
DOI: http://doi.org/10.1002/2014JA019776
Local time resolved dynamics of field-aligned currents and their response to solar wind variability

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Abstract Using 10 years of CHAMP measurements condensed into the empirical model of field-aligned currents through empirical orthogonal function analysis, the dynamics of field-aligned currents (FACs) is modeled and studied in separate magnetic local time (MLT) sectors. We investigate the distributions of FAC intensity and latitude and evaluate their predictability in terms of geospace parameters which are ranked according to their relative importance measured by a multivariate regression procedure. The response time to changes in solar wind variables is studied in detail and found to be much shorter for dayside FACs than on the nightside (15–25 min versus 35–95 min). Furthermore, dayside FACs can be parameterized more accurately; $R^2$ values maximize greater than 0.7 for FAC latitude and greater than 0.3 for FAC intensity, whereas the corresponding values on the nightside are smaller than 0.3 and 0.15, respectively. The results support the separation between directly driven coupling processes acting on the dayside and unloading processes controlling the nightside. In addition, the MLT-resolved standardized regression coefficients suggest that (1) FAC latitude is affected most significantly by the transpolar potential, substorm evolution, solar activity as represented by the $F_{10.7}$ index and its square, and the dipole tilt; (2) Region-1/2 current intensity is controlled most efficiently by substorm evolution, IMF $B_z$ and IMF $By$; and (3) cusp current intensity is influenced by conductivity, IMF $B_y$ and their cross item.

1. Introduction

The system of auroral field-aligned currents (FACs) comprises principally a pair of sheets, namely, Region 1 (R1) and Region 2 (R2) currents with opposite current flow directions in the morning and evening sectors, and the polarity switch around noon and midnight [Iijima and Potemra, 1976]. In the noon sector, cusp currents often appear at the poleward edge of the Region 1/2 pattern with their distribution strongly controlled by the $y$ component of the interplanetary magnetic field (IMF) [Cowley, 2000]. In the past decades, many studies focused on the empirical description of FACs [Anderson et al., 2002; Papitashvili et al., 2002], typically through preprocessing the magnetic data from low Earth orbiting satellites, and binning them into discrete categories according to controlling factors such as IMF orientation and magnitude. The present study builds on MFACe (model of field-aligned currents through empirical orthogonal function analysis), a high-resolution FAC model presented in an earlier paper [He et al., 2012]. MFACe is constructed from 10 years of data from the CHAllenging Minisatellite Payload (CHAMP) mission using a novel technique based on empirical orthogonal function (EOF) decomposition and comprehensive regression. Through analyzing regression variance, MFACe quantifies the predictability of FACs and response time of FACs to solar wind conditions.

FACs are important coupling agents in the solar wind-magnetosphere-ionosphere system. The system exhibits two basic modes of energy dissipation, namely, directly driven processes on the one hand and the unloading process on the other [Akasofu, 1979; Cowley and Lockwood, 1992]. The former mode dissipates energy directly from the solar wind principally through dayside reconnection at the magnetopause, while the latter releases energy stored previously in the magnetotail through tail reconnection, and hence is acting mainly on the nightside. The two modes are considered responsible for the delayed response of the magnetosphere to solar wind changes on two timescales: the former yields delays of about 20 min while the latter yields delays of about 1 h due to intermediate energy storage in the magnetotail [Bargatze et al., 1985]. In view of the day-night distribution of the two modes, one may expect a day-night dependence of the coupling in general and of FAC dynamics in particular. A main objective of the present work is to apply and to develop further the methods of MFACe to...
formulate a comprehensive description of local time resolved response of FACs to solar wind driving. In section 3, we quantify their predictability and the response times for FAC intensity and latitudinal variations. In sections 4 and 5, we study FAC dynamics in separate MLT sectors in terms of geophysical control factors. Rather than choosing a small set of variables beforehand as in previous studies that focused on the influence of particular factors such as ionospheric conductivity [Ohtani et al., 2014] or merging electric field [Wang et al., 2005], we first build a comprehensive list of potential geophysical control factors and then use multivariate regression to rank them according to their explanatory power measured by the relative contribution to the total variance. The method can take numerous factors simultaneously and flexibly into account, deal with the problem of mutually correlated input factors, maximize the efficiency of the utilization of observation by normalizing all events in terms of other factors, and capture the potential interaction effect between two factors by including their product in the list of input variables.

2. Analysis Methodology

The underlying data set and the processing and analysis procedures were explained in our previous study [He et al., 2012], and are briefly summarized here for convenience. In brief, the construction of MFACE entails (1) subtracting the POMME-6 model from 10 years of 1 s averaged CHAMP magnetic vector data, yielding the perturbation vector \( \mathbf{\delta B} \), (2) estimating the current intensity \( j_z \) as a function of geomagnetic latitude (MLAT) from \( \mathbf{\delta B} \) for each auroral oval crossing, (3) representing each \( j_z(\text{MLAT}) \) profile in terms of a group of variables, and (4) regressing the variables as a function of driving factors. Note that POMME-6 is a geomagnetic field model combining Earth’s core, crust, large-scale magnetospheric currents, and induced magnetic fields [Maus et al., 2006].

2.1. Determination of Auroral Current Center

Higuchi and Ohtani [2000] developed a method to determine the position and the number of current sheets automatically during an auroral oval crossing based on B spline fitting with variable nodes. The method requires a predefined sampling interval capturing FAC sheets entirely and may fail in identifying the geometrical structure if there are more than two dominant current sheets for one crossing [Ohtani et al., 2010]. To handle these limitations, He et al. [2012] defined an automatic approach to determine the latitudinal location of FACs. First, wavelet analysis is applied to the \( \mathbf{\delta B} \) vector yielding spectra \( \mathbf{\delta B}(t, l) \) as functions of time \( t \) and scale \( l \). Perturbation vectors \( \mathbf{\delta B} \) are then integrated over the range 200 km < \( l \) < 1600 km to yield a vector series \( \mathbf{P}(t) \). The maximum of \( |\mathbf{P}(t)| \) in each quarter orbit specifies the location of auroral current center (ACC). The ACC is supposed to correspond to the demarcation between R1 and R2 currents in the case of the double sheet structure, and to the center of the middle sheet in the triple-sheet case, see Figure 1 in He et al. [2012] for an example. The present study uses the ACC as a measure of FAC latitude and auroral oval location.

2.2. EOF Decomposition

In a 15° MLAT width window around the ACC (\([-10°, 5°]\) for the Northern Hemisphere and \([-5°, 10°]\) for the Southern Hemisphere), minimum variance analysis (MVA) is applied to \( \mathbf{\delta B}(\text{MLAT}) \), in the so-called Orbit-Geomagnetic (OGM) coordinates system [He et al., 2012], rather than in the traditional geomagnetic frame based on geomagnetic East and West directions which rotate by up to 180° during each crossing of the polar region. The current density \( j_z(\text{MLAT}) \) is determined according to Ampere’s law in an idealized geometry where FACs are organized in infinitely extended and parallel stationary sheets. The sheet normal vector is assumed to be in the direction of minimum variance of \( \mathbf{\delta B} \) in the OGM \( x - y \) plane. To remove small-scale fluctuations, \( j_z(\text{MLAT}) \) is low-pass filtered and then decomposed into linear combinations of Empirical Orthogonal Functions (EOFs): \( j_z(\text{MLAT}) = \sum_s s_i \cdot \text{EOF}_i(\text{MLAT}) \). Here \( s_i \) is the score for EOF\( _i \) and \( \mathbf{\delta MLAT} = \text{MLAT} - \text{MLAT}_{\text{ACC}} \) is the latitudinal difference relative to the ACC reference point. The empirical orthogonal functions EOF, for the Northern Hemisphere are shown in Figure S1 of the supporting information.

2.3. Regression Model

The MLAT\( _{\text{ACC}} \) and scores \( s_i \) up to a maximum order \( i = 12 \) are regressed separately as linear functions of a group of independent variables (called regressors), which are further employed to model \( j_z \). The quality of the model can be quantified through the determination coefficient \( R^2 \) (square of correlation coefficient \( R \), ranging from 0 to 1 and measuring the ratio of explained variance to the total variance). In MFACE [He et al., 2012], the
best model fit for FAC intensity, characterized by maximum $R^2$, was obtained with a 20 min time lag from solar wind variables, and the best fit for FAC latitude was obtained with a 35–40 min time lag. In the present study, we expand the procedures and carry out similar regression analyses but in separate geomagnetic local time (MLT) sectors. The regressor list includes day of year (DOY), IMF clock angle $\theta_{IMF}$ in GSM coordinates, IMF component in GSM y-z plane $B_t$, IMF magnitude $B$, solar wind speed $v_{SW}$, $F_{10.7}$ index, geomagnetic longitude $MLong$, and the SuperMAG derived $SMU$ and $SML$ indices improved and expanded from the AU and AL [Newell and Gjerloev, 2011]. The regression model can be written as follows:

$$\text{MLAT}_{\text{ACC}}(\text{DOY}, \theta_{\text{IMF}}, B_t, B, v_{\text{SW}}, F_{10.7}, MLong, SMU, SML) =$$

$$\alpha_{\sin} \sin(\theta_{\text{IMF}}) + \alpha_{\cos} \cos(\theta_{\text{IMF}}) + \alpha_{\cos \text{MLong}} \cos(\text{MLong}) + \alpha_{\cos \text{DOY}} \cos(2\pi \cdot (\text{DOY} + 10)/365.25) + \alpha_{107} F_{10.7} + \alpha_{2} B_t + \alpha_{3} \Phi(\theta_{\text{IMF}}, B_t, v_{\text{SW}}) + \alpha_{\text{SMU}} SMU + \alpha_{\text{SML}} SML + \ldots \text{(quadratic interaction and squared terms)}$$

(1)

The IMF parameters, retrieved from the NASA OMNI web service, refer to the Earth’s bow shock nose at a temporal resolution of 5 min. $\Phi$ is the empirical transpolar potential parameterized by a combination of solar wind parameters [Boyle et al., 1997], which is selected due to the presumed current-voltage relationship of the magnetosphere-ionosphere system.

### 2.4. Stability of the Regression Problem

The regression problem may become ill conditioned and unstable when regressors are mutually correlated. To handle this problem, we adopt the ridge regression procedure that deviates from the usual least squares approach where the estimated coefficient in the standard linear regression model, $y = X\beta + \epsilon$, is $\hat{\beta}_{\text{LS}} = (X^TX)^{-1}X^Ty$. The $n \times 1$ vector $y$ is the observed dependent variable corresponding to MLAT$_{\text{ACC}}$ in equation (1), and the $n \times p$ matrix $X$ contains the observed independent variables corresponding to all of the regressors listed in equation (1). For convenience, all independent variables are assumed to have been centered having mean 0 and scaled having standard deviation 1. The $p \times 1$ vector $\beta$ contains the coefficients to be estimated, corresponding to all $\alpha_i$ in equation (1). The $p \times 1$ vector $\epsilon \sim N(0, \sigma^2)$ is the experimental errors having mean 0 and unit variance $\sigma^2 = 1$. 

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**Figure 1.** (a) Determination coefficient $R^2$ in the regression of FAC latitude as a function of geomagnetic local time (MLT) and time lag to solar wind variables at the bow shock nose for the Northern Hemisphere. (b) Same plot as in Figure 1a but for the Southern Hemisphere. (c, d) Results of current intensity regression. The resolution is 1 h (MLT) by 5 min (time lag). Maximum $R^2$ values in each MLT sectors are marked by white dots. The diameter of the dots is proportional to the peak value on $R^2(\delta t)$. The $R^2$ peak provides a measure of the delay time of FACs in response to solar wind changes.
When regressors are mutually correlated, the matrix $X'X$ can be ill conditioned which in turn inflates the covariance matrix $\text{Var}(\hat{\beta}) = (X'X)^{-1}\sigma^2$ thus the uncertainty of the estimated coefficients. This statistical phenomenon is called multicollinearity. Multicollinearity in the regressions using equation (1) may result, e.g., from the dependence of geomagnetic indices on solar wind parameters or from correlations between first-order regressors and their quadratic interaction or squared terms.

The ridge regression estimator [Marquardt, 1970] addresses the multicollinearity issue by allowing for a small bias through a damping parameter $\lambda; \hat{\beta}^{\text{ridge}} = (X'X + \lambda I)^{-1}X'y$ and $\text{Var}(\hat{\beta}^{\text{ridge}}) = (X'X + \lambda I)^{-1}X'X(X'X + \lambda I)^{-1}\sigma^2$.

Often, a small bias leads to significant reductions in the variance $\text{Var}(\hat{\beta}^{\text{ridge}})$; $||\hat{\beta}^{\text{ridge}}||$ is a continuous monotone decreasing function of $\lambda$, such that as $\lambda = 0$, $||\hat{\beta}^{\text{ridge}}|| = ||\hat{\beta}||$, and as $\lambda \to \infty$, $||\hat{\beta}^{\text{ridge}}|| \to 0$. The present study determines the damping parameter $\lambda$ using the method of generalized cross validation [Golub et al., 1979].

2.5. Selection of Important Factors by Stepwise Regression

Note that ridge regression is used in the present work only to yield a full comparison, whereas in constructing MFACE a systematic method called stepwise regression is employed [Draper and Smith, 1998]. Starting from an initial model, the stepwise method considers additional potential factors and evaluates their significance using $p$ values of an $F$ statistic. In each step, regressors from the list of potential factors are included or removed until no further improvements are made. The method converges toward a locally optimal solution. The initial model and list of potential regressors must be chosen with care. The resulting regression model is supposed to yield significant explanatory power with a small number of regressors.

2.6. Time Delays in Solar Wind Parameters

The regression defined by equation (1) produces a group of coefficients $a_i$ and the determination coefficient $R^2$ as functions of MLT, $a_i'(\text{MLT})$ and $R^2_{\text{MLT}}$. Following He et al. [2012], we take a time lag $\delta t$ into account through replacing $\theta_{\text{MLT}}, B_t, B$, and $v_{\text{SW}}$ in equation (1) with their delayed values $\theta_{\text{MLT}}(\delta t), B_t(\delta t), B(\delta t)$, and $v_{\text{SW}}(\delta t)$. Here $\delta t$ ranges from 5 min to 110 min at a resolution of 5 min. The time lag refers to the values of solar wind parameters at the nose of the Earth's bow shock. The regression procedure thus effectively determines the coefficients $a_i$ and $R^2$ as functions of magnetic local time and time lag: $a_i'(\text{MLT}, \delta t)$ and $R^2_{\text{MLT}}(\text{MLT}, \delta t)$. After replacing MLAT ACC in equation (1) with the EOF scores $s_j$, we repeat the regression procedure to yield estimates $a_{ij}'(\text{MLT}, \delta t)$ and $R^2_{ij}(\text{MLT}, \delta t)$ for each of the scores $s_j$. The analysis of day-night difference in section 3 is based on the determination coefficients $R^2_{\text{iMLAT}}(\text{MLT}, \delta t)$ and $R^2_{\text{ijMLAT}}(\text{MLT}, \delta t)$. The coefficients $a_{i\text{MLAT}}(\text{MLT}, \delta t)$ and $a_{ij\text{MLAT}}(\text{MLT}, \delta t)$ form the basis of the analyses in sections 4 and 5, respectively.

3. Day-Night Difference in Response to Solar Wind Change

Figures 1a and 1b show the determination coefficient $R^2_{\text{iMLAT}}(\text{MLT}, \delta t)$ of the MLAT ACC regression for the Northern and Southern Hemispheres. A remarkable feature is that the Northern value of $R^2$ is greater by 0.1, most probably due to the fact that the regressors SMU and SML are derived from measurements collected in the Northern Hemisphere. Following He et al. [2012], in each MLT sector we determine the time lag $\delta t$ (marked by white dots in Figure 1) for which $R^2$ assumes its maximum. The response of auroral oval latitude to solar wind changes is faster on the dayside than on the nightside, with $R^2(\delta t)$ maximizing at 20–30 min during 09–17 MLT and at 35–60 min during 20–04 MLT. Figures 1c and 1d show the corresponding $R^2$ values for the regression of current intensity $R^2_{ij} = \sum_{\delta t = 5}^{55} R^2_{ij}(\text{MLT}, \delta t) g_j$. Here $g_j$ is the ratio of the variance on EOF, to the total.

The response time of current intensity also exhibits a remarkable day-night difference. On the dayside during 08–17 MLT, $R^2_{ij}(\delta t)$ maximizes at 15–20 min and at 55–100 min on the nightside during 21–03 MLT.

To investigate the stability of the estimated $R^2(\delta t)$ peaks in Figure 1, the following bootstrapping procedure is applied. In each MLT sector and for all $\delta t$, the data are resampled with replacement randomly and the $R^2$ value is computed. The size of the resampled data set equals to the size of the original one. Five hundred such bootstrapping iterations yield a distribution of 500 $R^2$ values from which we calculate the median and the lower and upper quartiles. The statistics are displayed in Figure 2. For better visibility we just show the results at noon and midnight, namely, in the MLT sectors 1000–1200, 1200–1400, 2200–2400, and 0000–0200. The Figures 2a–2d (top) illustrate that at noon all $R^2(\delta t)$ curves peak sharply at 20–25 min with a peak height...
greater than the interquartile range. In contrast to the dayside peaks, at midnight the $R^2(\delta t)_{\text{max}}$ maxima are less pronounced and appear later: at 30–45 min for the FAC latitude and 60–95 min for the intensity.

The difference between the two timescales was reported earlier in different contexts. Bargatze et al. [1985] found two lags near 20 min and 60 min by means of impulse response functions to describe the relationship between AL and solar wind changes at the bow shock derived from the IMP 8 observation. Using solar wind data from Explorer 33, the empirical analysis of Clauer et al. [1981] also demonstrated that two delay times are present. The delays were interpreted in the light of two basic driving mechanisms, namely, the directly driven process on the one hand and the unloading process on the other hand [e.g., Bargatze et al., 1985; Cowley and Lockwood, 1992]. The first mechanism is driven principally by dayside reconnection, corresponding to the 20 min timescale for the near-Earth magnetopause. The second mechanism is controlled by tail reconnection, corresponding to the 60 min delay which represents the time between solar wind changes and the formation of a near-Earth neutral line and the substorm current wedge (SCW) [McPherron et al., 1973]. The MLT-resolved lagged response presented in this study provides further evidence to support the distinction between driven and unloading processes in the Earth's magnetosphere. Due to internal magnetospheric instabilities involved in the unloading process, the predictability of FACs is expected to be higher on the dayside than on the nightside.

Correspondingly, the dayside $R^2$ coefficients are significantly higher than the nightside values in Figures 1 and 2. For the FAC latitude regressions in Figures 1a and 1b, the coefficients can assume values greater than 0.7 in the 08–17 MLT range, whereas in the 20–04 MLT range the values are always smaller than 0.4. For the FAC intensity in Figures 1c and 1d, the maximum coefficients are greater than 0.3 in the 08–17 MLT range, and smaller than 0.15 in the 20–04 MLT range.

4. Factors Controlling FAC Latitude Distribution

In this section we try to identify the factors that are most important in controlling the distribution of FAC latitudes as measured by the ACC. The issue of quantifying the relative importance of regressors is still controversial [cf., Nathans et al., 2012; Nimon and Oswald, 2013]. The measure used here is the set of standardized regression coefficients [Affifi and Clark, 1990]. The median of the coefficients $\hat{\alpha}_{\text{MLAT}}(\text{MLT}, \delta t)$ in the dimension of $\delta t$, $\hat{\alpha}_{\text{MLAT}}(\text{MLT})$, is normalized through division by the standard deviation of the corresponding regressor. The resulting values $\hat{\alpha}_i(\text{MLT})$ are displayed in Figure 3. The x axis annotation contains the...
names of the regressors, ranked according to their relative importance measured by the integrated power
\[ P = \sum_i \hat{\alpha}_i^2(\text{MLT}) \]. Only the first half of the list is shown for better visibility. The most important regressors comprises the transpolar potential \( \Phi \), the SuperMAG indices, \( F_{10.7} \) index, \( \text{CosDOY} \), \( \text{CosMLong} \), and part of their square and cross terms.

Figure 3 is a coefficient chart that allows to study the observational dependence of FAC latitude on particular parameters like \( F_{10.7} \) as reflected in the coefficients \( \hat{\alpha}_{107} \) and \( \hat{\alpha}_{107^2} \). The dependence on \( F_{10.7} \) in separate MLT intervals is shown in greater detail in Figure 4. In all MLT intervals, FACs move equatorward as \( F_{10.7} \) increases. The dependence is more pronounced at lower \( F_{10.7} \) levels and tends to become weaker with increasing \( F_{10.7} \) values or even reverses. This behavior can also be observed in DMSP magnetometer data [Ohtani et al., 2014]. The authors explained the dependence on \( F_{10.7} \) in terms of the dynamics of dayside R1 currents and the induced change in magnetospheric configuration. Increasing \( F_{10.7} \) goes along with increasing dayside ionospheric conductivity which in turn enhances the R1 current and its closure currents. The dayside magnetosphere shrinks further and forces FACs to move equatorward. A stronger R1 current also strengthens the lobe magnetic field and yields stretching of the tail magnetic field and thinning of the plasma sheet, so the nightside FACs also move equatorward.

Figure 3 is used further to investigate the dependence on SML. The second and third columns show that FAC latitude can change by more than 1° in response a unit variation of the normalized linear and quadratic SML coefficients (corresponding to 1 standard deviation in nonnormalized variables). The MLT-resolved evolution of FAC latitude in response to SML during substorms is illustrated further in Figure 5. The effective SML profile in Figure 5a is obtained from a superposed epoch analysis using the substorm onsets from the list of Newell and Gjerloev [2011]. The black line shows the median, and the shadowed region is the interquartile range reduced to 20% for better visibility. Figure 5b gives the response of MLATACC according to the coefficients \( \hat{\alpha}_{SML} \) and \( \hat{\alpha}_{SML^2} \) from Figure 3 at four MLTs, namely, 0000, 0600, 1200, and 1800. SML dynamics during substorms is similar to that of the AL index which serves to distinguish the three stages of substorm evolution.

During substorm growth, the energy from the solar wind is temporarily stored in the magnetotail. For the amount of the stored energy, a good indicator is the area of the polar cap since it represents the magnetic
flux in the tail lobe [Kamide et al., 1999]. The stored energy, characterized by the equatorward expansion of the polar cap and the FACs [e.g., Clausen et al., 2012], drives directly a systematic change, including enhancement of convection and increasing auroral electrojets in association with enhancement of AL and AU [Atkinson, 1993; Craven and Frank, 1987]. Accordingly, in Figure 5 and during the growth phase, the enhancement of SML index is accompanied by the equatorward shift of FACs at most MLTs. During the brief expansion phase, AL activity enhances shortly due to the SCW [e.g., Kamide et al., 1999] associated with the poleward expansion of the auroral bulge close to midnight sector. The auroral bulge begins to recover when substorm activity begins to decline. The dynamics of the auroral bulge may be responsible for the

Figure 4. Response of MLAT_{ACC} as a function of \( F_{10.7} \) in six MLT sectors, according to the coefficients \( \hat{\alpha}_{F_{10.7}} \) and \( \hat{\alpha}_{F_{10.7}^2} \) in Figure 3. The results are obtained by averaging values from the Northern and Southern Hemispheres.

Figure 5. (a) SML profile obtained from a superposed epoch analysis using substorm onsets taken from the list of Newell and Gjerloev [2011]. The black line shows the median, and the shadowed region is the interquartile range reduced to 20% for better visibility. (b) The response of the MLAT_{ACC} according to the coefficients \( \delta_{SML} \) and \( \delta_{SML}^2 \) in Figure 3 at four MLT, namely, 0000, 0600, 1200, and 1800. The results are obtained by averaging values from the Northern and Southern Hemispheres. Background colors represent substorm phases, namely, growth phase, expansion phase, and recovery phase.
The factors assumed to contribute to ionospheric conductivity are relative importance measured by the integrated power $P_{\alpha_i}$. Here, $\alpha_{\text{sym}}$ and $\alpha_{\text{asym}}$ represent the cusp current, we consider only the 8–16 MLT interval.

The factors assumed to contribute to ionospheric conductivity are $F_{10.7}$, DOY, and MLong so that equation (1) simplifies to

$$s_{\text{lf}}(\theta_{\text{IMF}}, B_{\text{I}}, B_{\text{VSM}}, B_{\text{SML}}, B_{\text{MLT}}, \text{DOY}, \text{MLong}, \text{MLAT}_{\text{ACC}}, \text{MLT}) =$$

$$a_{\text{sym}} \sin(\theta_{\text{IMF}}) + a_{\text{asym}} \cos(\theta_{\text{IMF}}) + a_{\text{B}} B_1 + a_{\text{SML}} SML + a_{\text{SMU}} + a_{\text{Phi}} \Phi(\theta_{\text{IMF}}, B_1, B_{\text{VSM}})$$

(2)

Here $G_i$ is the empirical solar illumination-induced ionospheric conductivity at ACC, parameterized by

$$G = \begin{cases} F10^{20} \cdot \exp(0.34 \cos(\zeta) + 0.93 \sqrt{\cos(\zeta)}) & \text{if } \zeta \leq 90^\circ \\ 0 & \text{if } \zeta > 90^\circ \end{cases}$$

[Moen and Brekke, 1993]. The solar zenith angle $\zeta$ is defined by DOY, MLong, MLAT$_{\text{ACC}}$, MLT, or alternatively by the time and geographic latitude and longitude of ACC. Note that equation (2) is used only for generating Figure 6, whereas for the $s_{\text{lf}}$ regressions in constructing MFACE we still use equation (1).

The decomposition of the coefficients into symmetric and antisymmetric components is motivated by interhemispheric differences in FAC dynamics noted already in our earlier paper [He et al., 2012]. The decomposition is defined by

$$\hat{a}_{\text{sym}} = (\hat{a}_{\text{northern}} + \hat{a}_{\text{southern}})/2,$$

$$\hat{a}_{\text{asym}} = (\hat{a}_{\text{northern}} - \hat{a}_{\text{southern}})/2.$$

The regressors are sorted according to their relative importance measured by the integrated power $P_{\alpha_i}$.

$$P_{\alpha_i} = \sum_{0 \leq \text{MLT} < 16} \hat{a}_{\text{sym}}^2 (\text{MLT})^2$$

for EOF1, and

$$P_{\alpha_i} = \sum_{8 \leq \text{MLT} < 16} \hat{a}_{\text{sym}}^2 (\text{MLT})^2$$

for EOF2. Since EOF2 represents the cusp current, we consider only the 8–16 MLT interval.
In Figure 6, a notable feature is that the most important antisymmetric components for both EOFs are IMF $B_y$ related, due to the fact that IMF $B_y$ influences the configuration of near-subsolar reconnection, and results in an interhemispheric antisymmetric flow [Cowley, 2000]. The EOF1 component, as shown in Figure 4 of He et al. [2012], represents basically the Region 1/2 double-ring pattern:

1. The intensity of the currents is modified by $B_z$, revealed also by the close correlation with $B_z$ in Figure 6a.
2. The polarity of the pattern switches around noon and midnight, and the MLT location of the switches is modified by the IMF $B_y$ component, revealed also by the $|\alpha_y|$ peaks at noon and midnight in Figure 6b.

Actually, the $|\alpha_y|$ peak at midnight in Figure 6b represents the IMF $B_y$ control on the MLT location of the Harang region [Rodger et al., 1984], which is the unique efficient influence from solar wind parameters on the current intensity at midnight according to all panels in Figure 6. With regard to substorm evolution, $\alpha_{SML}$ and

![Normalized Coefficients for the EOF1 Regression](image1)

![Normalized Coefficients for the EOF2 Regression](image2)

**Figure 6.** Similar plots as in Figure 3 but for the regression of current density after being decomposed into interhemisphere symmetric and antisymmetric components by $\alpha_{sym} = (\alpha_{northern} + \alpha_{southern})/2$, (a, b) The EOF1 regression. (c, d) The EOF2 regression. In the annotation of the x axis, G represents the empirical illumination-induced conductivity. Shown is just the first important half of all regressors. See the text for details.
\( \hat{a}_{SML} \) at the top ranks in the list in Figure 6a represent the enhancement of the Region 1/2 pattern before onset and its decrease after onset.

The EOF2 component, as indicated by Figure 4 in He et al. (2012), represents a triple-sheet structure, principally a cusp current signature around noon with polarity determined by IMF By. Correspondingly, in Figure 6d all By-related coefficients maximize at noon. In the list of Figures 6c and 6d, \( \hat{a}_G \) and \( \hat{a}_{G'} \) ranking second and fifth indicate that the dependence of cusp current intensity on the conductivity decreases with increasing conductivity. EOF2 is not correlated significantly with SuperMAG indices, indicating that cusp current intensity does not experience a representative evolution during substorms. The most important item in Figures 6c and 6d is the interaction between \( G \) and \( nB_y \), suggesting that the influence of the IMF clock angle \( \theta_{IMF} \) on cusp current intensity is modulated by conductivity \( G \) and becomes stronger with increasing \( G \).

6. Conclusions and Summary

The current study presents a comprehensive analysis of local time resolved FAC dynamics by means of multivariate regression methods used to construct the empirical FAC model MFACE. FAC latitude and intensity are regressed as linear functions of SML, SMU, \( F_{10.7} \), the IMF \( B_y \), the empirical transpolar potential \( \Phi \) derived from solar wind parameters, the first harmonic component of DOY, MLong and IMF clock angle \( \theta_{IMF} \), and their quadratic interaction and square terms. In the second step, multivariate regressions are repeated for lagged versions of the solar wind parameters \( \Phi, B_y \), and \( \theta_{IMF} \), i.e., \( \Phi(t), B_y(t) \), and \( \theta_{IMF}(t) \). The determination coefficient \( R^2 \) maximizes on the dayside at levels greater than 0.3 for FAC intensity and greater than 0.7 for FAC latitude, while on the nightside the \( R^2 \) values are less than 0.15 and 0.3, respectively. The day-night difference reveals a higher predictability of FACs on the dayside than on the nightside. In terms of the delay time \( \delta t \), \( R^2 \) maximizes at around 15–25 min on the dayside, whereas on the nightside we find significantly different values in the range of 35–95 min. These results can be explained in terms of the two principal solar wind-magnetosphere coupling modes, namely, directly driven processes acting primarily on the dayside and unloading processes responsible for the dynamics on the nightside.

The regression coefficients are standardized to evaluate the relative importance of each regressor. Our results suggest that the most important factors controlling FAC latitude are the empirical transpolar potential, SML and SMU indices and their square terms, \( F_{10.7} \) and its square term, and CosDOY and CosMLong. The factors represent the dependence of the FAC latitude distribution on substorm evolution, solar activity, and dipole tilt. In the case of FAC intensity, Region 1/2 currents represented by EOF1 are controlled most significantly by the SML index and its square term, IMF \( B_z \) and \( B_y \) and the empirical conductivity \( G \). The cusp currents represented by EOF2 are controlled by \( G \), IMF \( B_y \), and their product after division by \( B_\theta \). The dependencies suggest that Region-1/2 current intensity experiences a representative development during substorm activity, and the dependence of cusp current on conductivity level is modulated by \( \theta_{IMF} \).

To summarize, this report offers a comprehensive assessment of the influence of a large set of geophysical variables on FAC intensity and latitude distribution. The most important factors are integrated into an updated version of MFACE to produce a compact tool that comprises the salient physics and most important parameters of auroral FACs.

Acknowledgments

The authors acknowledge the online services provided by GFZ Potsdam (CHAMP data), NGDC (POMME-6.2 coefficients), John Hopkins University APL (AACGM coefficients and the SMU and SML indices), and NASA OMNI (IMF/SW and other geophysical parameters).

Financial support from the Deutsche Forschungsgemeinschaft through grant DFG HE6915/1-1 and DFG VO 855/3-1 is acknowledged. The compiled program of MFACE v3.0 is going to be released at www.faculty.jacobs-university.de/joerg/mface/ or http://sourceforge.net/projects/mface/.

Larry Kepko thanks Jesper Gjerloev and an anonymous reviewer for their assistance in evaluating this paper.

References


