

## Solar wind time history contribution to the day-of-year variation in geomagnetic activity

R. S. Weigel<sup>1</sup>

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[1] The day-of-year (DOY) variation in the average value of a solar wind driver of geomagnetic activity has been shown to explain only a minority of the observed amplitude of DOY variation in geomagnetic activity. The proxies for solar wind driving used to show this are averages of a solar wind measurement in the same hour or 3-hour interval as the geomagnetic activity measurement. This model of solar wind driving of geomagnetic activity does not account for the observation that the solar wind state in a given time interval can have an effect on activity that lasts many hours. In this work we show a model that includes the solar wind time history predicts a much higher DOY variation in both auroral zone and midlatitude geomagnetic activity. This model is used to estimate the solar wind contribution in two geomagnetic activity measures that exhibit a semiannual DOY variation: the *am* index and postmidnight ground magnetic field measurements in the auroral zone. The estimated solar wind driver contribution to the DOY variation in the *am* index is 75%, which is approximately twice the amount of previous estimates. Solar wind driving is estimated to explain 40–60% of the DOY variation in the magnetic field measured by auroral zone ground magnetometers in the postmidnight sector, where previous estimates were near zero.

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### 1. Introduction

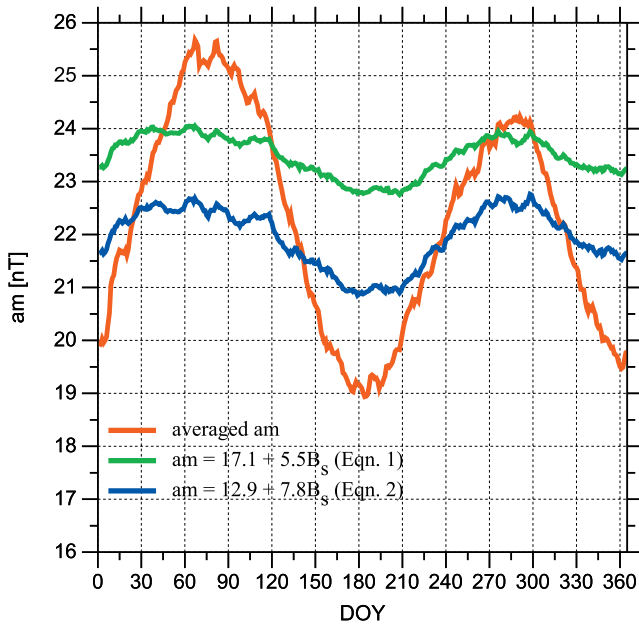
[2] *Boller and Stolov* [1970] noted that any semiannual variation in the solar wind driving process that causes geomagnetic activity would be expected to cause a semiannual variation in geomagnetic activity. They incorrectly noted that the merging process, as observed by *Fairfield and Ness* [1967] and predicted by *Dungey* [1961], would average out to zero over the course of a year. *Russell and McPherron* [1973] noted that the merging contribution would not average to zero because it depends on the rectified southward component of the interplanetary magnetic field (IMF) in the GSM coordinate system, which has a day-of-year (DOY) variation. They then developed a model that predicted a semiannual DOY variation in geomagnetic activity with peaks near those found in the DOY-averaged geomagnetic activity index *C9*. From this model, they concluded that the mechanism producing the semiannual variation in geomagnetic activity was isolated and due to  $B_s$  (the southward component,  $B_z$ , of the IMF) because (1) geomagnetic activity is at least in part caused by  $B_s$  and (2) a consistency of features such as the peak locations in the DOY-averaged geomagnetic index *C9* with that of a modeled  $B_s$ . An initial objection to this conclusion was that

the model did not reproduce the observed universal time (UT) variation in geomagnetic activity [*Mayaud*, 1974].

[3] Later works provided estimates of the  $B_z$  rectification influence by using DOY averages of a linear regression model of the 3-hour cadence *am* index using averaged values of  $B_s$  in the same 3-hour time interval [*Cliver et al.*, 2000]. The linear regression model had 17% of the peak-to-peak DOY variation of that in the actual *am* index. Besides a contribution due to changes in the average effective southward component of the IMF predicted by the *Russell and McPherron* [1973] hypothesis, *Cliver et al.* [2000] tested the importance of the solar wind velocity by using the solar wind driving function  $v^2 B_s$  in the linear regression and found that it predicted a peak-to-peak DOY variation that was 37% of that in the actual *am* index. (A statistical result that demonstrates a DOY variation in  $v$  was presented by *Zieger and Mursula* [1998].)

[4] Even with the addition of the solar wind velocity, the universal time problem noted by *Mayaud* [1974] still exists. *Newell et al.* [2002] showed that if the data were averaged by UT and DOY, the two-dimensional correlation between *am* and  $B_s$  was  $-0.17$  and the correlation between *AL* and  $B_s$  was  $0.03$ . An alternative form of the solar wind driving function yielded correlations of  $0.42$  for *am* and  $-0.05$  for *AL*. Of particular interest is the comparatively low correlation between the *AL* index and the solar wind driver functions and the fact that the *am* correlation increased while the *AL* correlation decreased when an improved solar wind driving function is used.

<sup>1</sup>Department of Computational and Data Sciences, George Mason University, Fairfax, Virginia, USA.



**Figure 1.** Day-of-year (DOY)-averaged  $am$  index data (red line) and averages of two linear regression models that specify  $am$  as a function of  $B_s$  (green and blue lines). The averaged  $am$  curve was generated using only time intervals for which three hourly averaged values of  $B_s$  are also available. The average on a given day of year,  $DOY_0$ , was determined by averaging all measurements with a day-of-year label of  $DOY_0 \pm 30$ . The model curves exhibit the long-standing problem with the *Russell and McPherron* [1973] explanation of the semiannual variation in geomagnetic activity: although the actual and predicted curves have a semiannual variation, the amplitude of the modeled variation far smaller than the actual variation.

[5] In light of the apparent smallness of the amount of DOY variation in geomagnetic activity predicted by the DOY variation in  $B_s$ , even when combined with the DOY solar wind speed variation documented by *Zieger and Mursula* [1998], attempts have been made to explain the variation by other means. *Crooker and Siscoe* [1986] developed a model that showed how a change in merging efficiency may result from a change in the merging line length, which varies with DOY. A semiannual variation in merging line length was reproduced by *Russell et al.* [2003] using a magnetohydrodynamic simulation and was proposed to be the cause of the DOY variation not explained by the combined effect of  $B_s$  and  $v$ . *Newell et al.* [2002] has proposed a mechanism that has a semiannual variation due to an ionospheric solar insulation effect that depends on the total UV conductance in the midnight sector of both auroral zones. The model predicts a higher probability of geomagnetic activity near equinox when the midnight sector auroral zone is in darkness in both hemispheres.

[6] Thus current efforts to explain the semiannual DOY variation in geomagnetic activity that is not explained by DOY changes in the average level of solar wind driving by merging (or, in contemporary terms, dayside magnetopause reconnection, or DMR) invoke changes in either the efficiency of the DMR process or an ionospheric process that

does not require a DOY variation in near-Earth solar wind plasma conditions. In this work we reconsider the statistical methods used to quantify the role of the solar wind in causing a DOY variation in geomagnetic activity. *Cliver et al.* [2000] showed that refining the solar wind driver parameter by including the solar wind velocity can lead a higher amplitude in the predicted DOY average of geomagnetic activity. Here we consider an additional refinement that includes the effect of a time delayed response by developing a model that uses the recent solar wind time history as an input.

## 2. Data

[7] The data used in this work include the hourly averaged solar wind measurements of magnetic field,  $B$ , and bulk ion velocity,  $v$ , in the OMNIWeb data set obtained from the National Space Science Data Center (<http://nssdc.nasa.gov>) in the years 1963–2003. The 3-hour cadence geomagnetic index  $am$  from 1963 to 2003 is based on data from a total of 23 northern and southern ground magnetometer stations [*Mayaud*, 1980] and the indexed data were obtained from the National Geophysical Data Center (<http://ngdc.noaa.gov>). The 1-hour cadence  $AL$  index data in the years 1966–1994 were obtained from the International Service of Geomagnetic Indices (<http://www.cetp.ipl.fr/~isgi>). The 1-hour cadence north–south component of the ground magnetic field in the years 1963–2003 measured at the magnetometer station ABK were obtained from the Danish Meteorological Institute World Data Center (<http://web.dmi.dk/projects/wdcl>). ABK has a geographic latitude and longitude of [68.4, 18.8] and had a geomagnetic latitude and longitude of [65.4, 101.6] in the year 2003 and [65.15, 103.5] in the year 1963 (<http://modelweb.gsfc.nasa.gov/models/cgm/cgm.html>).

## 3. Analysis

### 3.1. The $am$ Index

[8] *Cliver et al.* [2000] determined the relationship

$$am = 17.1 + 5.5B_s, \quad (1)$$

where the unit of  $B_s$  and  $am$  are both nanoteslas, using data from 1963–1997 in 3-hour intervals for which three 1-hour averaged values of  $B_s$  were available and  $B_s$  was in the range 0–4 nT. The measurements fitting these criteria were binned in intervals of 0.25 nT of  $B_s$  and the resulting 16 data points were used to determine the linear regression coefficients in equation (1). This model was then used to estimate the fraction of the peak-to-peak DOY variation in  $am$  that could be attributed to a DOY variation in  $B_s$ .

[9] In Figure 1, the DOY-averaged curve of equation (1) is shown along with the actual DOY-averaged  $am$  index. The peak-to-peak DOY variation in the curve representing equation (1) is 1.0 nT while the peak-to-peak variation in the data is 6.7 nT. The ratio of these two values is 0.15. The slope of 5.5 in equation (1) has been reproduced using the same time interval and method as *Cliver et al.* [2000]. With the addition of data from the years 1998–2002, the slope changes to 5.6 and the peak-to-peak variation is still 1.0 nT.

[10] In Figure 1, the average on a given day-of-year was determined using all measurements with day-of-year labels in a range of  $\pm 30$  days. (When there are no data gaps, this is identical to what is obtained by computing a 30-day moving average and then averaging across all years of data. However, the approach used in this work places equal weight on each value, whereas the moving average method has the potential of placing more weight on days in years that have very little data, which is the case for later analysis, where solar wind data is used and there are many years for which very few solar wind measurements are available.)

[11] Figure 1 also shows the DOY profile of a model derived using a method that differs from that used to determine equation (1). In this case a linear regression model was computed without a restriction on  $B_s$  values and without the use of the binning procedure of *Cliver et al.* [2000]. The result is

$$am = 12.7 + 7.9B_s, \quad (2)$$

where the number of  $am-B_s$  pairs is  $6.1 \cdot 10^4$ . We omit the use of binning because subsequent analysis will include more regression variables, which makes binning impractical as it reduces the number of points available for the regression calculation. The restriction on the amplitude of  $B_s$  will not be used because we are interested in a model that is valid for arbitrary levels of solar wind conditions. Consistent with equation (1), the model derived with this method predicts a peak-to-peak variation that is small (1.9 nT) in comparison to the 6.7 nT variation (ratio = 0.28).

[12] Figure 1 highlights the problem with the hypothesis of *Russell and McPherron* [1973], which states that the semiannual variation in geomagnetic activity is due to a semiannual variation in  $B_s$ . Straightforward linear regression models of the relationship between  $B_s$  and geomagnetic activity predict a much smaller variation than that observed.

[13] As an alternative to the ratio of peak-to-peak values for the comparison of DOY curves, we will also report a prediction efficiency,  $PE$ , which is one minus the ratio of the mean squared difference between the actual and predicted DOY curves to the variance of the actual DOY curve:

$$PE = 1 - \frac{(1/N) \sum_{t=1}^N (am_t^a - am_t^p)^2}{\text{var}(am^a)}, \quad (3)$$

where the sum is taken over the  $N$  time intervals where a prediction is available, the variance (var) is over  $am$  values in the same  $N$  intervals, and the superscripts  $a$  and  $p$  represent actual and predicted, respectively.

[14] If the predicted and actual curves are identical, the prediction efficiency is 1. The prediction efficiency is a measure of the fraction of the variance in the measured curve that can be explained by the model curve. The prediction efficiency is reported in addition to the peak-to-peak values because the predicted and actual DOY curves can be quite different in phase and still have identical peak-to-peak values. The prediction efficiency is a correlation-type measure of fit and has the advantage over the more familiar correlation coefficient in that if the predicted curve is equal to the actual curve, except has a fraction of its amplitude, the correlation is 1, but the prediction efficiency

is less than 1. Thus the prediction efficiency accounts for both the variation amplitude as in the peak-to-peak measure and the phasing of the curves as in the correlation coefficient. The prediction efficiency of the DOY curve of equation (2) is 0.43.

[15] It is important to note that the parameters used to create the curve for the model of equation (2) were determined so that the model provides an optimal (in the linear least squares sense) predictions of the 3-hour values of  $am$ . That is, the parameters were determined from a least squares optimization of an ensemble  $am-B_s$  pairs. The parameters were not determined in such a way as to maximize the prediction efficiency of the model DOY curve or the peak-to-peak ratio.

[16] *Cliver et al.* [2000] also considered a generalization of Equation 1 that used the formula  $v^2 B_s$  instead of  $B_s$  and found that it explained 37% of the DOY variation in  $am$ . Repeating the procedure used to compute equation (2) using  $v^2 B_s$  instead of  $B_s$  gives a peak-to-peak variation (not shown) of 2.9 nT (ratio = 0.43), where the number of points available for the regression is  $5.1 \cdot 10^4$ . This ratio is consistent with the estimate of a 37% influence of the solar wind driving parameter  $v^2 B_s$  determined by *Cliver et al.* [2000].

[17] Generalizing the notation in equation (1) so that  $G_t$  is the geomagnetic activity variable and  $S_t$  is the solar wind driving variable measured in time interval  $t$  gives

$$G_t = h_\Delta + h_0 S_t, \quad (4)$$

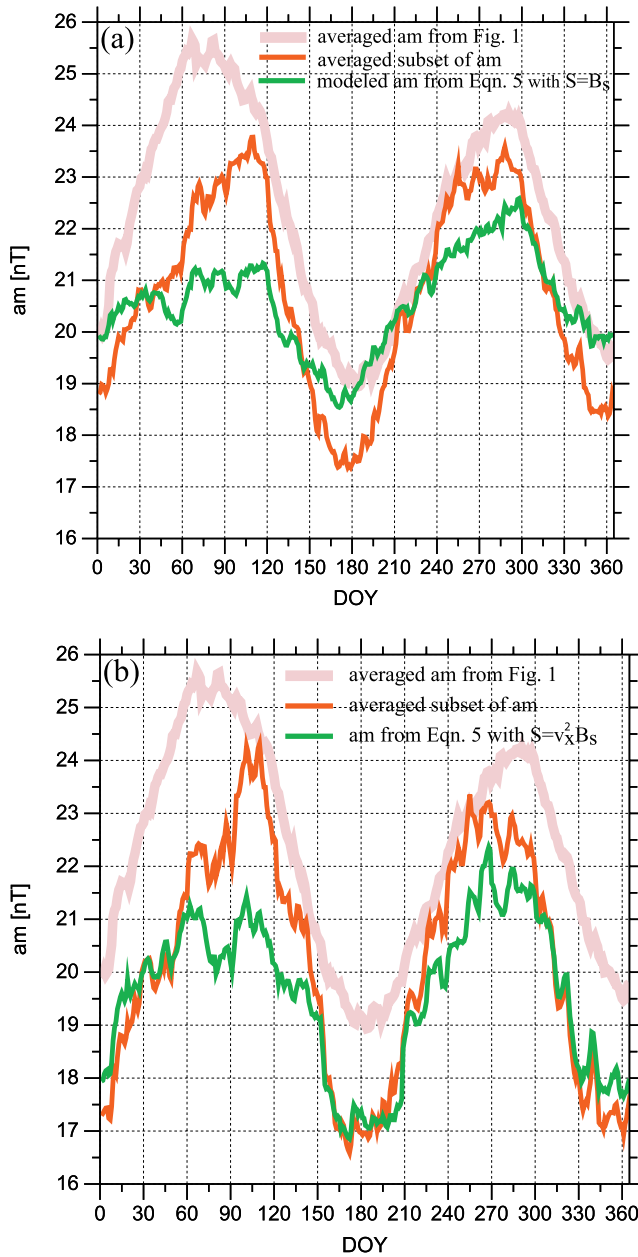
where  $h_\Delta$  and  $h_0$  are parameters that represent an offset and slope, respectively. The next generalization accounts for the fact that a portion of a signal representing magnetospheric activity (which is measured by geomagnetic indices) can be approximated by a dynamical system in the form of a linear set of ordinary differential equations [*Iyemori et al.*, 1979; *Vassiliadis*, 2006]. When discretized, the relationship between the input variable,  $S_t$ , and the output variable,  $G_t$ , at integer time interval  $t$  takes the form

$$G_t = h_\Delta + \sum_{\tau=0}^{\tau_c} h_\tau S_{t-\tau} \quad (5)$$

[*Box and Jenkins*, 1976]. If  $\tau_c = 0$ , this is the linear regression model of equation (4) that specifies the value of  $G_t$  given  $S$  in the same time interval. The form of equation (5) is similar to that of multidimensional linear regression, where the additional variables are measured values of the input variable at different time delays. The parameters  $h_\tau$  are found by solving the overdetermined set of equations that are generated using measurements of the input variable,  $S_t$ , and an output variable,  $G_t$ , at times  $t$ . The number of time intervals of data used to determine the free parameters  $h_\tau$  must be equal to or greater than the length of the filter,  $\tau_c + 1$ . In the data sets considered, the number of time intervals is always at least 50 times greater than  $\tau_c + 1$ .

[18] Figure 2a shows the DOY average of a time history model optimized to predict  $am$  values with  $\tau_c = 24$ . The  $am$  index line is not the same as that in Figure 1 because only  $am$  values for which 24 previous consecutive values of  $B_s$  are available were used. Of the 6.4 nT peak-to-peak





**Figure 2.** (a) DOY-averaged  $am$  index shown in Figure 1, DOY average of  $am$  index intervals that had 24 previous consecutive values of  $B_s$  available, and DOY average of a time history model of  $am$  that uses 24 values of  $S = B_s$  in equation (5). (b) Same as Figure 2a except the time history model of  $am$  uses  $S = v_x^2 B_s$  in equation (5).

variation in this subset of  $am$  data, the time delayed  $B_s$  model has a peak-to-peak variation of 4.0 nT (ratio = 0.64) and the prediction efficiency is 0.63. These results are shown in Table 1. From this we conclude that a model of  $am$  based on time-delayed values of  $B_s$  shows a greater peak-to-peak DOY variation than a model that uses only one  $B_s$  value. In comparison, equation (1) gave 0.15 and equation (2) gave 0.28 for the peak-to-peak ratio.

[19] The process used to select  $\tau_c = 24$  is that it should be long enough to capture the dynamic response of the  $am$

index to a solar wind input, but not too long that it increases the ratio of number of model coefficients to the number of data points to the level where overfitting may be a problem. With an unlimited amount of data, we could set  $\tau_c$  arbitrarily large with the realization that the computation will yield  $h_\tau = 0$  above the value of  $\tau_c$  for which a solar wind impulse has an effect that is not detectable. The trend for all models in this work is that its prediction efficiency and peak-to-peak values increase with increasing  $\tau_c$  up until a point where they appear to saturate. We also find that as the prediction efficiency and peak-to-peak ratio increases, the saturation value for  $\tau_c$  decreases. However, for consistency in comparison, we use the same  $\tau_c$  for all analysis in this paper.

[20] Note that the feature of different subsets of  $am$  index data giving different DOY profiles as found in Figure 2 is robust. We have explored this by performing our averaging procedure to compute DOY profiles using a random subset of half of the available  $am$  index data. The differences in the DOY profiles are consistent with that observed in Figure 2a. Each DOY profile has approximately the same peak-to-peak difference, but the average values tend to differ by  $\pm 1$  nT. This will not have an influence on either the previous or present results. In the case of the present result, we find that both the model and the subset of data exhibit the same offset for the subinterval of study, and we are comparing the model with data from the same subinterval.

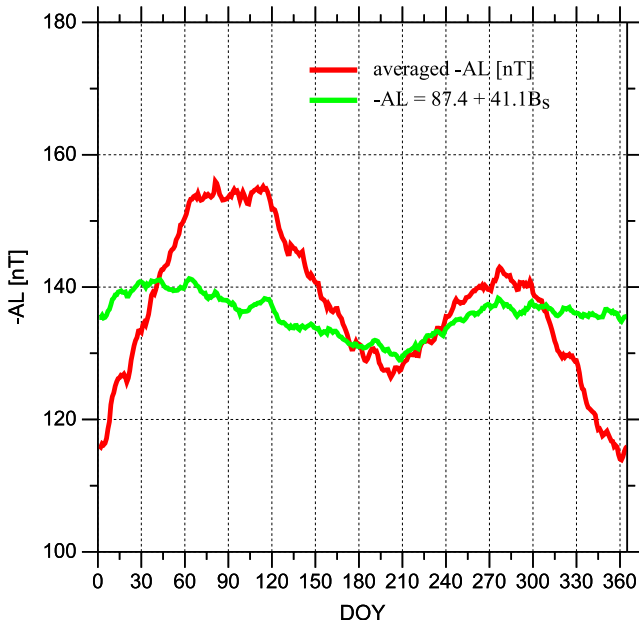
[21] We have also considered a number of other forms for the input variable  $S$ , including  $vB_s \sin(\theta/2)^2$ ,  $vB_s$ ,  $\rho^{1/6} vB_s \sin(\theta/2)^2$  [Gonzalez, 1990]. The simplest model that gives the best predictions of the 3-hour values of  $am$  is  $v_x^2 B_s$ . The DOY curve for this model is shown in Figure 2b. This model also gives the largest peak-to-peak DOY variation of 5.7 nT with respect to the measured  $am$  variation of 7.7 nT (ratio = 0.72) and a prediction efficiency of 0.80. From this we conclude that a model which uses only solar wind measurements as input predicts approximately three-quarters of the observed DOY variation in the  $am$  index.

[22] To determine an uncertainty for the peak-to-peak ratio and the prediction efficiency, we have repeated the calculation used to determine the model coefficients of equation (5) using 50 random samples of half of the  $1.2 \cdot 10^4$   $am - v_x^2 B_s$  pairs. The result is an average peak-to-peak ratio of 0.72 with a standard deviation for the fifty samples of 0.02 and an average prediction efficiency of 0.80 with a standard deviation in the fifty samples of 0.01. The uncertainty calculations have been performed for each reported peak-to-peak and prediction efficiency value; unless listed, they are all less than 0.03.

**Table 1.** Summary of Model Results<sup>a</sup>

$G$	$S$	P-P	PE	P-P <sub>th</sub>	PE <sub>th</sub>
$am$	$B_s$	0.28	0.43	0.64	0.63
$am$	$v_x^2 B_s$	0.41	0.65	0.72	0.80
$-AL$	$B_s$	0.30	0.14	0.35	-0.25
$-AL$	$v_x^2 B_s$	0.27	0.36	0.38	0.34
ABK -X	$B_s$	0.01	0.26	0.23	0.28
ABK -X	$v_x^2 B_s$	0.10	0.36	0.46	0.55

<sup>a</sup>Comparison of prediction efficiency (PE) and peak-to-peak ratio (P-P) between model that uses a time history (indicated with subscript th) of  $S$  and a model that uses only one value of  $S$ .



**Figure 3.** DOY-averaged  $AL$  and a linear regression model of  $AL$  that uses  $B_s$ . The  $AL$  curve was generated using only time intervals for which an hourly value of  $B_s$  is also available. The *Russell and McPherron* [1973] explanation fails in two ways here. First, the modeled and actual peaks differ. Second, the amplitude of the modeled variation is far smaller than the actual variation.

[23] We have also considered alternative methods of solving for the  $h_\tau$  coefficients. *Füllekrug* [1996] has developed a method that accounts for the fact that the noise amplitude in  $h_\tau$  may be nonzero, contrary to what is assumed when using the standard method of solution. We find that this alternative method has no significant impact on the peak-to-peak values or prediction efficiencies.

[24] One of the early objections to the explanation of *Russell and McPherron* [1973] was that although their model predicted peaks in the DOY profile of geomagnetic activity that were near those found in geomagnetic activity indices, their model predicted a universal time variation which was quite different than that observed [*Mayaud*, 1974]. If one allows that the more appropriate model includes a time history, then one should not expect that the geomagnetic index data should have a universal time variation that is the same as that of  $B_s$  because such a model includes  $B_s$  values from many universal times.

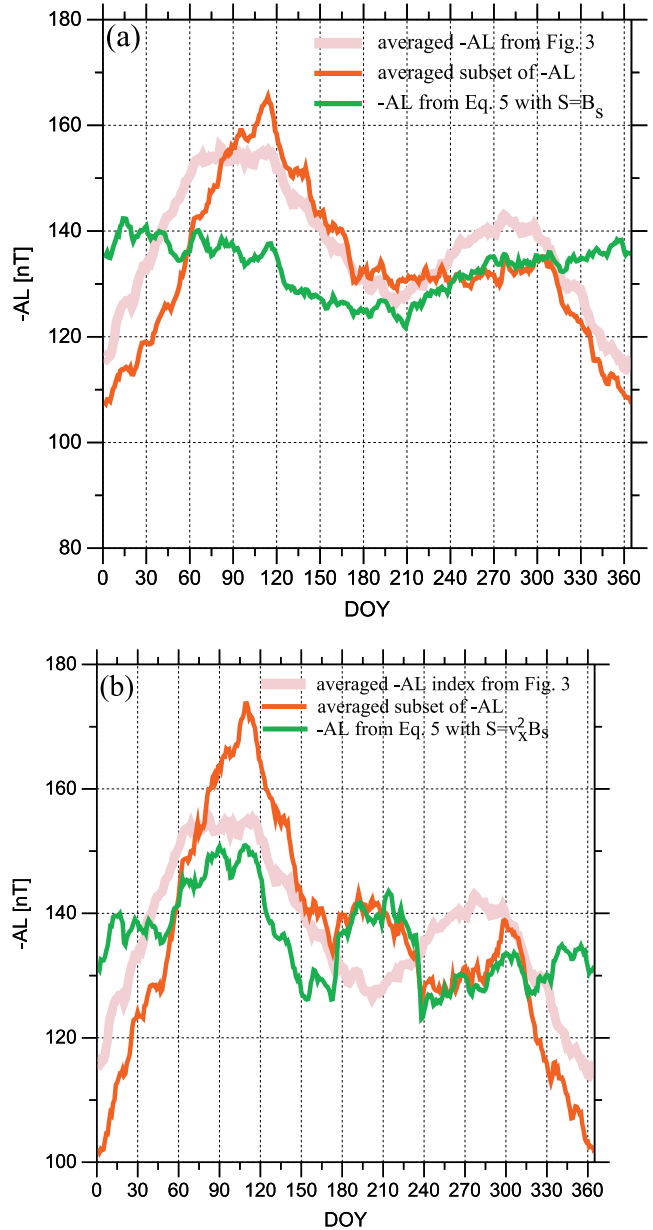
### 3.2. $AL$ Index and Auroral Zone Variations

[25] A significant result of *Newell et al.* [2002] is that the DOY-UT averaged  $AL$  index is nearly uncorrelated with the DOY-UT average of various solar wind driving parameters. In contrast, the DOY-UT averaged  $am$  index was found to have a correlation of 0.42 with a solar wind driving parameter. One interpretation is that the factor causing the  $am$  variation not predicted by changes in the average solar wind conditions near Earth has a stronger influence on the  $AL$  index, which is primarily based on postmidnight auroral zone ground magnetometer measurements. In this section we will first consider the DOY variation of the  $AL$  index. We will then look at the DOY variation of geomagnetic

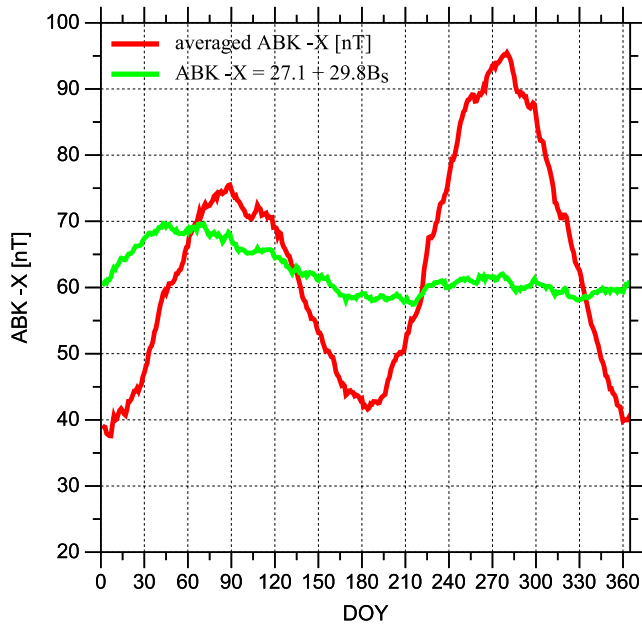
activity in the postmidnight sector auroral zone more directly by using measurements from individual magnetometers while they are in that region.

[26] Figure 3 shows the DOY-averaged plot of  $B_s$  and a linear regression model for  $AL$  derived using only 1-hour intervals where  $B_s$  and  $AL$  are both available. The ratio of the peak-to-peak amplitudes and prediction efficiency are 0.30 and 0.14, respectively, and the number of  $AL$ - $B_s$  pairs is  $1.4 \cdot 10^5$ .

[27] Figure 4a shows the DOY profile from Figure 3, the subset of  $AL$  data used to generate the coefficients for a time history  $B_s$  model, along with the DOY profile of the model.



**Figure 4.** (a) DOY-averaged  $AL$  index data from Figure 3, DOY average of  $AL$  index intervals that had 24 previous consecutive values of  $B_s$  available, and DOY averages of a time history model of  $AL$  that uses 24 values of  $S = B_s$  in equation (5). (b) Same as Figure 4a except the time history model of  $AL$  uses  $S = v_x^2 B_s$  in equation (5).



**Figure 5.** DOY-averaged north–south (X) component of the ground magnetic field measured at magnetometer station ABK when in the postmidnight sector and a linear regression model of ABK X that uses  $B_s$ . The ABK X curve was generated using only time intervals in which an hourly value of  $B_s$  is also available.

The number of values used to compute the model coefficients is  $5.7 \cdot 10^4$ . Although the ratio of the peak-to-peak variation of the model to that of the data is slightly higher at 0.35, the prediction efficiency between the two profiles is negative ( $-0.25$ ), indicating that this model is not a good predictor of the actual DOY variation.

[28] Figure 4b shows the DOY profile for the  $v_x^2 B_s$  model, which gives a prediction efficiency of 0.34. The number of values used to compute the model coefficients is  $3.5 \cdot 10^4$ . The DOY profile of the  $v_x^2 B_s$  model has a peak-to-peak ratio of 0.38, which is only slightly higher than that given by the corresponding  $B_s$  model (0.35).

[29] Figure 4 shows that in contrast to the  $am$  index, the peak-to-peak ratio and prediction efficiency do not increase such that the time history model accounts for a majority of the actual DOY variation in  $AL$ . For  $am$ , the time history model using  $B_s$  accounted for approximately twice as much of the DOY variation than the model that used only a single value of  $B_s$ . For  $AL$ , the time history model yielded only a small increase in the peak-to-peak ratio and a large decrease in the prediction efficiency over the model that used only a single value of  $B_s$ .

[30] The reasons for also analyzing the measurements from an individual magnetometer that contributes to the  $AL$  index are the following. First, in Figure 4 the subset of the  $AL$  index data used to generate the model does not display a clear semiannual DOY variation with two peaks as in the  $am$  index. More important, the  $AL$  index construction method is such that its primary contribution is from a single auroral zone magnetometer when it is in the postmidnight magnetic local time sector of 0–3. (That is, the percentage of time that the  $AL$  amplitude depends on only a single

postmidnight magnetometer is typically greater than 75% [Allen and Kroehl, 1975].) This is in contrast to the  $am$  index, which is an average of measurements from many magnetometers at different magnetic local times. In that the  $AL$  index is nearly a reflection of measurements from a single magnetometer when it is in a restricted magnetic local time range, the interpretation of the results will be more straightforward if magnetometer data in a known and specified MLT range is used instead of indexed data. The tradeoff is that we will have fewer data intervals. However, even with the restricted amount of data, the ratio of the number of model coefficients to the number of measurements used to compute the coefficients is small (less than 1/50).

[31] Figure 5 shows the results of the calculation for ABK made in the same way as that for  $am$  in Figure 1 and  $AL$  in Figure 3. ABK is one of stations that contributes to the  $AL$  index. The measurements used are hourly averaged values of the detrended north–south component of the ground magnetic field with MLT values of 0.83, 1.83, and 2.83 (by using the hourly averaged data which have center values of UT = 21.5, 22.5, and 23.5). The hourly averaged time series within each year were detrended by subtracting off the yearly average value from the measurements in that year. The peak-to-peak ratio and prediction efficiency are 0.23 and 0.01, respectively, and the number of data points was  $5.8 \cdot 10^3$ .

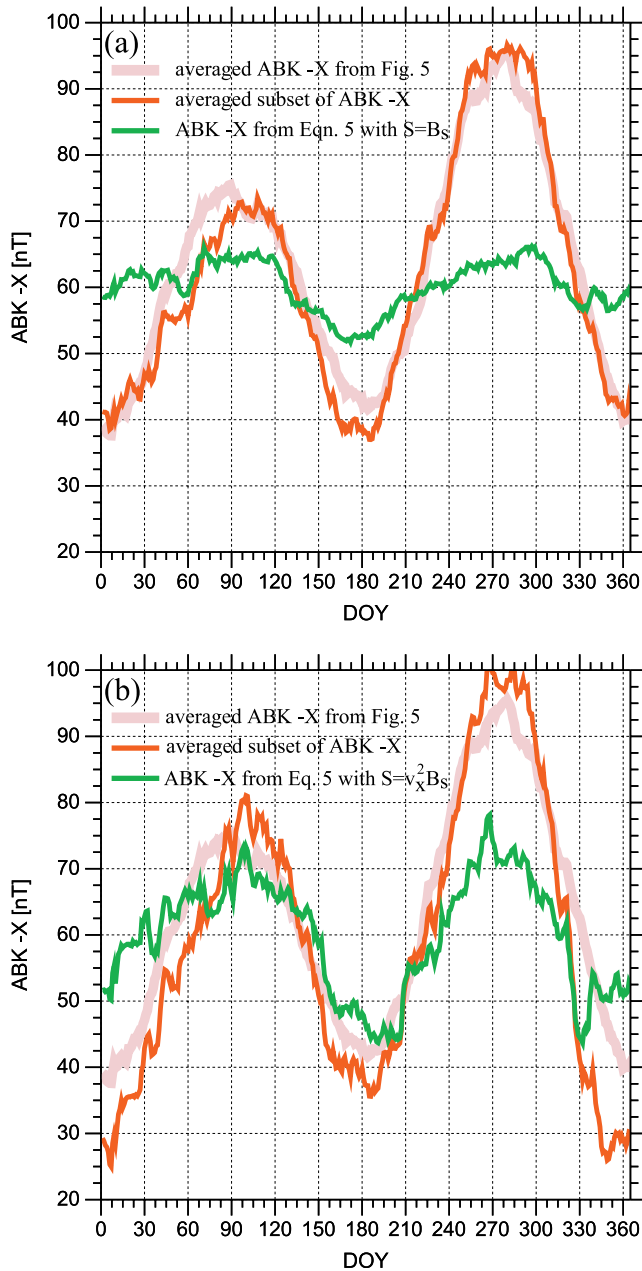
[32] Figure 6 shows the results of the calculation for ABK made in the same way as that for  $am$  in Figure 2 and  $AL$  in Figure 4. In Figure 6a, the peak-to-peak ratio and prediction efficiency are 0.28 and 0.26, respectively, and the number of values used to compute the model coefficients was  $2.7 \cdot 10^3$ . In Figure 6b, the peak-to-peak ratio and prediction efficiency are  $0.46 \pm 0.04$  and  $0.55 \pm 0.04$ , respectively, and the number of values used to compute the model was  $1.3 \cdot 10^3$ .

[33] We have repeated the calculation of Figure 6b using the auroral zone magnetometer CMO when it has MLT = 0.5, 1.5, 2.5 (by using hourly averaged data with center values of UT = 11.5, 12.5, 13.5). In this case, the peak-to-peak ratio and prediction efficiency is 0.42 and 0.44, respectively. These numbers are similar to those found for the other auroral zone magnetometers we have tested (MCQ, SOD, BRW), which yield values in the range of 0.30–0.60 for both measures. This result indicates that the near zero DOY-UT correlation between  $AL$  and various solar wind driving parameters found by Lyatsky *et al.* [2001] and Newell *et al.* [2002] does not indicate that the solar wind has on average zero influence on the DOY variation in geomagnetic activity in the postmidnight sector auroral zone. Instead, the process used to compute the  $AL$  index is a more likely explanation.

#### 4. Conclusion

[34] Early studies of the solar wind influence on the DOY variation in geomagnetic activity relied on the comparison of a DOY-averaged proxy for solar wind driving and a DOY-averaged geomagnetic index in a single time interval. This method gives a fraction of variation in the DOY-average of geomagnetic indices that can be explained by DOY-variations in the solar wind driving conditions that is on the order of 33% for  $am$  and zero for the DOY-UT variation in the  $AL$  index. Recent analysis on the cause of





**Figure 6.** (a) DOY-averaged ABK X from Figure 5, DOY average of intervals that had 24 previous consecutive values of  $B_s$  available, and DOY averages of a time history model of ABK X that uses 24 values of  $S = B_s$  in equation (5). (b) Same as Figure 6a except the time history model of ABK X uses  $S = v_x^2 B_s$  in equation (5).

the remaining variation have generally invoked new mechanisms, including a DOY variation in the responsiveness of the magnetosphere to a given solar wind input or an ionospheric insulation process that causes a DOY dependence in auroral zone geomagnetic activity.

[35] We have used a generalization of a previous modeling approach used to estimate the solar wind contribution to the DOY variation in geomagnetic activity. This approach accounts for the fact that the response of the magnetosphere to a solar wind input is not instantaneous. With a time

history model of solar wind driving, significantly more DOY variation in geomagnetic activity can be attributed to DOY variations in average solar wind conditions. A time history model that uses only  $B_s$  explains approximately 60% of the observed DOY variation in  $am$ , in comparison to the 30% that is explained by a model that uses only a single value of  $B_s$ . A time history model of  $am$  that uses the solar wind driving parameter  $v_x^2 B_s$  has a peak-to-peak variation in its DOY profile that is 72% of that in the measured  $am$  index and predicts 80% of the variance in the measured  $am$  DOY profile.

[36] This result raises an important consideration in the study of coupling functions that specify a magnetospheric activity parameter given plasma measurements in the upstream solar wind. Many coupling function results are based on the optimization of parameters from a nontime history model [Gonzalez, 1990]. As shown in this work, the time history has a significant contribution, and by neglecting it, the form of the coupling function may have a significant nonphysical contribution that is a result of the unmodeled time delay effect.

[37] We have applied this generalization to the auroral zone index  $AL$  and find that, consistent with other analysis, the solar wind has a small influence on the DOY profile of  $AL$  when only a single hourly averaged  $B_s$  value is used as the solar wind driving proxy. If data from a single magnetometer that contributes to  $AL$  is used, the  $B_s$  influence is also near zero. We have considered data from individual magnetometer stations that contribute to the  $AL$  index and find that a model that includes the solar wind time history can account for approximately 40% of the observed DOY variation. From this we conclude that the DOY variations in the average solar wind conditions do have a signature at postmidnight auroral zone latitudes. We also conclude that the  $AL$  index is not a good measure of the influence of the solar wind on DOY-UT variations in postmidnight sector auroral zone activity. Although the average DOY-UT correlation between  $AL$  and solar wind driving parameters is zero, we find that 40–50% of the DOY variation in measurements from individual magnetometers at universal times when they are in the postmidnight sector is explained by the solar wind.

[38] Having developed a method that allows for the estimation of the solar wind influence on the DOY variation in ground magnetometer measurements and geomagnetic indices, it is natural to ask what explains the variation that is not predicted by this method. There are at least three possibilities. First, an improved model may explain more of the variation. A refined coupling function and a model that includes a solar wind time history both yielded increases in the variation explained by the solar wind. For this reason, it is reasonable to expect that further refinements may yield further increases. Second, there may be a variation in the response efficiency of the magnetosphere such that on certain DOYs the geomagnetic response to identical solar wind conditions may differ. To study this, one would need to develop a DOY-dependent model. Finally, there are explanations that invoke a nonsolar wind driven process, such as the solar insulation mechanism of [Newell et al., 2002], which has a DOY variation that is similar to the variation not explained by the time history model developed in this work.

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R. S. Weigel, Department of Computational and Data Sciences, George Mason University, 4400 University Drive, Fairfax, VA 22030, USA. (rweigel@gmu.edu)