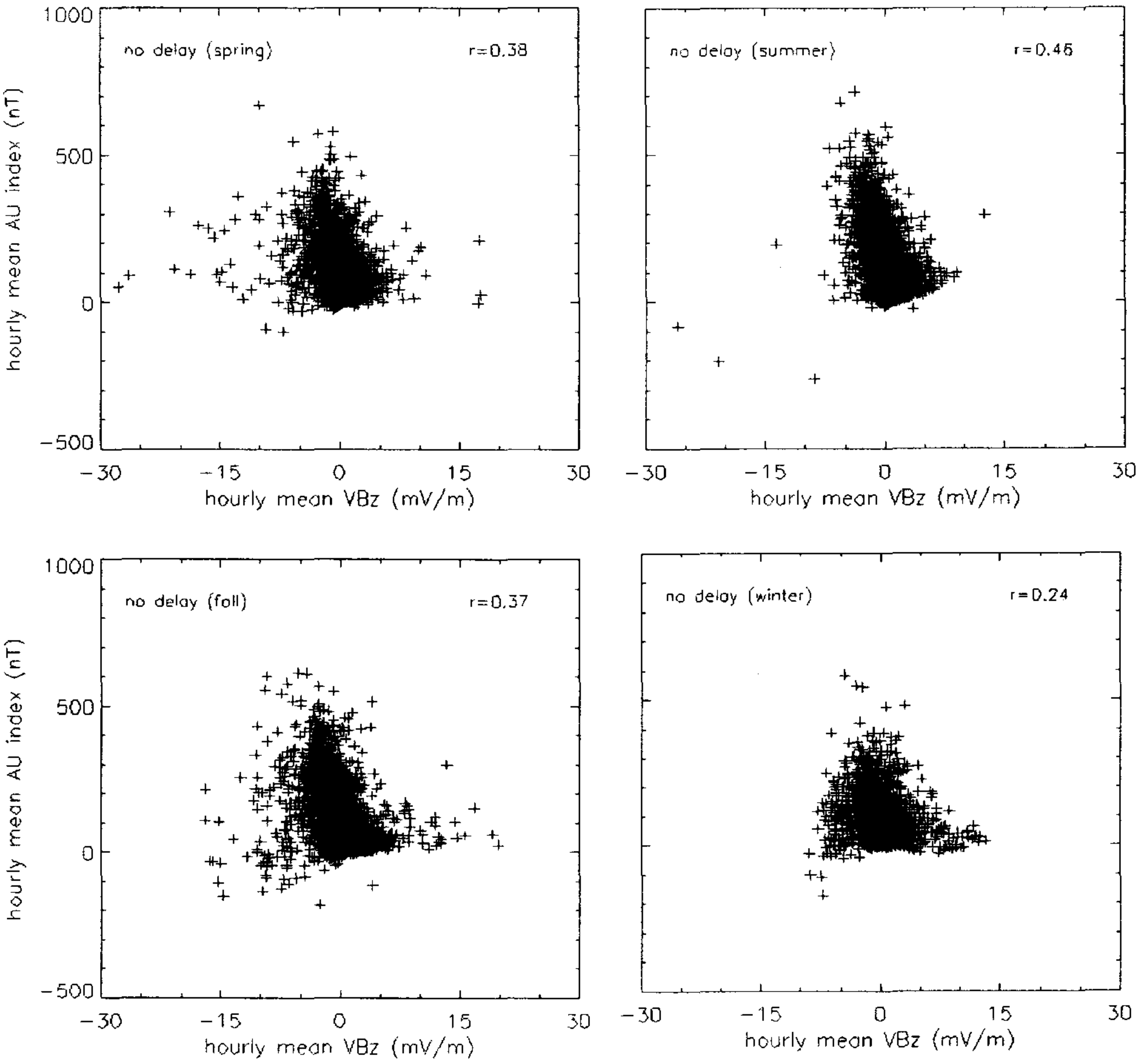

Figure 2. The correlation between the AU and VBz during four seasons. "No delay" means that the response time has not been considered. The number shown in the upper right-hand corner represents the correlation coefficient.

not seem to be very sensitive to the length of lag time. Figure 1 shows an example of the variations of the AU, AL, Dst indices and the solar wind electric field during February 17-18, 1998.

3. The correlation between the AU and VBz

The AU index has been reported to show significant seasonal variation (Allen & Kroehl 1975, Ahn et al. 2000a) largely due to the seasonal change of the ionospheric conductivity distribution over the polar ionosphere. According to Allen & Kroehl (1975), the intensity of the AU index changes systematically, higher during summer than during winter by a factor of two or higher. They attributed the variation to the seasonal change of the ionospheric conductivity over the dusk sector, which is largely associated with the solar EUV radiation. On the other hand, the solar wind-magnetosphere coupling is reported to be more efficient during equinoctial season than others (e.g., Russell & McPherron 1973). Their argument is based on the idea that at the equinox the earth's dipole axis makes the largest possible angle to the ecliptic normal, thus increasing the size of the southward component of the IMF. Therefore, the higher efficiency during equinoctial season is associated with strong negative VBz, namely the solar wind electric field. If the ionospheric conductivity over the dusk sector is significant and more or less uniform due to the solar EUV radiation, while the one associated with auroral precipitation is insignificant, the equinoctial effect would be reflected reasonably well on the AU index. This is the reason why the AU index has been assumed to be a convection index. This study will test this argument. Allowing that the electric field and the ionospheric conductivity particularly of the solar origin show different seasonal variations, the correlation study between the AU and VBz during four seasons would further provide us with a clue about their relative contribution to the intensification of the eastward electrojet.

Figure 2 shows the correlation between the hourly mean AU index (nT) and hourly mean VBz (mV/m) without considering any response time. Although it is not easy to establish any statistically reliable relationship between them, there seems to be a tendency of higher AU for a larger VBz for southward IMF period particularly during summer. It is also interesting to note that the highest AU for a given negative VBz is registered during summer. If the higher efficiency of the solar wind magnetosphere coupling in terms of the electric field enhancement during equinoctial season is the main contributor to the eastward electrojet, the highest correlation would be noted during equinoctial season. On the contrary, it is registered during summer, reflecting that the effect of the ionospheric conductivity enhancement during summer exceeds that of the electric field intensification during equinoctial season. The opposite tendency is clearly noted during winter. When the ionospheric conductivity is low, so is the AU index. Since there is no particular reason to expect weaker magnetospheric convection during winter than summer, one can conclude that the AU index reflects only reasonably well the magnetospheric convection whenever the ionospheric conductivity over the dusk sector is generally high and uniform. In other words, even with a strong magnetospheric convection, it is highly unlikely that the eastward electrojet can be activated during winter when the ionospheric conductivity in the dusk sector is extremely low. Therefore, the AU index can be used as a reliable indicator of the magnetospheric convection only during summer when the solar EUV radiation is strong enough.

4. The correlation between the AL and VBz

According to Allen & Kroehl (1975), the AL index is most often derived from the records of AE stations located around 0315 MLT, where the strongest westward electrojet tends to flow. On the other hand, Ahn et al. (1999) showed that the ionospheric conductivity over the region from the midnight to early morning sector, roughly co-located with the strongest part of the westward electrojet, is controlled largely by auroral particle precipitation. Furthermore, the contribution of the solar EUV radiation to the ionospheric conductivity over the region is minimal. Taking into account these observations, the correlation between the AL and VBz would not show any significant seasonal dependence associated with the ionospheric conductivity. As expected, no apparent seasonal dependence is noted in Figure 3 showing the correlations between the AL and VBz during four seasons. The trends noted between the AL and VBz are quite similar regardless of season with high |AL| during the time of enhanced solar wind electric field, i.e., negative VBz. Although the correlation is not high, 0.56, one can see that the |AL| index tends to increase with the enhancement of negative VBz. It is the same tendency noted between the AU and VBz, particularly during summer. Considering that the auroral electrojet is a combined result of the electric field and ionospheric conductivity

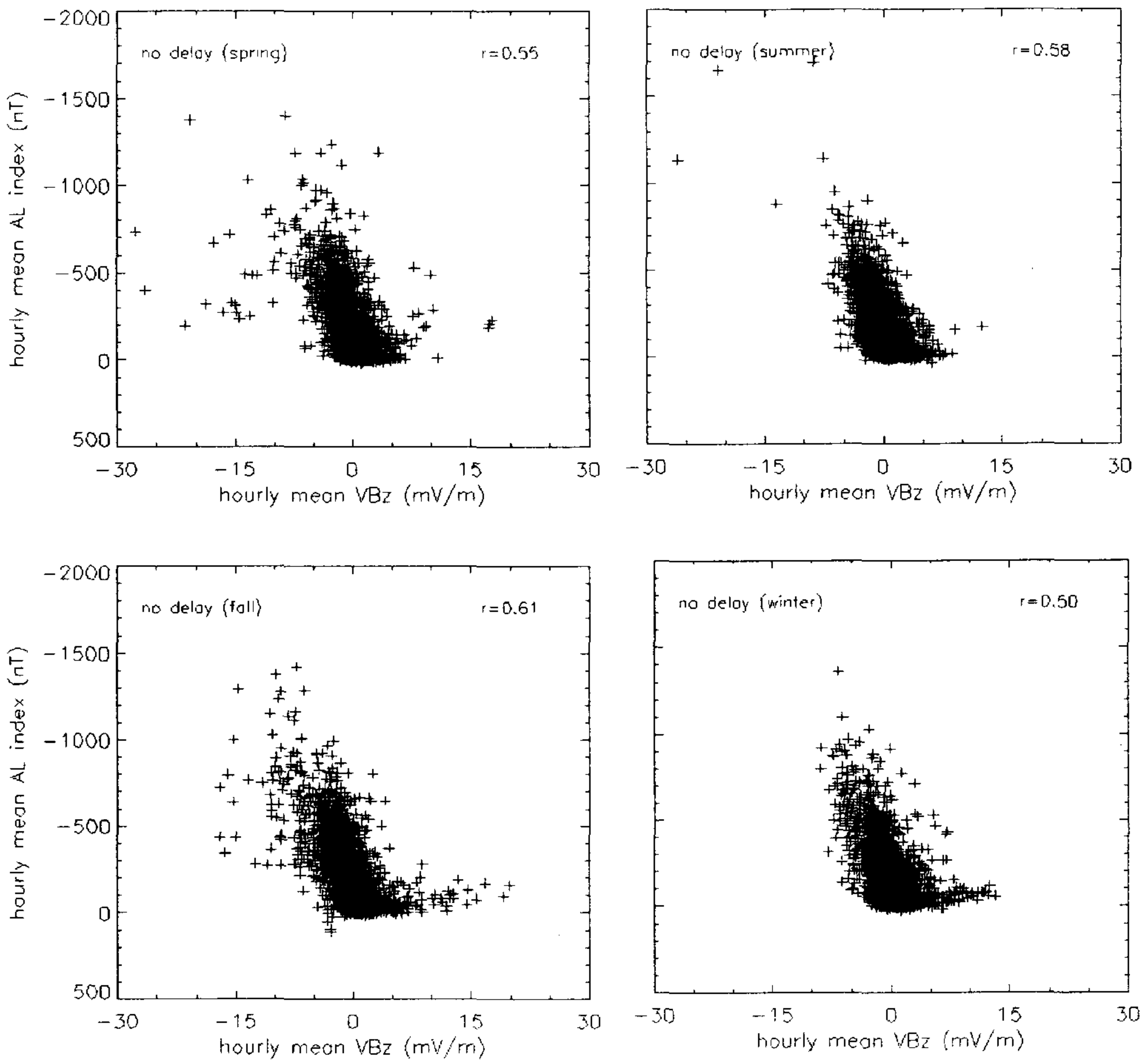

Figure 3. Same as Figure 1 but for the AL and VBz relationship.

enhancement, the intensification of the two quantities seems to occur concurrently with the increase of the solar wind electric field. It is an indication that the AL index is a convection index rather than substorm index as far as the time scale is an hour.

Fig. 3 shows a hint of the equinoctial effect. The events with hourly mean VBz less than -5 mV/m is appreciable only during equinoctial season, suggesting that the Russell & McPherron effect may work during the season. Ahn et al. (2000a) also noted such an effect from the seasonal variations of the AL index. Interestingly, the relationship between the AL and VBz for such extreme events with hourly mean VBz of less than -5 mV/m does not seem to follow the tendency noted during the periods with VBz > -5 mV/m. Note that the AL index registers quite often unrealistically lower level during VBz < -10 mV/m. In other words, the AL does not seem to follow the VBz variation properly, when VBz is less than -5 mV/m. It indicates that the enhanced interplanetary electric field (< -5 mV/m) during equinoctial season seems to be more effective at intensifying the electric field than the ionospheric conductivity associated with auroral precipitation over the auroral oval region, thus occasionally failing in intensifying the westward electrojet. Therefore, one should keep in mind that extreme VBz events during equinoctial season do not necessarily intensify the AL index accordingly, thus making the AL unable to represent the enhanced level of magnetospheric convection properly.

While a significant difference is noted in the relationships between the AU index and VBz during summer and winter, the AL index does not show such a difference. Although the major source of the ionospheric conductivity over the nightside auroral oval is largely associated with auroral particle precipitation, the contribution from the solar EUV radiation over the region even during summer is non-negligible. It suggests that the ionospheric conductivity over the nightside auroral oval during summer is higher or at least not lower than that of winter. Then the AL index should be more intensified during summer than during winter for a given level of VBz. According to Figure 3, however, this is not the case. It indicates that the ionospheric conductivity associated with auroral precipitation during winter is higher than during summer for the same auroral activity. Actually Newell et al. (1996) showed that the occurrence rate of intense discrete auroras is suppressed by sunlight, i.e., discrete auroras are more likely to occur in winter than in summer, thus reducing the ionospheric conductivity associated with auroral precipitation during summer. This is the reason why the AL index during winter seems to be higher or at least not lower than that of summer for a given level of negative VBz.

5. The correlation between the Dst and VBz

Figure 4 shows the correlation between the Dst index and VBz during four seasons. One can see that there is a tendency that Dst index becomes more negative with decreasing VBz. Although the difference is subtle, the correlation coefficients noted in Figure 4 are slightly higher than those in Figures 2 and 3. This suggests that the magnetospheric convection is more effective in activating the ring current than the auroral electrojets. Also apparent is that the ring current is more intensified during equinoctial than solstitial seasons. Note that the events with VBz < -10 mV/m are quite rare during solstitial seasons. It is a clear indication that the Russell and McPherron effect works during equinoctial season.

It should further be noted that there seems to be an upper limit in the Dst index for a given level of VBz. A line is drawn such that most of the data($>$ 99.9%) are included in the upper left part of the correlation plot during spring season. The equation of the line is approximated by Dst (nT) = 15·VBz (mV/m) + 50 during the southward IMF period. The Dst index is, for example, less than or equal to -100 nT when VBz registers -10 mV/m. Such a tendency is also apparent during fall season with the same equation being applicable. When one wants to predict the size of storm with a given level of VBz, it provides us with an idea for the lower limit of the storm size. Figure 4 tells us that such a scheme of predicting the Dst from VBz can be applicable to all seasons. Then a question emerges. What is the other factor(s) that determines the size of the individual storm other than VBz? For example, when VBz registers -5 mV/m, the Dst index varies as widely as 200 nT during fall. In this context, it is worth mentioning the argument that frequent occurrence of substorms is also very important in forming the storm time ring current (Kamide et al. 1998). Thus, one may attribute the wide range of the Dst for a given level of VBz to the frequency of substorm occurrence. Through a simulation study, Fok et al. (2000) concluded that global convection and substorm dipolarization cooperate to inject plasma energy more deeply into the magnetosphere than either one would do individually. Even if that is the case, a question remains unanswered. What is the factor that controls the frequency of substorm occurrence for a given level of VBz? Another possibility is available. Considering the fact that the storm time ring current is an accumulated result of the solar wind electric field (e.g., Echer et al. 2008), the history of interplanetary condition,

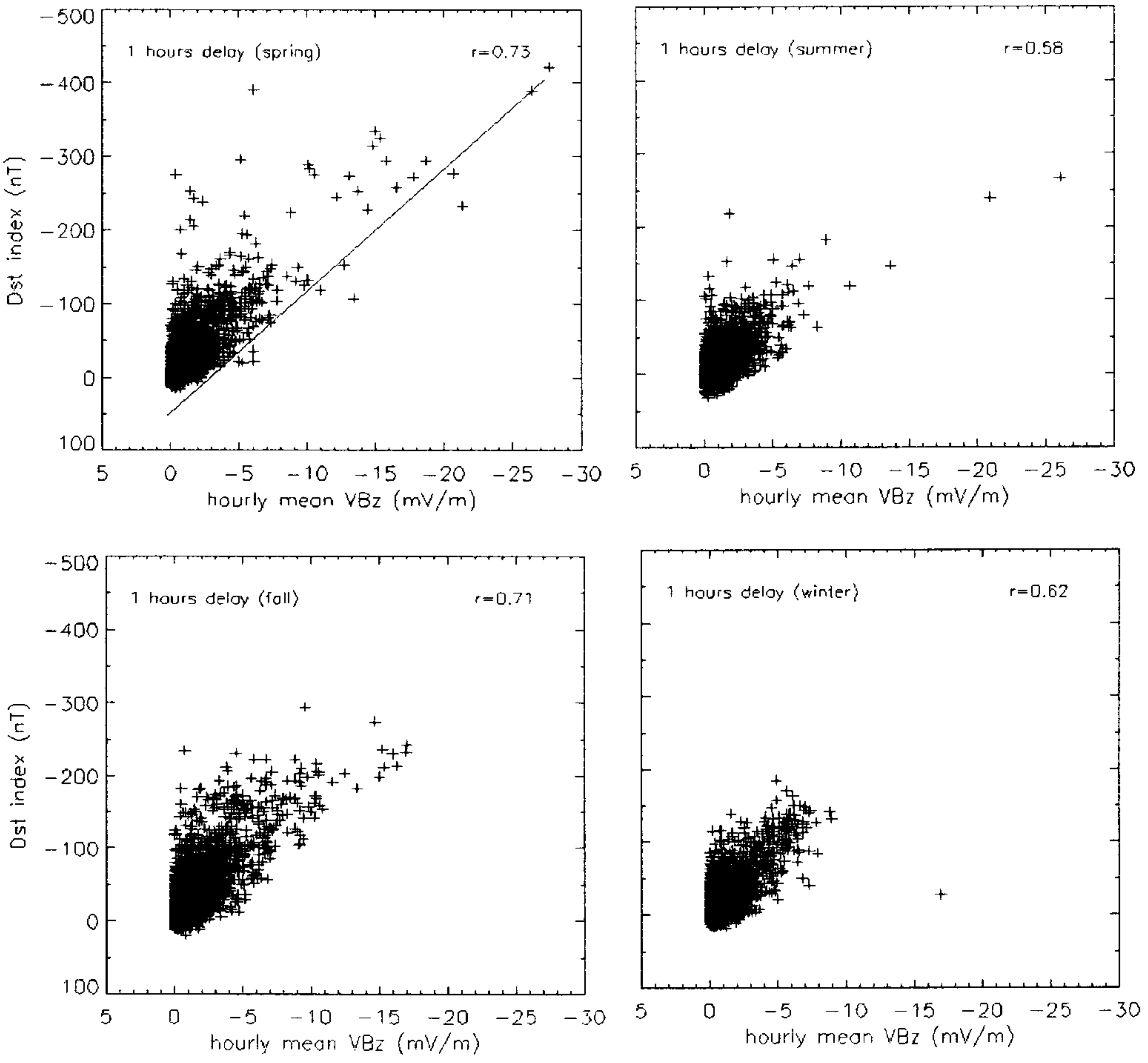

Figure 4. Same as Figure 1 but for the Dst and VBz relationship. The straight line shown in the panel for spring denotes the upper limit of the Dst value for a given level of VBz.

particularly of the duration time of southward IMF period before the time interval considered, would also affect the Dst index, thus possibly resulting in such a scatter shown in Figure 4. Unfortunately, it was not possible to test the idea in this study.

6. Summary

We examined how the geomagnetic activity indices AU, AL and Dst respond to the variations of the solar wind electric field, VBz. For this purpose we utilized hourly mean Quick Look AU and AL indices and Dst index provided by the World Data Center for Geomagnetism at Kyoto University. The solar wind data were measured by ACE satellite located L1 point. By examining the correlation between those indices and VBz, several interesting tendencies have emerged. (1) The AU index shows a noticeable correlation with VBz (southward IMF period) only during summer. Considering that the ionospheric conductivity over the afternoon/early evening sector mainly determined by the solar EUV radiation is appreciable and more or less uniform during summer, it is safe to suggest that the AU index properly reflects the variation of the magnetospheric convection during summer. (2) The correlation between the AU and VBz is insignificant during winter season. This is not because the intensity of the magnetospheric convection diminishes during winter but because the ionospheric conductivity over the afternoon/early evening sector is too low to activate the eastward electrojet. This is why the AU shows the minimum during winter regardless of the enhancement of VBz. Therefore, it is not recommended to use the AU index as a reliable convection index except during summer. (3) Judging from the fact that the AL variation with respect to VBz shows the similar tendency of the AU during summer, the AL index is considered as more like a convection index rather than a substorm index as far as hourly time scale is concerned. (4) Since the electric field and particularly the ionospheric conductivity associated with auroral precipitation drive the westward electrojet, the proportionality noted between AL and VBz suggests that the intensification of the auroral precipitation seems to occur concurrently with the enhancement of the electric field as far as hourly time scale is concerned. (5) Contrary to common belief, the smaller $|AL|$ during summer than winter could be explained by the fact that discrete auroras are suppressed in sunlit hemisphere (Newell et al. 1996), thus reducing the ionospheric conductivity. (6) There seems to be an upper limit to the Dst index for a given level of VBz during southward IMF described by the relationship Dst (nT) = $15 \cdot VBz + 50$, indicating that the magnetspheric convection plays a major role in determining the minimum size of a magnetic storm. (7) The significant scatter of the Dst index during a given level of VBz suggests that there is another factor(s) contributing to the intensification of magnetic storms other than the magnetospheric convection, possibly substorms, as well as the accumulated result of the solar wind electric field.

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