Auroral electrojet *AL* index and polar magnetic disturbances in two hemispheres

Sonya Lyatskaya,[1] W. Lyatsky,[2] and G. V. Khazanov[2]

Received 22 January 2009; revised 18 March 2009; accepted 24 April 2009; published 18 June 2009.

[1] Earlier we found that the auroral electrojet *AL* index, indicating substorm activity in the northern hemisphere, in local summer months correlates much better with geomagnetic activity not in the nearby polar cap but in the opposite polar cap; we explained this effect as a result of interhemispheric field-aligned currents, which suppress substorm field-aligned currents in the summer hemisphere but increase these currents in the winter hemisphere. In the present paper, we took into account this effect and examined a method for reliably monitoring the substorm auroral electrojet, measured with the auroral electrojet *AL* index, by using hourly averages of geomagnetic field from two polar observatories (Thule and Vostok) in two hemispheres. We tested this method for 3 years. The correlation between the predicted and actual *AL* indices for these years was stable and very high, and it showed no significant dependence on season and a relatively weak UT variation. The correlation coefficient between the predicted and actual *AL* indices for these three years was about 0.89. The proposed method, based on using magnetic field data from two polar geomagnetic observatories in two hemispheres, not only significantly improves the reliability of monitoring the westward auroral electrojet in the northern hemisphere but it may also be used for monitoring the westward auroral electrojet in the southern hemisphere where no *AL* index is available because a significant portion of the southern auroral zone is located over the oceans. The results of this paper show that measurements of geomagnetic field in two hemispheres are of high importance for reliably monitoring the geomagnetic activity and related events in each hemisphere.

Citation: Lyatskaya, S., W. Lyatsky, and G. V. Khazanov (2009), Auroral electrojet *AL* index and polar magnetic disturbances in two hemispheres, *J. Geophys. Res.*, *114*, A06212, doi:10.1029/2009JA014100.

1. Introduction

[2] The westward auroral electrojet is an important feature of magnetospheric substorms [e.g., *Akasofu*, 1977; *Kamide and Kokubun*, 1996] which play a vital role in global geomagnetic activity and related events in the magnetosphere and ionosphere. The westward auroral electrojet is measured with the *AL* index, which is derived from twelve or more geomagnetic observatories, spread along the northern auroral zone. The maximal negative magnitudes of the magnetic field meridional component at these observatories are used for deriving the *AL* index [e.g., *Mayaud*, 1980].

[3] Because the geomagnetic stations responsible for derivation of the auroral electrojet indices in many cases are located in remote territories, quick processing the data from these stations in many cases is impossible, and *AL* indices are not available in real time. The situation is even more complicated in the southern hemisphere, where there is no possibility to derive the traditional auroral electrojet indices because most of the southern auroral zone is located over oceans. Attempts to develop a geomagnetic activity index similarly to the *AL* index for the southern hemisphere by using measurements of the magnetic field from Antarctic polar cap stations [*Ballatore et al.*, 1998] were not successful enough because most of Antarctic observatories are located well poleward of the southern auroral zone.

[4] *Lyatsky et al.* [2006] proposed another method for monitoring the westward auroral electrojet on the basis of the analysis of magnetic field variations from polar cap stations and accounting for the effect of both ionospheric and remote substorm field-aligned currents. Later, *Lyatsky and Khazanov* [2008] developed a new, polar magnetic *PM* index, computed from magnetic field variations at near-pole geomagnetic observatories and showing a good correlation with *AL* index (the average correlation coefficient for the years 1995–2004 was ~0.85). A relatively good correlation between *AL* index and the polar cap *PC* index was reported earlier by *Vennerstrøm et al.* [1991] (the correlation coefficient for the years 1978–1984 was ~0.8–0.85 in winter and ~0.75–0.8 in summer) and by *Vassiliadis et al.* [1996] (the correlation coefficient in winter months of 1978–1979 was ~0.8).

[1]Department of Physics, Alabama A&M University, Normal, Alabama, USA.
[2]NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

Copyright 2009 by the American Geophysical Union.
0148-0227/09/2009JA014100

[5] In our previous paper [*Lyatskaya et al.*, 2008], we found an unexpected and interesting result: Substorm activity, which is measured with the auroral electrojet *AL* index, in summer months correlates much better with geomagnetic activity not in the nearby polar cap but in the opposite polar cap. We suggested that this phenomenon may be caused by the interhemispheric field-aligned currents, flowing from the sunlit high-latitude ionosphere and closing through the ionosphere in the opposite auroral zone. These interhemispheric currents are directed oppositely to the substorm field-aligned currents in summer hemisphere but along the substorm field-aligned currents in winter hemisphere. As a result, the interhemispheric currents reduce the total field-aligned currents and their contribution to magnetic disturbances in summer hemisphere but increase the total currents and magnetic disturbances in winter hemisphere. The interhemispheric field-aligned currents may be responsible for the asymmetry, observed in the patterns of the ionospheric convection and currents in two hemispheres [*Fujii et al.*, 1981; *Benkevich et al.*, 2000; *Liou et al.*, 2001; *Papitashvili et al.*, 2002; *Christiansen et al.*, 2002; *Østgaard et al.*, 2005; *Ohtani et al.*, 2005a, 2005b; *Ridley*, 2007], and they may significantly contribute to the well-known seasonal and UT variation of geomagnetic activity [e.g., *Cliver et al.*, 2000; *Lyatsky et al.*, 2001].

[6] The purpose of this paper is to examine an interesting opportunity to monitor the substorm auroral electrojet by using the magnetic field data from two polar magnetic observatories in two hemispheres. We will show that this method improves significantly the reliability of monitoring the westward auroral electrojet, as measured with *AL* index, and it may be applied to monitoring the westward auroral electrojet in both northern and southern hemispheres.

2. Data and Method

[7] For the analysis, we used hourly averages of geomagnetic field from two near-pole geomagnetic observatories Thule (Greenland) and Vostok (Antarctica) for three years: 1995, 1997, and 1998, when the data from both observatories were available. The data are available from the World Data Centers in Kyoto, Japan, and Copenhagen, Denmark, at http://swdcwww.kugi.kyoto-u.ac.jp and http://web.dmi.dk, respectively. We also used the auroral electrojet *AL* index obtained from the web site of the World Data Center in Kyoto, Japan. The data from Vostok station and *AL* index for the year 1996 are not available.

[8] Using the geomagnetic field data from Thule and Vostok observatories, we computed the polar magnetic *PM* indices in the northern and southern hemispheres. We will call these indices the *PMn* and *PMs* indices, respectively. The method of computing the *PM* index and the results of the comparison between *PM* index and other indices are described in details in [*Lyatsky and Khazanov*, 2008]. The main difference between *PC* and *PM* indices is that *PC* index measures the magnetic effect from transpolar equivalent ionospheric currents, flowing along their average (predominant) direction while the *PM* index is accounting for the magnetic effect of these currents even when they are significantly deflected from their average direction. As a result, *PM* index shows significantly better correlation with both solar wind coupling function, geomagnetic disturbances (including the westward auroral electrojet), and key ionospheric parameters such as the cross-polar-cap potential drop and hemispheric Joule heating, than *PC* index does [*Lyatsky and Khazanov*, 2008]).

[9] Thus *PM* index shows the geomagnetic field in the polar cap from both overhead ionospheric currents and remote field-aligned currents, including the Region 1 currents (related to the generation of the *DP-2* current system), substorm current wedge, and other currents, responsible for geomagnetic activity in the auroral zone and at middle latitudes. Accounting for the magnetic effect of the Region 1 currents is, however, not necessary to reduce the correlation between *PM* index and *AL* index, because both Region 1 currents and substorms show a good correlation with coupling function which is thought to be responsible primarily for the Region 1 currents [e.g., *Lyatsky et al.*, 2006; *Lyatsky and Khazanov*, 2008]. We also note that *PM* index is always positive and measured in nT that corresponds approximately to magnetic disturbances in the polar cap, while *PC* index may be both positive and negative, and is measured in relative units.

[10] Then, taking into account that *AL* index in the northern hemisphere correlates better with either northern *PMn* index or southern *PMs* index dependently on season, for improving the monitoring of *AL* index we introduced a combined index, accounting for *PMn* and *PMs* indices in two hemispheres. We derived this combined index for year 1995 and tested how it is working for two other (1997 and 1998) years.

3. Main Results

[11] For the analysis, we used the cross-correlation between hourly values of *AL* index and two, *PMn* and *PMs* indices related to the northern and southern hemispheres, respectively. Figure 1 demonstrates the correlation between northern (*PMn*) and southern (*PMs*) indices for winter (November, December, and January) and summer (May, June, and July) months in the northern hemisphere, as well as for the six "equinoctial" (February–April and August–October) months for two years, 1997–1998. This and the next figures show the squared correlation coefficients between *PMn* and *PMs* indices, which are more appropriate in the case of high correlation than the linear correlation coefficients. Figure 1 shows that the correlation between *PMn* and *PMs* indices is maximal for equinoctial months (the squared correlation coefficient $R^2 \approx 0.83$ as compared with the linear correlation coefficient $\sim$0.91) while for winter and summer months the correlation is somewhat lower ($R^2 \approx 0.79$). The high correlation between *PMn* and *PMs* indices shows a tight link between currents and magnetic disturbances in two hemispheres even at very high latitudes.

[12] Figure 2 shows the correlation of the *PMn* and *PMs* polar magnetic indices with *AL* index (showing substorm activity in the northern hemisphere) for winter (January, November, and December) and summer (May, June, and July) months of 1997–1998. The top two panels show the correlation between *AL* and *PMn* indices while the bottom two show the correlation between *AL* and *PMs* indices. Figure 2 shows a high correlation ($R^2 \approx 0.78$–0.79) of *AL* index with *PMn* and *PMs* indices for local winter (northern

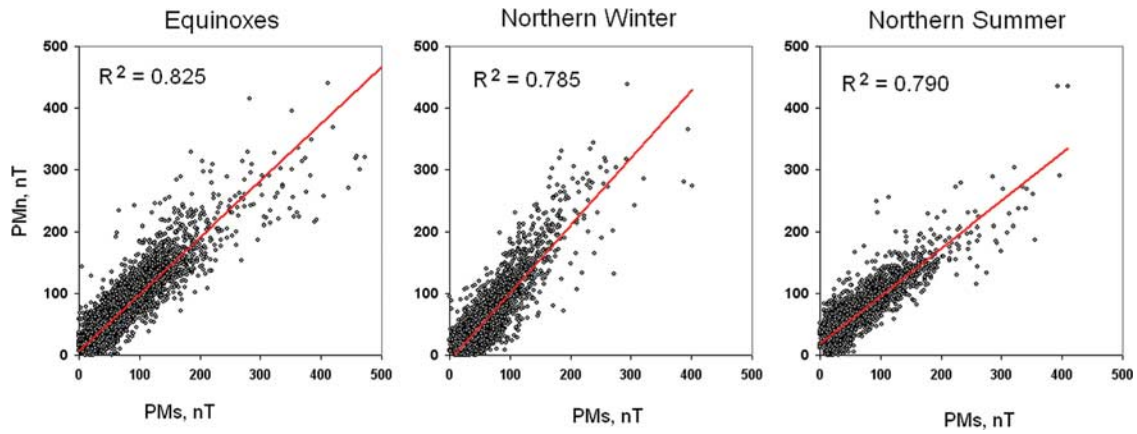

Figure 1. Correlation between *PMn* and *PMs* polar magnetic indices in two hemispheres for equinoxes, winter and summer months for 2 years, 1997–1998. The squared correlation coefficients, R^2, are shown.

winter for *PMn* index and northern summer for *PMs* index) but a significantly weaker correlation ($R^2 \approx 0.64$–0.67) for local summer. These results are consistent with those obtained by *Lyatskaya and Khazanov* [2008].

[13] The high correlation of *AL* index with *PMn* index in northern winter and *PMs* index in northern summer opens an attractive opportunity for the trustworthy evaluation of the magnitude of *AL* index from two polar magnetic indices in two hemispheres. For this purpose, we introduced a

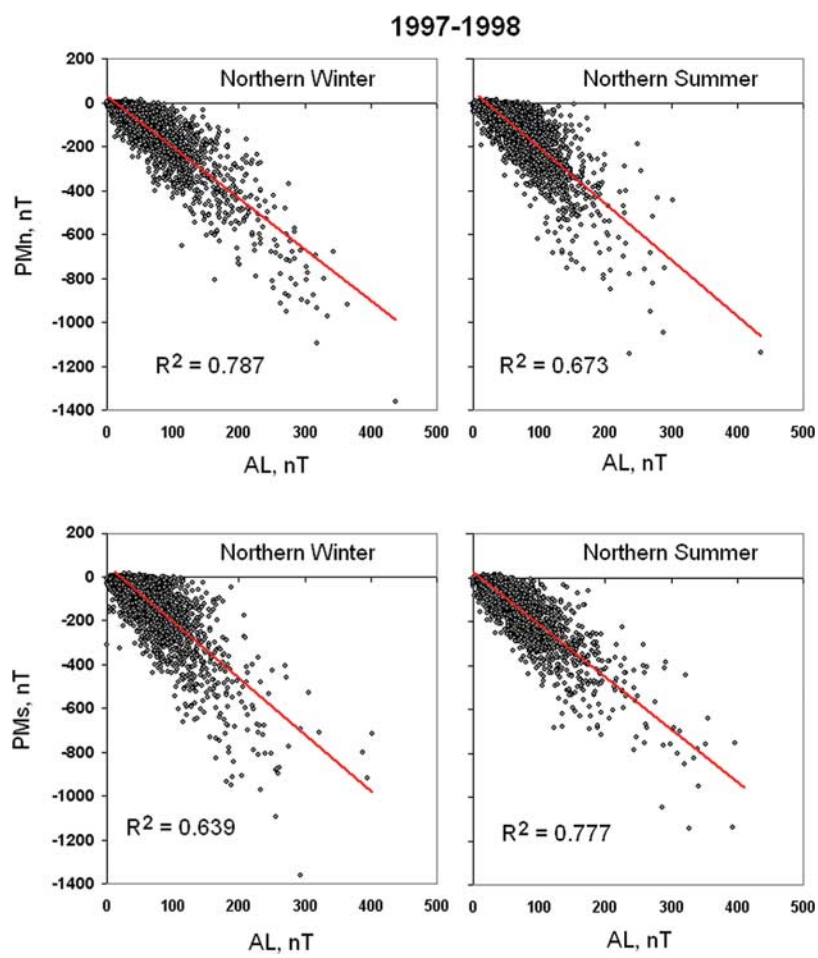

Figure 2. Correlation between the *AL* index and two *PMn* and *PMs* polar magnetic indices during the northern winter (January, November, and December) and summer (May, June, and July) months for 2 years, 1997–1998.

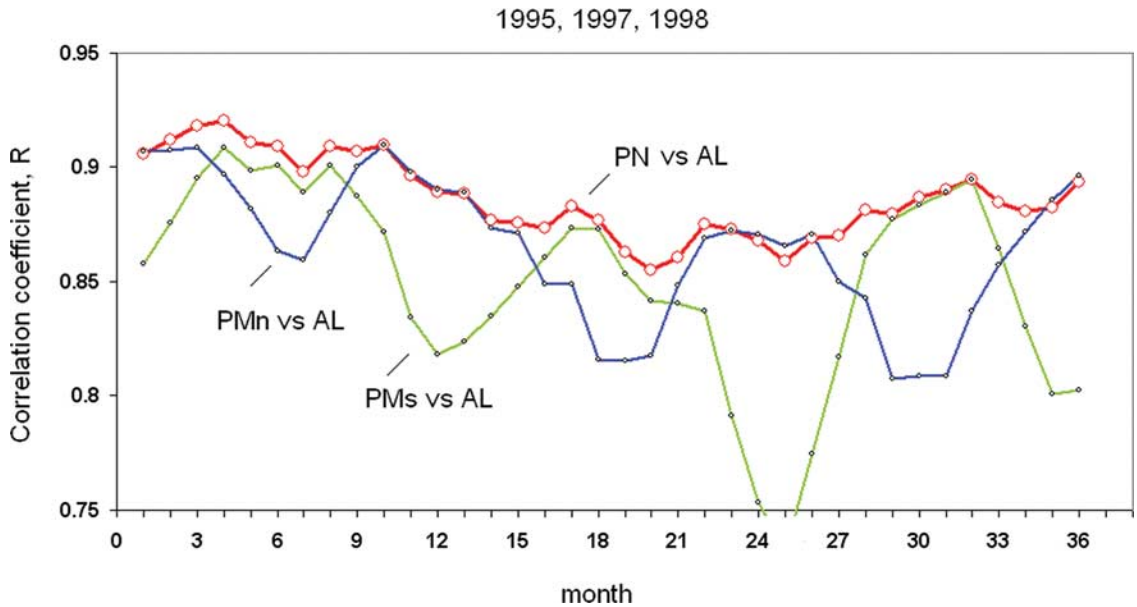

Figure 3. The linear correlation coefficients, *R*, between the auroral electrojet *AL* index and three indices (northern *PMn*, southern *PMs*, and combined *PN* indices, shown in red, blue, and green, respectively) for 3 years (1995, 1997, and 1998). To smooth the curves, the 3-month running averages of the linear correlation coefficients are shown. The month number is shown along the horizontal axis; the first 12 months are related to year 1995, the following months are related to years 1997–1998. Each point in Figure 3 is computed from about 2000 (or 4000 for the combined *PN* index) of hourly mean values.

combined index, including both *PMn* and *PMs* indices, which show geomagnetic activity in the polar caps in two hemispheres. To provide reliable monitoring of the *AL* index in northern hemisphere, this combined index (we will call it the *PN* index) should be proportional to the northern *PMn* index during the northern winter and the southern *PMs* index during the southern winter, and have the intermediate values for other seasons. Such *PN* index, allowing a trustworthy evaluation of *AL* index in the northern hemisphere, may be derived from the following expression.

$$PN = \frac{1}{2}\left\{PMn\left[1 + k\cos\left(\frac{2\pi(\mathrm{D}+\mathrm{d})}{365}\right)\right]^{\mu} + PMs\left[1 - k\cos\left(\frac{2\pi(\mathrm{D}+\mathrm{d})}{365}\right)\right]^{\mu}\right\} \quad (1)$$

where k is a factor, D is a day of year, d is a "reference" day, and μ is a constant. For winter conditions equation (1) is primarily accounting for *PMn* index, for summer conditions for *PMs* index, and for equinoctial months for the averages of these indices. Because the dependence of the *PN* index on *PMn* and *PMs* indices in equation (1) may be more complicated than just to be proportional to $[1 \pm \cos(2\pi D/365)]$, we introduced the values d, k, and power μ. These values were found to provide the best correlation between the *PN* and *AL* indices, namely $k = 0.8$, $d = 4$, and $\mu = 0.75$. For validation of this formula, we derived these values for year 1995 and then used this formula for two other years, 1997–1998.

[14] By analogy with equation (1), we may also introduce a similar index (*PS* index) for evaluation of the auroral electrojet *AL* index in the southern hemisphere.

$$PS = \frac{1}{2}\left\{PMn\left[1 - k\cos\left(\frac{2\pi(D+d)}{365}\right)\right]^{\mu} + PMs\left[1 + k\cos\left(\frac{2\pi(D+d)}{365}\right)\right]^{\mu}\right\} \quad (2)$$

[15] We note that the signs before the coefficient k in this formula are opposite to those in equation (1), and the magnitudes of the parameters k, d, and μ in this formula may be different from those in equation (1). Unfortunately, at present we cannot determine these parameters as there is no reliable *AL* index (deduced from the experimental data) for the southern hemisphere. Therefore in this paper we will restrict ourselves with the consideration of the *PN* index for the northern hemisphere only.

[16] Figure 3 shows the linear correlation coefficients, *R*, between *AL* index and the three other indices: the northern *PMn*, southern *PMs*, and *PN* index, given by equation (1). As mentioned earlier, the year 1996 was not included because both data from Vostok observatory and *AL* index are not available for this year.

[17] Figure 3 shows the significant seasonal variations in the correlation of *AL* index with *PMn* and *PMs* indices, seen as the strong drops in the correlation coefficients in local summer months, centered approximately at 6th, 18th, and 30th months for *PMn* index and at 12th, 24th, and 36th months for *PMs* index. The red curve in Figure 3 shows the

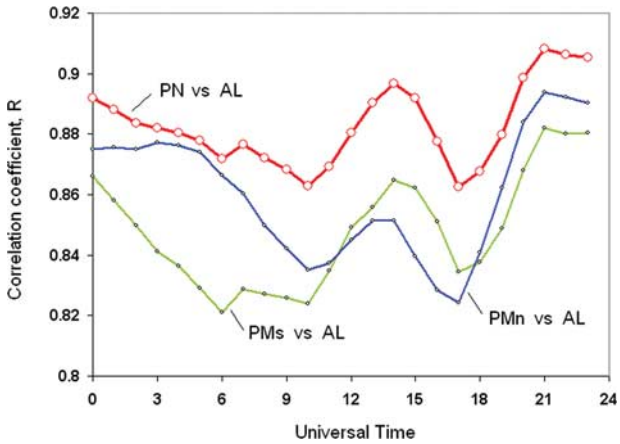

Figure 4. The linear correlation coefficients, *R*, between the auroral electrojet *AL* index and three indices (northern *PMn*, southern *PMs*, and combined *PN* indices, shown in red, blue, and green, respectively) as a function of UT, computed for data united for 3 years (1995, 1997, and 1998). Shown are the running 3-hr averages of the correlation coefficients. Each point in the Figure 4 is computed from about 8760 (or 17,520 for the combined *PN* index) of hourly mean values.

correlation between *AL* index and the *PN* index, which is the combination of the polar magnetic indices from two hemispheres.

[18] One can see that the correlation of *AL* index with *PN* index in Figure 3 is significantly improved, and the correlation coefficient, *R*, for *AL* versus *PN* varies in the range from 0.86 up to 0.92. This shows that *PN* index, derived from geomagnetic disturbances in two polar caps, may be used as a good proxy to *AL* index, and that accounting for geomagnetic variations in two polar caps provides a significantly better evaluation of *AL* index than the polar magnetic indices, computed from magnetic field data from one hemisphere only.

[19] Figure 4 shows the correlation coefficients, *R*, between *AL* index and the same three (*PMn*, *PMs*, and combine *PN*) indices as a function of the Universal Time for the same three years 1995, 1997, and 1998. One can see that the correlation between *AL* and *PN* indices is not only significantly higher than that between *AL* and *PMn*/*PMs* indices but it also shows a weaker UT dependence. The average correlation coefficient for *AL* versus *PN* index in Figure 4 is ~0.89.

4. Discussion and Conclusion

[20] In our previous work [*Lyatskaya et al.*, 2008], we found that substorm activity in the northern hemisphere as measured with *AL* index shows an unexpected dependence on magnetic disturbances in two polar caps. For the northern winter, the *AL* index correlates better with geomagnetic activity in the northern polar cap; however, for northern summer the result is opposite: the *AL* index correlates much better with geomagnetic activity in the opposite, southern polar cap.

[21] This finding opens an interesting opportunity to monitor the *AL* index from two polar magnetic *PM* indices, computed in two hemispheres. For this purpose, we computed a combined *PN* index, derived from two polar magnetic indices in two hemispheres. In northern winter, this *PN* index is accounting primarily for the northern polar magnetic *PMn* index while in northern summer for the southern polar magnetic *PMs* index. We tested the correlation between *PN* and *AL* indices for three years when polar magnetic indices in two hemispheres were available, and we found that method, including the data of magnetic field measurements in two hemispheres, indeed allows us to improve significantly the reliability of monitoring the *AL* index.

[22] The results of the present paper may be summarized as the follows.

[23] 1. This paper is a continuation of our previous paper [*Lyatskaya et al.*, 2008], where we showed that the auroral electrojet *AL* index, measuring substorm activity, in summer months correlates better with geomagnetic activity not in the nearby polar cap but in the opposite polar cap. By using this finding, in this paper we proposed a simple method, which significantly improves the reliability of monitoring the auroral electrojet *AL* index from geomagnetic disturbances in polar regions in two hemispheres.

[24] 2. We tested this method by using the data for three years (1995, 1997, and 1998). We found that using the polar magnetic disturbances in two hemispheres improves significantly the reliability of deriving the *AL* index from geomagnetic data, obtained from polar geomagnetic observatories. The linear correlation coefficient between the predicted and actual *AL* indices for these three years was about 0.89.

[25] 3. The correlation between the predicted and actual *AL* indices during these three years showed the high stability in time, no significant dependence on season, and a relatively weak UT variation. The correlation coefficient was very high for any 3-month interval during these three years, varying from 0.86 up to 0.92.

[26] 4. The results show that accounting for magnetic disturbances in two hemispheres may significantly improve the monitoring reliability of the westward auroral electrojet *AL* index.

[27] **Acknowledgments.** We gratefully acknowledge efforts of the staff of the World Data Center for Geomagnetism in Kyoto, Japan, and World Data Center for Geomagnetism in Copenhagen, Denmark, in providing geomagnetic data from high-latitude geomagnetic observatories. This research was performed while Wladislaw Lyatsky held a NASA Senior Postdoctoral Program appointment at NASA/MSFC. Funding in support of this study was provided partially by the NASA HQ POLAR Project and the NASA LWS Program.

[28] Wolfgang Baumjohann thanks Patrick Newell and another reviewer for their assistance in evaluating this paper.

References

Akasofu, S.-I. (1977), *Physics of Magnetospheric Substorms*, Springer, New York.

Ballatore, P., C. G. Maclennan, M. J. Engebretson, M. Candidi, J. Bitterly, C.-I. Meng, and G. Burns (1998), A new southern high-latitude index, *Ann. Geophys.*, *16*, 1589–1598.

Benkevich, L., W. Lyatsky, and L. L. Cogger (2000), Field-aligned currents between conjugate hemispheres, *J. Geophys. Res.*, *105*(A12), 27,727–27,737.

Christiansen, F., V. O. Papitashvili, and T. Neubert (2002), Seasonal variations of high-latitude field-aligned currents inferred from Ørsted and Magsat observations, *J. Geophys. Res.*, *107*(A2), 1029, doi:10.1029/2001JA900104.

Cliver, E. W., Y. Kamide, and A. G. Ling (2000), Mountains versus valleys: Semiannual variation of geomagnetic activity, *J. Geophys. Res.*, *105*(A2), 2413–2424.

Fujii, R., T. Iijima, T. Potemra, and M. Sugiura (1981), Seasonal dependence of large-scale Birkeland currents, *Geophys. Res. Lett.*, *8*(10), 1103–1106.

Kamide, Y., and S. Kokubun (1996), Two-component auroral electrojet: Importance for substorm studies, *J. Geophys. Res.*, *101*(A6), 13,027–13,046.

Liou, K., P. T. Newell, and C.-I. Meng (2001), Seasonal effects on auroral particle acceleration and precipitation, *J. Geophys. Res.*, *106*(A4), 5531–5542.

Lyatskaya, S., W. Lyatsky, and G. V. Khazanov (2008), Relationship between substorm activity and magnetic disturbances in two polar caps, *Geophys. Res. Lett.*, *35*, L20104, doi:10.1029/2008GL035187.

Lyatsky, W., and G. V. Khazanov (2008), A new polar magnetic index of geomagnetic activity, *Space Weather*, *6*, S06002, doi:10.1029/2007SW000382.

Lyatsky, W., P. T. Newell, and A. M. Hamza (2001), Solar illumination as cause of the equinoctial preference for geomagnetic activity, *Geophys. Res. Lett.*, *28*(12), 2353–2356.

Lyatsky, W., A. Tan, and S. Lyatskaya (2006), Monitoring the auroral electrojet from polar cap stations, *J. Geophys. Res.*, *111*, A07202, doi:10.1029/2004JA010989.

Mayaud, P. N. (1980), *Derivation, Meaning, and Use of Geomagnetic Indices*, *Geophys. Monogr. Ser.*, vol. 22, AGU, Washington, D. C.

Ohtani, S., G. Ueno, and T. Higuchi (2005a), Comparison of large-scale field-aligned currents under sunlit and dark ionospheric conditions, *J. Geophys. Res.*, *110*, A09230, doi:10.1029/2005JA011057.

Ohtani, S., G. Ueno, T. Higuchi, and H. Kawano (2005b), Annual and semiannual variations of the location and intensity of large-scale field-aligned currents, *J. Geophys. Res.*, *110*, A01216, doi:10.1029/2004JA010634.

Østgaard, N., N. A. Tsyganenko, S. B. Mende, H. U. Frey, T. J. Immel, M. Fillingim, L. A. Frank, and J. B. Sigwarth (2005), Observations and model predictions of substorm auroral asymmetries in the conjugate hemispheres, *Geophys. Res. Lett.*, *32*, L05111, doi:10.1029/2004GL022166.

Papitashvili, V. O., F. Christiansen, and T. Neubert (2002), A new model of field-aligned currents derived from high-precision satellite magnetic field data, *Geophys. Res. Lett.*, *29*(14), 1683, doi:10.1029/2001GL014207.

Ridley, A. J. (2007), Effects of seasonal changes in the ionospheric conductances on magnetospheric field-aligned currents, *Geophys. Res. Lett.*, *34*, L05101, doi:10.1029/2006GL028444.

Vassiliadis, D., V. Angelopoulos, D. N. Baker, and A. J. Klimas (1996), The relation between the northern polar cap and auroral electrojet geomagnetic indices in the wintertime, *Geophys. Res. Lett.*, *23*(20), 2781–2784.

Vennerstrøm, S., E. Friis-Christensen, O. A. Troshichev, and V. G. Andersen (1991), Comparison between the polar cap index, PC, and the auroral electrojet indices AE, AL, and AU, *J. Geophys. Res.*, *96*(A1), 101–113.

G. V. Khazanov and W. Lyatsky, NASA Goddard Space Flight Center, 8800 Greenbelt Road, Code 673, Greenbelt, MD 20771, USA.

S. Lyatskaya, Department of Physics, Alabama A&M University, 4900 Meridian Street, Normal, AL 35762, USA. (sonya.lyatskaya@gmail.com)