Substorm Identification With The WINDMI Magnetosphere - Ionosphere Nonlinear Physics Model

Purbi Adhya, Edmund A. Spencer, and Mayowa Kayode-Adeoye

1University of South Alabama

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Abstract

We investigate the applicability and performance of the plasma physics based WINDMI model to the analysis and identification of substorm onsets. There are several substorm onset criteria that have been developed into event lists, either from auroral observations or from auroral electrojet features. Five of these substorm onset lists are available at the SuperMAG website. We analyze these lists, aggregate them and use the WINDMI model to assess the identified events, emphasizing the loading unloading mechanism in substorm dynamics. The WINDMI model employs eight differential equations utilizing solar wind data measured at L1 by the ACE satellite as input to generate outputs such as the geotail current, the ring current and the field-aligned currents (FACs). In particular, the WINDMI model current output $I_1$ represents the westward auroral electrojet, which is related to the substorm SML index. We analyze a decade of solar wind and substorm onset data from 1998 to 2007, encompassing over 15,000 onsets. Our findings reveal a significant correlation, with WINDMI-derived enhancements in FAC coinciding with the identified substorm events approximately 40\% of the time. This suggests that a substantial proportion of substorms may be attributed to solar wind driving that results in the loading and unloading of energy in the magnetotail.
Substorm Identification With The WINDMI Magnetosphere - Ionosphere Nonlinear Physics Model

P. Adhya\textsuperscript{1}, E. Spencer\textsuperscript{1}, M. Kayode-Adeoye\textsuperscript{1}

\textsuperscript{1}Electrical and Computer Engineering Department, University of South Alabama, Mobile, AL, U.S.A.

Key Points:

- The WINDMI model, a plasma physics-based nonlinear model, is used to analyze 10 years of substorm onsets obtained from the SuperMAG dataset.
- The WINDMI model method of detecting substorm onsets is compared to auroral-image-based and SML-based rules employed by various authors.
- The influence of solar wind parameters in triggering substorm onsets through the energy loading-unloading mechanism is analyzed.

Corresponding author: P. Adhya, purbiadhya@southalabama.edu
Abstract
We investigate the applicability and performance of the plasma physics based WINDMI model to the analysis and identification of substorm onsets. There are several substorm onset criteria that have been developed into event lists, either from auroral observations or from auroral electrojet features. Five of these substorm onset lists are available at the SuperMAG website. We analyze these lists, aggregate them and use the WINDMI model to assess the identified events, emphasizing the loading unloading mechanism in substorm dynamics. The WINDMI model employs eight differential equations utilizing solar wind data measured at L1 by the ACE satellite as input to generate outputs such as the geotail current, the ring current and the field-aligned currents (FACs). In particular, the WINDMI model current output $I_1$ represents the westward auroral electrojet, which is related to the substorm SML index. We analyze a decade of solar wind and substorm onset data from 1998 to 2007, encompassing over 15,000 onsets. Our findings reveal a significant correlation, with WINDMI-derived enhancements in FAC coinciding with the identified substorm events approximately 40% of the time. This suggests that a substantial proportion of substorms may be attributed to solar wind driving that results in the loading and unloading of energy in the magnetotail.

Plain Language Summary
The WINDMI model was designed to study the interactions between the solar wind and the outermost part of Earth’s atmosphere (magnetosphere and ionosphere). This study focuses on analyzing the model’s effectiveness in predicting the onset of substorms, which are disturbances in Earth’s magnetic field at high latitudes. We compared the model’s results in analyzing substorms with studies based on observations of auroral images and ground measurements of magnetic fields at high latitudes, known as SML indices. As input to the model, we used solar wind speed and solar wind magnetic field strength, measured by the ACE spacecraft. From the outcomes of the model, we analyzed the behavior of an electric current in the region near the poles, called the Region 1 (R1) current. Our study found a strong correlation between the behavior of the R1 current and SML indices, demonstrating that the model successfully predicted many substorm onsets. We discovered that some substorms are more influenced by the solar wind than others, and the model could accurately predict these. However, we believe that there are other external factors that play a significant role in triggering substorms.

1 Introduction
Substorms are explosive events in the magnetosphere-ionosphere system that occur typically over a 20 minute to 1-3 hour time scale (Baker et al., 1999). For decades, substorms have been identified by observing changes in auroral brightenings in the auroral oval (Akasofu, 1964; Loomis, 1960; Feldstein et al., 1997). During the earliest days, substorms were studied by observing auroras, and they were interpreted as a large number of energetic particles entering the magnetosphere. Researchers investigated how solar wind energy is transmitted in the magnetosphere (Axford & Hines, 1961). Later, as solar wind data became available, studies on solar wind parameters and their combinations and their influence became more prominent (Akasofu, 1981). Recently, substorms have been identified using the SML index (P. T. Newell & Gjerloev, 2011a, 2011b), which is a generalization of the AL index that can identify substorms.

The events that occur during substorms can be divided into three phases. Firstly, there is a brightening of the auroral arc, followed by the arc translating toward the polar region. In the end, the arc begins to dim, marking the conclusion of the substorm. These same events are also observed in the SML index. Whenever a substorm occurs, the SML index shows a sudden and sharp declination, with the values remaining negative for a certain amount of time before starting to recover. Based on the events ob-
served in auroras and the signature seen in the SML index, substorms can be considered to have three phases. The growth phase is characterized by auroral brightening and a slightly lower value in the SML index. The expansion phase is marked by the sudden intensification of auroral brightening and a sharp declination in the SML index. During the recovery phase, the auroral brightening dims down, and the SML index slowly increases toward a value that was present before the substorm occurred.

The identification of the precise event triggering a substorm is a subject of ongoing research. However, authors such as Frey, Liou, Newell, Forsyth, and Ohtani employed various methods to detect substorm onsets. Frey and Liou utilized polar UVI and IMAGE-FUV data, relying on auroral images for detection. Their method involved searching for poleward-spreading brightenings in the aurora lasting at least 20 minutes, with a minimum 30-minute gap between successive onsets. Newell introduced the SML index, which exhibited an 0.86 correlation with auroral power, rendering it useful for substorm onset detection. According to Newell’s rules, a substorm onset was identified based on specific criteria involving SML index differences. Forsyth’s technique relied on percentile changes in the SML index, detecting substorm onsets when crossing certain thresholds. Ohtani modified Newell’s method particularly for isolated substorms, incorporating a sharp declination of the SML index and introducing a knee-like curvature condition, defined as the double rate of change of the SML index exceeding 1.5 mT/sec².

In this paper, we demonstrate that the field-aligned current often shows enhancement during substorms. Our goal through this paper is to establish a relationship between the field-aligned current $I$ and the SML index and compare our results with the substorm list provided by the five authors (Frey et al., 2004; Liou, 2010; P. Newell & Gjerloev, 2011; Forsyth et al., 2015; Ohtani & Gjerloev, 2020). Since WINDMI uses data from the solar wind, we could infer that the substorms that resulted in enhancements in the field-aligned current $I$ were directly driven by the solar wind but influenced by the internal dynamics of energy storage and release within the magnetosphere. This will help motivate further research on what really causes substorms.

The paper is organized as follows: the second section describes the data used in this study and the methodology adopted to condition the WINDMI model. Additionally, certain features like the trigger function were added to ensure the model’s capability to detect substorms, and conditions were applied to the field-aligned current $I$. The section also outlines how the results were measured against the merged substorm list, derived by combining onset lists from various authors. In this study, the five substorm lists were amalgamated to create a unified list with weighted values indicating the number of authors detecting a particular onset. The results obtained by running the model under these specific conditions are detailed in the results section.

2 Substorm onset detection by WINDMI

This section briefly describes the WINDMI model, the solar wind data and the parameters of the WINDMI model most significant in detecting substorm onsets. It outlines the trigger function introduced into the model, along with the specific conditions under which the model was run.

2.1 The WINDMI model

The WINDMI model (Horton & Doxas, 1996, 1998) is a plasma-physics-based model that takes solar wind data as input. The model utilizes eight nonlinear differential equations to determine the energy flow through various components, including the magnetosphere tail, the neutral plasma sheet, the field lines connecting the tail of the magnetosphere and the ionosphere (Spencer et al., 2007). Several parameters, such as inductance, capacitance, and conductance of the magnetosphere tail and the ionosphere, are
crucial in the model. The values of these parameters have been previously estimated (Mays et al., 2009; Spencer et al., 2007). The model has demonstrated success in predicting and analyzing geomagnetic storm signatures. The eight nonlinear differential equations encompass these parameters, contributing to a comprehensive understanding of the complex interactions within the Earth’s magnetosphere-ionosphere system. The model is given by:

\[
\begin{align*}
L \frac{dI}{dt} &= V_{sw}(t) - V + M \frac{dI_1}{dt} \\
C \frac{dV}{dt} &= I - I_1 - I_{ps} - \Sigma V \\
\frac{3 dp}{dt} &= \frac{\Sigma V^2}{\Omega_{cps}} - u_0 p K_l^{1/2} \theta(I - I_c) - \frac{p V A_{eff}}{\Omega_{cps} B_l L_y} - \frac{3p}{2\tau_E} \\
\frac{dK_l}{dt} &= I_{ps} V - K_l \frac{V}{\tau_l} \\
L_1 \frac{dI_1}{dt} &= V - V_I + M \frac{dI_1}{dt} \\
C_I \frac{dV_{I}}{dt} &= I_I - I_2 - \Sigma_I V_I \\
L_2 \frac{dI_2}{dt} &= V_I - (R_{prc} + R_{A2}) I_2 \\
dW_{rc}/dt &= R_{prc} I_2^2 + \frac{p V A_{eff}}{B_l L_y} - \frac{W_{rc}}{\tau_{rc}}
\end{align*}
\]

where \( V_{SW}(t) \) is the solar wind coupling function. \( L, C, \) and \( \Sigma \) are the inductance, capacitance, and conductances of the magnetosphere tail, and \( L_I, C_I, \) and \( \Sigma_I \) are the inductance, capacitance, and conductances of the ionosphere. Among the eight state variables, \( I \) denotes the geotail current, and \( I_1 \) denotes the region 1 field-aligned current.

Substorm initiation is caused by magnetic reconnections that occurs at the magnetosphere’s tail. As a result of the reconnection, there is a current flow that occurs from the tail of the magnetosphere to the region 1 part of the ionosphere. This increase in the flow of current should also be visible in the variation of the field-aligned current. Thus, this enhancement should also be observable in \( I_1 \), the state variable of the WINDMI model.

### 2.2 Solar wind data

The solar wind data, serving as an input to the WINDMI model, includes solar wind velocity and interplanetary magnetic field data obtained from the ACE satellite. The product of these two parameters undergoes a filtering process, wherein the product is set to zero whenever \( B_z \) is positive. Subsequently, a small threshold voltage of 4kV is added to the product. To account for the time it takes for solar wind to travel from the Lagrange point, where the satellite is located, to the nose of the magnetosphere, the data is time-shifted. This time shift is achieved by dividing the distance from the Lagrange point to the magnetosphere’s nose by a 15-minute time-averaged value of the solar wind velocity.

The rectified \( vB_z \) coupling function is computed using the formula:

\[
vB_z = \begin{cases} V_0 + L_y |v_x| |B_z|, & \text{if } B_z < 0, \\
V_0, & \text{otherwise.}
\end{cases}
\]

where \( V_0 \) is the small threshold voltage that is added to the coupling function \( vB_z \), \( v_x \) is the solar wind velocity along the line joining the centers of the Earth and the Sun, and \( B_z \) is the North-South interplanetary magnetic field.
Figure 1. Illustration of the half-wave rectified $vB_z$ coupling function used as input for the WINDMI model throughout a day. (a) Solar wind velocity along the Sun-Earth line. (b) IMF $B_z$ indicating the North-South magnetic field, with the blue dashed line denoting the 0 value. (c) Rectified input obtained by multiplying solar wind velocity and southward-directed magnetic field, supplemented with a 4kV threshold voltage.

Figure 1 illustrates how the input for the WINDMI model is derived from solar wind data. The plot represents the calculation for a single day of ACE data, generating the input for the model. In Figure 1, Panel (a) displays the magnitude of the solar wind velocity towards Earth in km/sec throughout the day. Panel (b) illustrates the IMF in the north-south direction. To focus on periods potentially causing magnetic reconnection and initiating substorms, only intervals with a primarily southward-directed magnetic field were considered. Periods when the IMF was negative were either discarded or treated as zero during the coupling function calculation. Panel (c) demonstrates the resulting coupling function, representing the product of the solar wind velocity towards Earth and the IMF along the North-South direction when the IMF is directed southwards. Otherwise, it is set to zero, and a 4kV threshold voltage is added.

2.3 Conditions of the WINDMI model and trigger

To detect substorm onsets, a trigger function is used in the WINDMI model (Horton & Doxas, 1996, 1998). The function is defined as a hyperbolic tangent function that reaches 1 whenever $I$ crosses $I_c$, but otherwise remains at zero. The value of $\Delta I$ was kept at 0.1, determining how fast the transition from 0 to 1 occurs.

$$\theta(I - I_c) = \frac{1}{2} \left[ 1 + \tanh \left( \frac{I - I_c}{\Delta I} \right) \right]$$

(10)
where \( I_c \) is a critical current above which energy unloading occurs, and \( \Delta I \) controls the rate of turn on. The overall character (growth, expansion, recovery phases) is strongly controlled by the first three equations of the model.

For each day of substorm onset detection, the WINDMI model was run under two different conditions to identify substorm onsets. Initially, it was run with high critical current values set at \( 2 \times 10^7 \) kA. This setup ensures that the trigger value always remains at 0. Subsequently, the model was run with critical current values set at the 70th percentile of the values obtained from the first run.

Figure 2 illustrates how the trigger function enhances the region 1 current, emulating the triggering of a substorm and resulting in a sudden increase in field-aligned currents. The figure presents results from the WINDMI model for a day, with Panel (a) displaying the geotail current \( I \) in kA, Panel (b) showing the trigger function \( \theta(I - I_c) \), and Panel (c) depicting the region 1 current \( I_1 \) in kA, alongside the trigger function \( \theta \) shaded in green. In Panel (a), which shows the geotail current, a blue dashed line represents the critical current \( I_c \) in kA. The panel demonstrates that the geotail current increases and crosses the threshold current.

To identify substorm onsets from the WINDMI model output, the trigger value was employed, and a threshold was set for the trigger. Whenever the trigger exceeded 0.1, we considered it as the onset time for substorms, as indicated by WINDMI.

**Figure 2.** Figure: Illustration of the WINDMI model’s trigger function \( \theta(I - I_c) \) during a day. (a) Geotail current \( I \) and critical current \( I_c \) (blue dashed line). (b) Trigger function \( \theta \), increasing when \( I \) crosses \( I_c \) and decreasing when below. (c) Changes in region 1 field-aligned current values, with green shading indicating periods of high \( \theta \) values.

### 2.4 Comparison with other models

To compare the results obtained from WINDMI and evaluate their consistency with substorm lists generated by Frey, Liou, Newell, Forsyth, and Ohtani, the triggering times
of the WINDMI model were cross-referenced with a merged list of substorm onsets from the aforementioned authors. To determine the statistics of how often WINDMI’s outputs on substorm onsets align with the substorm list, a 15-minute window was considered. If any substorm onset coincided with the triggering of the WINDMI model within the window, it was considered a positive result.

The SML index serves as a measure of the near-Earth magnetic field in the polar region. It is an enhancement over the AL index, which is the lower bound of the auroral electrojet index. After introduction of the SML index, Gjerloev’s baseline elimination technique (Gjerloev, 2012) involved a three-step process for determining the baseline of a given station and component, incorporating a slowly varying offset or trend mainly attributed to the Earth’s main field and a diurnal component largely associated with the solar quiet current system.

Following the methods devised by Frey, Liou, Newell, Forsyth, and Ohtani, there are five lists containing the onset times of substorms listed on the SuperMAG website. Substorm data were obtained from the SuperMAG website. The five lists were then merged, applying the criterion that if two or more onsets occurred within 15 minutes of each other, their onset times were averaged, and the coincided onset was considered a single substorm onset event. This resulted in a total of over 15,000 substorm onsets over a span of 10 years.

Figure 3 illustrates an example of merging three substorm onsets by different methods into one. The figure displays SML data during January 7, 2000, from 09:00 to 10:30 UT. The SML index value was initially slightly negative at around 09:00 UT, and it gradually decreased starting around 09:20 UT, suggesting the approximate growth phase. Around 09:30 UT, the SML value started to decrease rapidly, exhibiting multiple sudden declinations for about 30 minutes, indicating the expansion phase of the substorm. After 10:00 UT, the SML index value began to recover, signifying the recovery period of the substorm.
Substorm onset is generally classified as the beginning of the expansion phase. Newell’s substorm onset detection technique positions an onset whenever the index shows a sharp change in value $<-45\,\text{nT/sec}$, placing it just before the sharpest decline. On the other hand, Ohtani’s identification method places the substorm onset around the inflection point of the curve, as it relies on identifying a knee-like nature in the SML curve. Forsyth, utilizing changes in percentage threshold, often detects substorm onsets before they are identified by other methods (Forsyth et al., 2015).

3 Results

The results section describes the input and output data for two selected days when the WINDMI model was run under the conditions outlined in the methodology section. The chosen dates are March 17, 1998, and January 07, 2000. The results from the model during these days are presented alongside the substorm list produced by combining the substorm onset lists from the five different authors.

3.1 March 17, 1998

Figure 4. WINDMI output and SML index on March 17, 1998. (a) Solar wind input $v_B$ (black line) and IMF $B_z$ (blue shades) with 0 nT reference line. (b) Geotail current $I$ with critical threshold $I_c$ (blue dashed line). (c) R1 current $I_1$ and trigger function $\theta$ in green. (d) SML indices with substorm onsets as dashed lines, color-coded by the number of concurring methods, and labeled by detecting authors’ abbreviations.

Figure 4 illustrates the WINDMI input and output during March 17, 1998. Panel (a) displays the solar wind input $v_B$ in kV throughout the day, including the IMF $B_z$ in nT. The horizontal blue dashed line in the middle represents the zero magnetic field value. The shaded region above the dashed line represents northward, and the region be-
low the line represents southward IMF, contributing to the coupling function \( v_B \). Panel (b) shows the geotail current \( I \) when the model is run with the input from panel (a). The critical current during the day, obtained from running the model with a high critical current \( I_c = 2 \times 10^7 \) kA, is depicted as a blue dashed line. The resulting geotail current was used, and the 75th percentile of the current was employed for the second run of the model. The critical current is shown as a blue dashed line in the panel. The current is observed to have increased above the critical current seven times throughout the day. Panel (c) presents the resulting region 1 field-aligned current \( I_1 \) during the second run of the model. The periods when the trigger was on are indicated as regions shaded in green. When the trigger turns on, \( I_1 \) exhibits a knee-like bend in the current.

The knee-like shape is especially visible during the presumed substorm onsets near 01:30, 11, and 22 UT. The vertical dotted lines indicate the substorm onsets detected by the different authors mentioned previously. Throughout the day, it is observed that the enhancements in the currents and the knee-like bend in the current, approximately representing substorm onsets, coincide with the onsets from the substorm list for the two substorms occurring near 01:30 and 22 UT. The enhancements roughly align with the onsets near 03 and 11 UT. Conversely, no enhancements in currents were observed during the substorm onset near 07 UT. Incidentally, the substorm onset was detected by all four methods of substorm onset detection that were active during that period. Panel (d) displays the SML indices, and the vertical dashed lines with two-letter labels representing the authors’ names associated with the methods used to detect the onsets show the substorm onset times. If more authors detected the same onset, the colors of the lines are reddish. An onset detected by only one method is shown in yellow. In the panel showing the R1 current, it is evident that the substorm onset at 22 UT is associated with the highest current enhancement and is also declared as a substorm onset by the four different techniques. Additionally, some enhancements in R1 current \( I_1 \) were not associated with any substorm occurrence, for example, the enhancement around 13 UT. During the two-hour period from 10 to 12 UT, there were two enhancements, but only one substorm signature was observed on the SML index.

### 3.2 January 07, 2000

Figure 4 displays WINDMI output during the day of January 07, 2000. On that day, Panel (a) illustrates that the solar wind input was sporadic and significant for most of the day, with long periods when the IMF was notable and southward. Panels (b) and (c) depict the resulting geotail and region 1 field-aligned current derived from the differential equations of the WINDMI model. Panel (b) demonstrates that the geotail current \( I \) exceeded the critical threshold current \( I_c \) significantly four times, resulting in four trigger events seen in Panel (c). Panel (d) shows all the detected substorms during the day, displaying the SML index, indicating that several substorms were detected by Ohtani and Forsyth. However, not all methods agreed on the onset times of the substorms.

On the other hand, the R1 current shows four enhancements resulting from the trigger events. During the trigger events and corresponding current enhancements that occurred at 04, 16, and 18 UT, there were substorm signatures on SML indices. The event that occurred at 16 UT was detected by all four active methods during the period. The enhancements that occurred at 18 UT and 04 UT were detected by three and one methods, respectively. On the other hand, there is a major enhancement that occurred between 11 to 12 UT when no substorm signature is seen on the SML index. However, there was a major substorm that occurred near 09 UT that was detected by all four methods. There was a slight geotail current enhancement during the period, but the enhancement didn’t surpass the critical current during the day and hence couldn’t trigger a substorm. Similar events occurred during substorm events that were detected from the SML indices at 01, 02, 14, and 21 UT. During these events, there were enhancements in the geotail.
Figure 5. WINDMI output and SML index on January 7, 2000. (a) Solar wind input $v_B$ (black line) and IMF $B_z$ (blue shades) with 0 nT reference line. (b) Geotail current $I$ with critical threshold $I_c$ (blue dashed line). (c) R1 current $I_1$ and trigger function $\theta$ in green. (d) SML indices with substorm onsets as dashed lines, color-coded by the number of concurring methods, and labeled by detecting authors’ abbreviations.

current but not enough to cause a trigger event. Additionally, there were slight enhancements near 08 UT or 23 UT when there were no substorms in proximity in time.

Following the method described in section 2.3 for the comparison of methods with the results from WINDMI, each substorm from the substorm list was compared with the WINDMI model output $I_1$ to analyze if there were trigger events associated with the onsets or not. For that, 15-minute windows were considered around the substorm events to check for trigger events. The resulting data is tabulated in Table 1, which shows that 40% of the time WINDMI is identifying substorm onsets detected by the five methods. Since only Frey or Liou’s method was active at a single point in time during the chosen range of years, the two methods were combined into a single row representing the methods that used auroral images to detect substorm onsets. It can be observed from the data in the table that the triggered events by WINDMI mostly coincide with onsets detected by Newell and Forsyth and coincide least with the onsets detected by Ohtani and Frey/Liou. The coincidence of WINDMI’s outputs with the five methods, divided into four categories categorized as Frey/Liou, Newell, Forsyth, and Ohtani, show 39%, 45%, 40%, and 36% coincidence with WINDMI.

4 Discussion

The analysis of substorms over a range of 10 years and their coincidence with WINDMI current enhancements demonstrates that using only solar wind data as input allows un-
Table 1. Comparison table for other methods against WINDMI.

<table>
<thead>
<tr>
<th>Methods</th>
<th>WINDMI (detected)</th>
<th>WINDMI (not detected)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frey/Liou</td>
<td>896 (39%)</td>
<td>1416 (61%)</td>
<td>2312</td>
</tr>
<tr>
<td>Newell</td>
<td>2109 (45%)</td>
<td>2558 (55%)</td>
<td>4667</td>
</tr>
<tr>
<td>Forsyth</td>
<td>2230 (40%)</td>
<td>3369 (60%)</td>
<td>5599</td>
</tr>
<tr>
<td>Ohtani</td>
<td>917 (36%)</td>
<td>1650 (64%)</td>
<td>2567</td>
</tr>
</tbody>
</table>

Understanding the flow of energy and currents through the magnetosphere and ionosphere. The increased energy from solar wind manifests as enhanced current, often considered the result of substorm triggering within the magnetosphere. This enhanced current, along with other factors, significantly contributes to the sudden decrease in the SML index. The study aimed to analyze WINDMI results against the signatures on the SML index, manifested as five substorm lists by different methods. The goal was to measure WINDMI’s performance in detecting substorm onsets.

Additionally, since only solar wind data was used as input, the positive results may indicate that the detected substorms were directly driven by solar wind with less contribution from other factors.

To emulate the triggering of substorms at the magnetotail resulting in an increase and sudden release of energy at the geotail, the $\theta(I-I_c)$ function was added to the WINDMI equations. This not only replicated conditions during substorms but also mimicked the knee-like nature in the SML index that occurs during substorms (Ohtani & Gjerloev, 2020).

The 15-minute window used to measure the results of WINDMI against the methods followed the window used to merge substorm onsets if they occurred within the same timeframe. This window was chosen for consistency, claiming that a substorm might have a questionable onset time, and the error window is 15 minutes according to the study’s assumptions.

Colors of the substorm onsets shown in vertical lines, ranging from yellow to red, were added to assign weights to the detected onsets. If one substorm onset was detected by all four active methods during the time, they were considered significant compared to the others. The two selected days were chosen to showcase different types of detected onsets, meaning onsets detected by four, three, two, or one method, in decreasing order of assumed importance.

For this study, the parameters of the model were kept at nominal values as shown in table 1 of (Mays et al., 2009). Furthermore, recent studies on parameter variations by 20% revealed that the model results don’t change considerably until a 10% change, especially the changes due to variations in inductance (L), which are very insignificant. However, significant changes in capacitance (C) cause variations in current values resulting from the model, altering the energy flow pattern, and varying the periods of enhancements significantly (Kayode-Adeoye, 2023).

Moreover, the values of $I_c$ fixed for each day could be considered a variable parameter representing the threshold of energy and current that should be surpassed during the triggering of substorms. As the value was kept fixed, the geotail current often approached but didn’t surpass it, failing to trigger substorms. Keeping $I_c$ variable and finding its dependence on other parameters is the main focus in the future, with ongoing studies on how the values of parameters affect the model.

Many WINDMI enhancements didn’t transcend into substorms even though there was clear indication of energy storage in the geotail. This can be addressed in future by
making the critical current $I_c$ a varying parameter in time. Several substorm onset times were also seen to shift initiation times compared to the substorm onset list by the authors. This might also result from a variable threshold; for example, if the energy storage threshold was lower during the substorm on January 07, 2000, around 10 UT, it could show a modified result if the threshold was low during that period. The slight enhancement in the current during that time could manifest into a substorm, contributing to the intense nature and prolonged recovery phase of the substorm.

5 Summary and Conclusions

In this work, we are trying to refine our approach to detect substorm onsets using the nonlinear physics model WINDMI, which consists of eight differential equations describing the energy flow through the magnetosphere-ionosphere system. Our goal in this paper was to utilize this model to determine onsets based on the flow of field-aligned currents, which often exhibit significant variations and enhancements during substorms. To achieve this, we used the WINDMI variables $\theta(I-I_c)$ and $I_1$, designed to identify specific enhancements in region 1 field-aligned current resulting from the increased geotail current triggered by substorms. These enhancements were then compared against a substorm list obtained by merging lists from five different authors, employing a 15-minute window for merging. Similarly, 15-minute windows were used to verify whether onsets detected by WINDMI were also identified by other detection methods. The resulting statistics, as shown in Table 1, suggest that positive results from WINDMI can be associated with substorms significantly influenced by solar wind.

The two selected days discussed in the paper, namely March 17, 1998, and January 07, 2000, reveal frequent enhancements in the region 1 field-aligned current ($I_1$) during substorms, as indicated by the substorm lists. These enhancements are triggered by the activation of the $\theta$ function. The critical current ($I_c$) was held constant from day to day and optimized to a level where the trigger would activate only when the geotail current value exceeded a specific daily average. The primary reason the model struggles to predict substorms are that it can only do so when substorms are solely driven by solar wind and can be attributable to the dynamics of energy loading and unloading. Additionally, the critical current value needs to be somewhat variable to enable the enhancements corresponding to onset that generate substorms.

The final statistics demonstrate that the WINDMI model can predict substorms 40% of the time when provided with solar wind data. This capability proves valuable for approximating substorm times, estimating substorm intensities, and increases our understanding of substorm occurrences primarily attributable to the energy loading - unloading mechanism.

6 Open Research

The solar wind data utilized in this study were acquired from https://cdaweb.gsfc.nasa.gov/index.html. The substorm lists used were obtained from https://supermag.jhuapl.edu/substorms/. MATLAB 2023b was the software employed to execute the WINDMI codes, with the Simulink library being specifically utilized to model the WINDMI equations. The dataset generated from this study is available for download from the following link: https://zenodo.org/records/11061738.

Acknowledgments

The authors express their gratitude to various contributors for their substorm timing lists, including the SOPHIE technique by Forsyth et al. (2015), and techniques by Frey et al. (2004); Frey and Mende (2006), Liou (2010), the Newell and Gjerloev technique (P. Newell & Gjerloev, 2011), and the Ohtani and Gjerloev technique (Ohtani & Gjerloev, 2020).
They also acknowledge the SuperMAG collaboration (Gjerloev, 2012) and the NASA/GSFC’s Space Physics Data Facility for providing open-source access to the relevant data. This research received support from NSF Grant 2134451, and the authors extend their thanks to the Department of Electrical and Computer Engineering at the University of South Alabama for their cooperation.

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Substorm Identification With The WINDMI 
Magnetosphere - Ionosphere Nonlinear Physics Model

P. Adhya\textsuperscript{1}, E. Spencer\textsuperscript{1}, M. Kayode-Adeoye\textsuperscript{1}

\textsuperscript{1}Electrical and Computer Engineering Department, University of South Alabama, Mobile, AL, U.S.A.

Key Points:

- The WINDMI model, a plasma physics-based nonlinear model, is used to analyze 10 years of substorm onsets obtained from the SuperMAG dataset.
- The WINDMI model method of detecting substorm onsets is compared to auroral-image-based and SML-based rules employed by various authors.
- The influence of solar wind parameters in triggering substorm onsets through the energy loading-unloading mechanism is analyzed.

Corresponding author: P. Adhya, purbiadhya@southalabama.edu
Abstract
We investigate the applicability and performance of the plasma physics based WINDMI model to the analysis and identification of substorm onsets. There are several substorm onset criteria that have been developed into event lists, either from auroral observations or from auroral electrojet features. Five of these substorm onset lists are available at the SuperMAG website. We analyze these lists, aggregate them and use the WINDMI model to assess the identified events, emphasizing the loading unloading mechanism in substorm dynamics. The WINDMI model employs eight differential equations utilizing solar wind data measured at L1 by the ACE satellite as input to generate outputs such as the geotail current, the ring current and the field-aligned currents (FACs). In particular, the WINDMI model current output $I_1$ represents the westward auroral electrojet, which is related to the substorm SML index. We analyze a decade of solar wind and substorm onset data from 1998 to 2007, encompassing over 15,000 onsets. Our findings reveal a significant correlation, with WINDMI-derived enhancements in FAC coinciding with the identified substorm events approximately 40% of the time. This suggests that a substantial proportion of substorms may be attributed to solar wind driving that results in the loading and unloading of energy in the magnetotail.

Plain Language Summary
The WINDMI model was designed to study the interactions between the solar wind and the outermost part of Earth's atmosphere (magnetosphere and ionosphere). This study focuses on analyzing the model's effectiveness in predicting the onset of substorms, which are disturbances in Earth's magnetic field at high latitudes. We compared the model's results in analyzing substorms with studies based on observations of auroral images and ground measurements of magnetic fields at high latitudes, known as SML indices. As input to the model, we used solar wind speed and solar wind magnetic field strength, measured by the ACE spacecraft. From the outcomes of the model, we analyzed the behavior of an electric current in the region near the poles, called the Region 1 (R1) current. Our study found a strong correlation between the behavior of the R1 current and SML indices, demonstrating that the model successfully predicted many substorm onsets. We discovered that some substorms are more influenced by the solar wind than others, and the model could accurately predict these. However, we believe that there are other external factors that play a significant role in triggering substorms.

1 Introduction
Substorms are explosive events in the magnetosphere-ionosphere system that occur typically over a 20 minute to 1-3 hour time scale (Baker et al., 1999). For decades, substorms have been identified by observing changes in auroral brightenings in the auroral oval (Akasofu, 1964; Loomis, 1960; Feldstein et al., 1997). During the earliest days, substorms were studied by observing auroras, and they were interpreted as a large number of energetic particles entering the magnetosphere. Researchers investigated how solar wind energy is transmitted in the magnetosphere (Axford & Hines, 1961). Later, as solar wind data became available, studies on solar wind parameters and their combinations and their influence became more prominent (Akasofu, 1981). Recently, substorms have been identified using the SML index (P. T. Newell & Gjerloev, 2011a, 2011b), which is a generalization of the AL index that can identify substorms.

The events that occur during substorms can be divided into three phases. Firstly, there is a brightening of the auroral arc, followed by the arc translating toward the polar region. In the end, the arc begins to dim, marking the conclusion of the substorm. These same events are also observed in the SML index. Whenever a substorm occurs, the SML index shows a sudden and sharp declination, with the values remaining negative for a certain amount of time before starting to recover.
served in auroras and the signature seen in the SML index, substorms can be considered to have three phases. The growth phase is characterized by auroral brightening and a slightly lower value in the SML index. The expansion phase is marked by the sudden intensification of auroral brightening and a sharp declination in the SML index. During the recovery phase, the auroral brightening dims down, and the SML index slowly increases toward a value that was present before the substorm occurred.

The identification of the precise event triggering a substorm is a subject of ongoing research. However, authors such as Frey, Liou, Newell, Forsyth, and Ohtani employed various methods to detect substorm onsets. Frey and Liou utilized polar UVI and IMAGE-FUV data, relying on auroral images for detection. Their method involved searching for poleward-spreading brightenings in the aurora lasting at least 20 minutes, with a minimum 30-minute gap between successive onsets. Newell introduced the SML index, which exhibited an 0.86 correlation with auroral power, rendering it useful for substorm onset detection. According to Newell’s rules, a substorm onset was identified based on specific criteria involving SML index differences. Forsyth’s technique relied on percentile changes in the SML index, detecting substorm onsets when crossing certain thresholds. Ohtani modified Newell’s method particularly for isolated substorms, incorporating a sharp declination of the SML index and introducing a knee-like curvature condition, defined as the double rate of change of the SML index exceeding 1.5nT/sec².

In this paper, we demonstrate that the field-aligned current often shows enhancement during substorms. Our goal through this paper is to establish a relationship between the field-aligned current \(I_1\) and the SML index and compare our results with the substorm list provided by the five authors (Frey et al., 2004; Liou, 2010; P. Newell & Gjerloev, 2011; Forsyth et al., 2015; Ohtani & Gjerloev, 2020). Since WINDMI uses data from the solar wind, we could infer that the substorms that resulted in enhancements in the field-aligned current \(I_1\) were directly driven by the solar wind but influenced by the internal dynamics of energy storage and release within the magnetosphere. This will help motivate further research on what really causes substorms.

The paper is organized as follows: the second section describes the data used in this study and the methodology adopted to condition the WINDMI model. Additionally, certain features like the trigger function were added to ensure the model’s capability to detect substorms, and conditions were applied to the field-aligned current \(I_1\). The section also outlines how the results were measured against the merged substorm list, derived by combining onset lists from various authors. In this study, the five substorm lists were amalgamated to create a unified list with weighted values indicating the number of authors detecting a particular onset. The results obtained by running the model under these specific conditions are detailed in the results section.

2 Substorm onset detection by WINDMI

This section briefly describes the WINDMI model, the solar wind data and the parameters of the WINDMI model most significant in detecting substorm onsets. It outlines the trigger function introduced into the model, along with the specific conditions under which the model was run.

2.1 The WINDMI model

The WINDMI model (Horton & Doxas, 1996, 1998) is a plasma-physics-based model that takes solar wind data as input. The model utilizes eight nonlinear differential equations to determine the energy flow through various components, including the magnetosphere tail, the neutral plasma sheet, the field lines connecting the tail of the magnetosphere and the ionosphere (Spencer et al., 2007). Several parameters, such as inductance, capacitance, and conductance of the magnetosphere tail and the ionosphere, are
crucial in the model. The values of these parameters have been previously estimated (Mays et al., 2009; Spencer et al., 2007). The model has demonstrated success in predicting and analyzing geomagnetic storm signatures. The eight nonlinear differential equations encompass these parameters, contributing to a comprehensive understanding of the complex interactions within the Earth’s magnetosphere-ionosphere system. The model is given by:

\[
\frac{dI}{dt} = V_{SW}(t) - V + M \frac{dI_1}{dt} \\
C \frac{dV}{dt} = I - I_1 - I_{ps} - \Sigma V \\
\frac{3 \rho}{2} \frac{dp}{dt} = \frac{\Sigma V^2}{\Omega_{cps}} - u_0 p K^{1/2}\theta(I - I_c) - \frac{p V A_{eff}}{\Omega_{cps} B_{tr} L_y} - \frac{3 \rho}{2 \tau_E} \\
\frac{dK}{dt} = I_{ps} V - K \frac{\rho}{\tau_E} \\
L_{I} \frac{dI_1}{dt} = V - V_I + M \frac{dI_1}{dt} \\
C_{I} \frac{dV_{I}}{dt} = I_1 - I_2 - \Sigma_{I} V_I \\
L_{2} \frac{dI_2}{dt} = V_I - (R_{prc} + R_{A2}) I_2 \\
\frac{dW_{rc}}{dt} = R_{prc} I_2^2 + \frac{p V A_{eff}}{B_{tr} L_y} - \frac{W_{rc}}{\tau_{rc}}
\]

where \(V_{SW}(t)\) is the solar wind coupling function. \(L, C, \) and \(\Sigma\) are the inductance, capacitance, and conductances of the magnetosphere tail, and \(L_{I}, C_{I}, \) and \(\Sigma_{I}\) are the inductance, capacitance, and conductances of the ionosphere. Among the eight state variables, \(I\) denotes the geotail current, and \(I_1\) denotes the region 1 field-aligned current.

Substorm initiation is caused by magnetic reconnections that occur at the magnetosphere’s tail. As a result of the reconnection, there is a current flow that occurs from the tail of the magnetosphere to the region 1 part of the ionosphere. This increase in the flow of current should also be visible in the variation of the field-aligned current. Thus, this enhancement should also be observable in \(I_1\), the state variable of the WINDMI model.

### 2.2 Solar wind data

The solar wind data, serving as an input to the WINDMI model, includes solar wind velocity and interplanetary magnetic field data obtained from the ACE satellite. The product of these two parameters undergoes a filtering process, wherein the product is set to zero whenever \(B_z\) is positive. Subsequently, a small threshold voltage of 4kV is added to the product. To account for the time it takes for solar wind to travel from the Lagrange point, where the satellite is located, to the nose of the magnetosphere, the data is time-shifted. This time shift is achieved by dividing the distance from the Lagrange point to the magnetosphere’s nose by a 15-minute time-averaged value of the solar wind velocity.

The rectified \(vB_x\) coupling function is computed using the formula:

\[
vB_x = \begin{cases} 
V_0 + L_y |v_x||B_z|, & \text{if } B_z < 0, \\
V_0, & \text{otherwise.}
\end{cases}
\]

where \(V_0\) is the small threshold voltage that is added to the coupling function \(vB_x, V_x\) is the solar wind velocity along the line joining the centers of the Earth and the Sun, and \(B_z\) is the North-South interplanetary magnetic field.
Figure 1 illustrates how the input for the WINDMI model is derived from solar wind data. The plot represents the calculation for a single day of ACE data, generating the input for the model. In Figure 1, Panel (a) displays the magnitude of the solar wind velocity towards Earth in km/sec throughout the day. Panel (b) illustrates the IMF in the north-south direction. To focus on periods potentially causing magnetic reconnection and initiating substorms, only intervals with a primarily southward-directed magnetic field were considered. Periods when the IMF was negative were either discarded or treated as zero during the coupling function calculation. Panel (c) demonstrates the resulting coupling function, representing the product of the solar wind velocity towards Earth and the IMF along the North-South direction when the IMF is directed southwards. Otherwise, it is set to zero, and a 4kV threshold voltage is added.

2.3 Conditions of the WINDMI model and trigger

To detect substorm onsets, a trigger function is used in the WINDMI model (Horton & Doxas, 1996, 1998). The function is defined as a hyperbolic tangent function that reaches 1 whenever $I$ crosses $I_c$, but otherwise remains at zero. The value of $\Delta I$ was kept at 0.1, determining how fast the transition from 0 to 1 occurs.

$$\theta(I - I_c) = \frac{1}{2} \left[ 1 + \tanh \left( \frac{I - I_c}{\Delta I} \right) \right]$$  \hspace{1cm} (10)
where $I_c$ is a critical current above which energy unloading occurs, and $\Delta I$ controls the rate of turn on. The overall character (growth, expansion, recovery phases) is strongly controlled by the first three equations of the model.

For each day of substorm onset detection, the WINDMI model was run under two different conditions to identify substorm onsets. Initially, it was run with high critical current values set at $2 \times 10^7$ kA. This setup ensures that the trigger value always remains at 0. Subsequently, the model was run with critical current values set at the 70th percentile of the values obtained from the first run.

Figure 2 illustrates how the trigger function enhances the region 1 current, emulating the triggering of a substorm and resulting in a sudden increase in field-aligned currents. The figure presents results from the WINDMI model for a day, with Panel (a) displaying the geotail current $I$ in kA, Panel (b) showing the trigger function $\theta(I - I_c)$, and Panel (c) depicting the region 1 current $I_1$ in kA, alongside the trigger function $\theta$ shaded in green. In Panel (a), which shows the geotail current, a blue dashed line represents the critical current $I_c$ in kA. The panel demonstrates that the geotail current increases and crosses the threshold current.

To identify substorm onsets from the WINDMI model output, the trigger value was employed, and a threshold was set for the trigger. Whenever the trigger exceeded 0.1, we considered it as the onset time for substorms, as indicated by WINDMI.

**Figure 2.** Figure: Illustration of the WINDMI model’s trigger function $\theta(I - I_c)$ during a day. (a) Geotail current $I$ and critical current $I_c$ (blue dashed line). (b) Trigger function $\theta$, increasing when $I$ crosses $I_c$ and decreasing when below. (c) Changes in region 1 field-aligned current values, with green shading indicating periods of high $\theta$ values.

### 2.4 Comparison with other models

To compare the results obtained from WINDMI and evaluate their consistency with substorm lists generated by Frey, Liou, Newell, Forsyth, and Ohtani, the triggering times
Figure 3. Example of merging substorm onset times obtained from different substorm lists from the SuperMAG website. The figure displays a 1.5-hour period. Both panels show the SML index in nT. Panel (a) features three dotted yellow vertical lines within approximately 5 minutes of each other, corresponding to Forsyth, Ohtani, and Newell (from left to right). Panel (b) illustrates the merged substorm onset as one dotted vertical line at the average of the three times shown in Panel (a).

of the WINDMI model were cross-referenced with a merged list of substorm onsets from the aforementioned authors. To determine the statistics of how often WINDMI’s outputs on substorm onsets align with the substorm list, a 15-minute window was considered. If any substorm onset coincided with the triggering of the WINDMI model within the window, it was considered a positive result.

The SML index serves as a measure of the near-Earth magnetic field in the polar region. It is an enhancement over the AL index, which is the lower bound of the auroral electrojet index. After introduction of the SML index, Gjerloev’s baseline elimination technique (Gjerloev, 2012) involved a three-step process for determining the baseline of a given station and component, incorporating a slowly varying offset or trend mainly attributed to the Earth’s main field and a diurnal component largely associated with the solar quiet current system.

Following the methods devised by Frey, Liou, Newell, Forsyth, and Ohtani, there are five lists containing the onset times of substorms listed on the SuperMAG website. Substorm data were obtained from the SuperMAG website. The five lists were then merged, applying the criterion that if two or more onsets occurred within 15 minutes of each other, their onset times were averaged, and the coincided onset was considered a single substorm onset event. This resulted in a total of over 15,000 substorm onsets over a span of 10 years.

Figure 3 illustrates an example of merging three substorm onsets by different methods into one. The figure displays SML data during January 7, 2000, from 09:00 to 10:30 UT. The SML index value was initially slightly negative at around 09:00 UT, and it gradually decreased starting around 09:20 UT, suggesting the approximate growth phase. Around 09:30 UT, the SML value started to decrease rapidly, exhibiting multiple sudden declinations for about 30 minutes, indicating the expansion phase of the substorm. After 10:00 UT, the SML index value began to recover, signifying the recovery period of the substorm.
Substorm onset is generally classified as the beginning of the expansion phase. Newell’s substorm onset detection technique positions an onset whenever the index shows a sharp change in value $< -45 \text{nT/ sec}$, placing it just before the sharpest decline. On the other hand, Ohtani’s identification method places the substorm onset around the inflection point of the curve, as it relies on identifying a knee-like nature in the SML curve. Forsyth, utilizing changes in percentage threshold, often detects substorm onsets before they are identified by other methods (Forsyth et al., 2015).

3 Results

The results section describes the input and output data for two selected days when the WINDMI model was run under the conditions outlined in the methodology section. The chosen dates are March 17, 1998, and January 07, 2000. The results from the model during these days are presented alongside the substorm list produced by combining the substorm onset lists from the five different authors.

3.1 March 17, 1998

![WINDMI output Mar 17, 1998](image)

Figure 4. WINDMI output and SML index on March 17, 1998. (a) Solar wind input $vB_s$ (black line) and IMF $B_z$ (blue shades) with 0 nT reference line. (b) Geotail current $I_c$ with critical threshold $I_c$ (blue dashed line). (c) R1 current $I_1$ and trigger function $\theta$ in green. (d) SML indices with substorm onsets as dashed lines, color-coded by the number of concurring methods, and labeled by detecting authors’ abbreviations.

Figure 4 illustrates the WINDMI input and output during March 17, 1998. Panel (a) displays the solar wind input $vB_s$ in kV throughout the day, including the IMF $B_z$ in nT. The horizontal blue dashed line in the middle represents the zero magnetic field value. The shaded region above the dashed line represents northward, and the region be-
low the line represents southward IMF, contributing to the coupling function $vB_z$. Panel (b) shows the geotail current $I$ when the model is run with the input from panel (a). The critical current during the day, obtained from running the model with a high critical current ($I_c = 2 \times 10^7$ kA), is depicted as a blue dashed line. The resulting geotail current was used, and the 75th percentile of the current was employed for the second run of the model. The critical current is shown as a blue dashed line in the panel. The current is observed to have increased above the critical current seven times throughout the day. Panel (c) presents the resulting region 1 field-aligned current $I_1$ during the second run of the model. The periods when the trigger was on are indicated as regions shaded in green. When the trigger turns on, $I_1$ exhibits a knee-like bend in the current.

The knee-like shape is especially visible during the presumed substorm onsets near 01:30, 11, and 22 UT. The vertical dotted lines indicate the substorm onsets detected by the different authors mentioned previously. Throughout the day, it is observed that the enhancements in the currents and the knee-like bend in the current, approximately representing substorm onsets, coincide with the onsets from the substorm list for the two substorms occurring near 01:30 and 22 UT. The enhancements roughly align with the onsets near 03 and 11 UT. Conversely, no enhancements in currents were observed during the substorm onset near 07 UT. Incidentally, the substorm onset was detected by all four methods of substorm onset detection that were active during that period. Panel (d) displays the SML indices, and the vertical dashed lines with two-letter labels representing the authors’ names associated with the methods used to detect the onsets show the substorm onset times. If more authors detected the same onset, the colors of the lines are reddish. An onset detected by only one method is shown in yellow. In the panel showing the R1 current, it is evident that the substorm onset at 22 UT is associated with the highest current enhancement and is also declared as a substorm onset by the four different techniques. Additionally, some enhancements in R1 current $I_1$ were not associated with any substorm occurrence, for example, the enhancement around 13 UT. During the two-hour period from 10 to 12 UT, there were two enhancements, but only one substorm signature was observed on the SML index.

### 3.2 January 07, 2000

Figure 4 displays WINDMI output during the day of January 07, 2000. On that day, Panel (a) illustrates that the solar wind input was sporadic and significant for most of the day, with long periods when the IMF was notable and southward. Panels (b) and (c) depict the resulting geotail and region 1 field-aligned current derived from the differential equations of the WINDMI model. Panel (b) demonstrates that the geotail current $I$ exceeded the critical threshold current $I_c$ significantly four times, resulting in four trigger events seen in Panel (c). Panel (d) shows all the detected substorms during the day, displaying the SML index, indicating that several substorms were detected by Ohtani and Forsyth. However, not all methods agreed on the onset times of the substorms.

On the other hand, the R1 current shows four enhancements resulting from the trigger events. During the trigger events and corresponding current enhancements that occurred at 04, 16, and 18 UT, there were substorm signatures on SML indices. The event that occurred at 16 UT was detected by all four active methods during the period. The enhancements that occurred at 18 UT and 04 UT were detected by three and one methods, respectively. On the other hand, there is a major enhancement that occurred between 11 to 12 UT when no substorm signature is seen on the SML index. However, there was a major substorm that occurred near 09 UT that was detected by all four methods. There was a slight geotail current enhancement during the period, but the enhancement didn’t surpass the critical current during the day and hence couldn’t trigger a substorm. Similar events occurred during substorm events that were detected from the SML indices at 01, 02, 14, and 21 UT. During these events, there were enhancements in the geotail...
Figure 5. WINDMI output and SML index on January 7, 2000. (a) Solar wind input $v_B$ (black line) and IMF $B_z$ (blue shades) with 0 nT reference line. (b) Geotail current $I$ with critical threshold $I_c$ (blue dashed line). (c) R1 current $I_1$ and trigger function $\theta$ in green. (d) SML indices with substorm onsets as dashed lines, color-coded by the number of concurring methods, and labeled by detecting authors’ abbreviations.

Current but not enough to cause a trigger event. Additionally, there were slight enhancements near 08 UT or 23 UT when there were no substorms in proximity in time.

Following the method described in section 2.3 for the comparison of methods with the results from WINDMI, each substorm from the substorm list was compared with the WINDMI model output $I_1$ to analyze if there were trigger events associated with the onsets or not. For that, 15-minute windows were considered around the substorm events to check for trigger events. The resulting data is tabulated in Table 1, which shows that 40% of the time WINDMI is identifying substorm onsets detected by the five methods. Since only Frey or Liou’s method was active at a single point in time during the chosen range of years, the two methods were combined into a single row representing the methods that used auroral images to detect substorm onsets. It can be observed from the data in the table that the triggered events by WINDMI mostly coincide with onsets detected by Newell and Forsyth and coincide least with the onsets detected by Ohtani and Frey/Liou. The coincidence of WINDMI’s outputs with the five methods, divided into four categories categorized as Frey/Liou, Newell, Forsyth, and Ohtani, show 39%, 45%, 40%, and 36% coincidence with WINDMI.

4 Discussion

The analysis of substorms over a range of 10 years and their coincidence with WINDMI current enhancements demonstrates that using only solar wind data as input allows un-
Table 1. Comparison table for other methods against WINDMI.

<table>
<thead>
<tr>
<th>Methods</th>
<th>WINDMI (detected)</th>
<th>WINDMI (not detected)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frey/Liou</td>
<td>896 (39%)</td>
<td>1416 (61%)</td>
<td>2312</td>
</tr>
<tr>
<td>Newell</td>
<td>2109 (45%)</td>
<td>2558 (55%)</td>
<td>4667</td>
</tr>
<tr>
<td>Forsyth</td>
<td>2230 (40%)</td>
<td>3369 (60%)</td>
<td>5599</td>
</tr>
<tr>
<td>Ohtani</td>
<td>917 (36%)</td>
<td>1650 (64%)</td>
<td>2567</td>
</tr>
</tbody>
</table>

Understanding the flow of energy and currents through the magnetosphere and ionosphere.

The increased energy from solar wind manifests as enhanced current, often considered the result of substorm triggering within the magnetosphere. This enhanced current, along with other factors, significantly contributes to the sudden decrease in the SML index.

The study aimed to analyze WINDMI results against the signatures on the SML index, manifested as five substorm lists by different methods. The goal was to measure WINDMI’s performance in detecting substorm onsets.

Additionally, since only solar wind data was used as input, the positive results may indicate that the detected substorms were directly driven by solar wind with less contribution from other factors.

To emulate the triggering of substorms at the magnetotail resulting in an increase and sudden release of energy at the geotail, the \( \theta(I - I_c) \) function was added to the WINDMI equations. This not only replicated conditions during substorms but also mimicked the knee-like nature in the SML index that occurs during substorms (Ohtani & Gjerloev, 2020).

The 15-minute window used to measure the results of WINDMI against the methods followed the window used to merge substorm onsets if they occurred within the same timeframe. This window was chosen for consistency, claiming that a substorm might have a questionable onset time, and the error window is 15 minutes according to the study’s assumptions.

Colors of the substorm onsets shown in vertical lines, ranging from yellow to red, were added to assign weights to the detected onsets. If one substorm onset was detected by all four active methods during the time, they were considered significant compared to the others. The two selected days were chosen to showcase different types of detected onsets, meaning onsets detected by four, three, two, or one method, in decreasing order of assumed importance.

For this study, the parameters of the model were kept at nominal values as shown in table 1 of (Mays et al., 2009). Furthermore, recent studies on parameter variations by 20% revealed that the model results don’t change considerably until a 10% change, especially the changes due to variations in inductance (L), which are very insignificant. However, significant changes in capacitance (C) cause variations in current values resulting from the model, altering the energy flow pattern, and varying the periods of enhancements significantly (Kayode-Adeoye, 2023).

Moreover, the values of \( I_c \) fixed for each day could be considered a variable parameter representing the threshold of energy and current that should be surpassed during the triggering of substorms. As the value was kept fixed, the geotail current often approached but didn’t surpass it, failing to trigger substorms. Keeping \( I_c \) variable and finding its dependence on other parameters is the main focus in the future, with ongoing studies on how the values of parameters affect the model.

Many WINDMI enhancements didn’t transcend into substorms even though there was clear indication of energy storage in the geotail. This can be addressed in future by...
making the critical current $I_c$ a varying parameter in time. Several substorm onset times were also seen to shift initiation times compared to the substorm onset list by the authors. This might also result from a variable threshold; for example, if the energy storage threshold was lower during the substorm on January 07, 2000, around 10 UT, it could show a modified result if the threshold was low during that period. The slight enhancement in the current during that time could manifest into a substorm, contributing to the intense nature and prolonged recovery phase of the substorm.

5 Summary and Conclusions

In this work, we are trying to refine our approach to detect substorm onsets using the nonlinear physics model WINDMI, which consists of eight differential equations describing the energy flow through the magnetosphere-ionosphere system. Our goal in this paper was to utilize this model to determine onsets based on the flow of field-aligned currents, which often exhibit significant variations and enhancements during substorms. To achieve this, we used the WINDMI variables $\theta(I - I_c)$ and $I_1$, designed to identify specific enhancements in region 1 field-aligned current resulting from the increased geotail current triggered by substorms. These enhancements were then compared against a substorm list obtained by merging lists from five different authors, employing a 15-minute window for merging. Similarly, 15-minute windows were used to verify whether onsets detected by WINDMI were also identified by other detection methods. The resulting statistics, as shown in Table 1, suggest that positive results from WINDMI can be associated with substorms significantly influenced by solar wind.

The two selected days discussed in the paper, namely March 17, 1998, and January 07, 2000, reveal frequent enhancements in the region 1 field-aligned current ($I_1$) during substorms, as indicated by the substorm lists. These enhancements are triggered by the activation of the $\theta$ function. The critical current ($I_c$) was held constant from day to day and optimized to a level where the trigger would activate only when the geotail current value exceeded a specific daily average. The primary reason the model struggles to predict substorms is that it can only do so when substorms are solely driven by solar wind and can be attributable to the dynamics of energy loading and unloading. Additionally, the critical current value needs to be somewhat variable to enable the enhancements corresponding to onset that generate substorms.

The final statistics demonstrate that the WINDMI model can predict substorms 40% of the time when provided with solar wind data. This capability proves valuable for approximating substorm times, estimating substorm intensities, and increases our understanding of substorm occurrences primarily attributable to the energy loading - unloading mechanism.

6 Open Research

The solar wind data utilized in this study were acquired from https://cdaweb.gsfc.nasa.gov/index.html. The substorm lists used were obtained from https://supermag.jhuapl.edu/substorms/. MATLAB 2023b was the software employed to execute the WINDMI codes, with the Simulink library being specifically utilized to model the WINDMI equations. The dataset generated from this study is available for download from the following link: https://zenodo.org/records/11061738.

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Supporting Information for “Substorm Identification With The WINDMI Magnetosphere - Ionosphere Nonlinear Physics Model”

P. Adhya¹, E. Spencer¹, M. Kayode-Adeoye¹

¹Electrical and Computer Engineering Department, University of South Alabama, Mobile, AL, U.S.A.

Additional Supporting Information (Files uploaded separately)

1. Caption for Data Set S1

Introduction

This supporting information contains a dataset covering substorm onsets observed between 1998 and 2007, including some key parameters that aid in detecting substorm onsets when the WINDMI model is run.

Data Set S1. Dataset information on substorm onset times, magnetic local times, magnetic latitudes, geographic latitudes, and longitudes, along with detection techniques and their abbreviations (utilized by authors Forsyth, Frey, Liou, Newell, and Ohtani). Columns denote the presence (1) or absence (0) of substorms detected by each technique. Time differences between substorms are recorded. Additionally, it includes counts of techniques detecting substorm onsets, WINDMI model trigger occurrences based on field-aligned current crossing a critical threshold $I_c$, Geotail current ($I$) with median ($I_{med}$) and
70th percentile ($I_c$), where $I_c$ doubles as the threshold for WINDMI substorm detection, and maximum field-aligned current during substorm onsets.