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Abstract.
The *Dst* index is produced using low-latitude ground magnetic field measurements and frequently is used as an estimate of the energy density of the ring current carried mainly by energetic ($\sim 10 - 200$ keV) ions relatively close to the Earth. However, other magnetospheric current systems can cause field perturbations at the Earth's surface: for example, dayside magnetopause currents are known to contribute to the *Dst* index. It has also been suggested that the nightside tail current sheet can significantly affect the *Dst* index during high magnetic activity periods when the currents are intense and flow relatively close to the Earth. In this study, several disturbed periods are input into Tsyganenko magnetic field models. From the time series of the external and internal fields an artificial *Dst* index is computed using the same procedure followed in the actual *Dst* calculation. A tail region in the magnetosphere is explicitly defined and the T96 and T89 models are used to calculate the effect of current within this tail region on ground measurements and therefore on *Dst*. The results are then compared with the measured *Dst* to determine the tail current contribution to *Dst*. It is found that for a geomagnetic storm and a storm-time substorm with *Dst* of $\sim$ 80 nT the tail current contribution is between 22 and 26 nT. The same analysis is also applied to several isolated non-storm-time substorms, yielding a nearly linear relationship between *Dst* and the tail current contribution. This contribution is approximately one quarter of *Dst*.

1. Introduction

The *Dst* index has long been used as an indirect measure of the ring current. It is important to note, however, that the *Dst* index is actually a measurement of the longitudinally averaged ground perturbation at low-latitude magnetometer stations and thus measures the effects of many terrestrial and magnetospheric current systems indiscriminately. Much work shows that the ring current does contribute significantly to the *Dst* index [e.g., *Greenspan et al.*, 2000; *Hamilton et al.*, 1988; *Kozyra et al.*, 1997; *Jordanova et al.*, 1998; *Roeder et al.*, 1996]. However, other current systems cannot be overlooked entirely in considering contributions to *Dst*.

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Effects due to induced currents in the ground were first discussed by *Dessler and Parker* [1959], who calculated that in a perfectly conducting planet, ground currents would enhance *Dst* by 50%. Later work by *Langel and Estes* [1985] indicates that the ground currents in the Earth are proportional to 29% of the external currents at dawn and 24% at dusk. Magnetopause currents have also been shown to contribute to the field perturbation felt on Earth. *Burton et al.* [1975] proposed the following formula to remove the magnetopause current contribution from the measured *Dst*:

$$Dst^* = Dst - b\sqrt{P} + c,$$

where P is the solar wind dynamic pressure, b and c are constants, and Dst^* is the so-called pressure-corrected *Dst*.

One of the ways in which *Dst* is used to represent the ring current is as an energy estimate via the Dessler-Parker-Sckopke relation. *Dessler and Parker* [1959] and *Sckopke* [1966] derived a formula which relates the total amount of energy in the ring current to the magnetic perturbation at the Earth's center by

$$\Delta B_{\text{particles}} = -\frac{\mu_0}{2\pi}\frac{W_{\text{particles}}}{B_0 R_E^3},$$

where $\Delta B_{\text{particles}}$ is the perturbation at the center of the Earth, R_E is an Earth radius (6372 km), μ_0 is the permeability of free space, B_0 is the surface dipole strength at the equator, and $W_{\text{particles}}$ is the energy in the ring current particles.

Work has also been done on the problem of the tail current effect on *Dst*. *Belova and Maltsev* [1994] conducted a study in which they modeled the contributions of the ring current and magnetopause currents and estimated that they were insufficient to produce the observed *Dst* variation. Instead, they suggested that magnetotail currents may provide the majority of *Dst*. *Alexeev et al.* [1996] used a dynamic model of the magnetosphere to try to reproduce short timescale variations in *Dst*. Their results indicated that the tail currents may have as large an effect on storm-time *Dst* as the ring current. *Maltsev et al.* [1996], also modeled *Dst* and contributing currents. They provided a formulation for *Dst* which subtracted off a tail current contribution. They claimed this formulation offered a better description of storm-time physics. *Arykov and Maltsev* [1996] concluded from their modeling result that the tail currents were the dominant contribution to *Dst*.

The present study focuses on the effects of magnetotail currents on *Dst*. Both the standard Tsyganenko models of the magnetospheric field and modified versions which have been optimized to fit spacecraft data in the magnetotail for particular events are used to recreate the measured *Dst*. These are then used to model the strength of *Dst* in the absence of the tail current systems. This analysis reveals a significant, though not dominant, contribution of tail currents to the *Dst* index.

2. Modeling *Dst*

The Tsyganenko magnetic field models were used in this study. Tsyganenko models are empirical models of the magnetic field, based on years of spacecraft data and parameterized by various activity indices and solar wind conditions. The *Tsyganenko* [1996] (T96) model takes as its inputs the solar wind B_Z and B_Y, solar wind dynamic pressure, and the measured *Dst*, and it outputs the magnetospheric field. It is important to note that the model uses the measured *Dst* coupled with dynamic pressure as a magnetospheric disturbance parameter and does not attempt to reproduce *Dst* either by altering the values at the ground stations or by creating a ring current of the appropriate magnitude. The *Dst* input is used in the T96 model only to parameterize the level of activity in the magnetosphere. The *Tsyganenko* [1989] (T89) model, which parameterizes activity using the *Kp* index, was also used for several events. For substorms for which the T89 model had been modified by *Pulkkinen et al.* [1991] to match data in the magnetotail, these modified T89 models were used. For other events, the T96 model was utilized.

2.1. Calculation of *Dst* From the Models

The standard *Dst* index is calculated using the designated *Dst* ground magnetometer stations (currently Alibag, Hermanus, Honolulu, Kakioka, and San Juan) according to the formula:

$$Dst(t) = \frac{1}{N}\sum_{i=1}^{N}\frac{\Delta H_i(t)}{cos(\theta_i)},$$

where ΔH_i is the change in the horizontal component of the field at a station relative to a monthly 5-day averaged "quiet day," θ_i is the magnetic latitude of the station, and N is the total number of stations. To model *Dst* using the Tsyganenko 1996 model, the model field was calculated at the surface of the Earth at the locations of the *Dst* stations for the entire month of the event, in order to calculate the quiet day residual. The algorithm described above was then applied. When using the T89 model, which was modified to replicate conditions for particular events, the quiet residual was estimated by modeling a quiet interval with $Kp = 1$.

2.2. Subtraction of Tail Current

In order to isolate the influence of the tail current, the model was used to calculate the magnetic field in a "box" in the $X - Z$ plane from $Z = -5$ to $Z = 5$ R_E and $X = -6$ to $X = -50$ R_E, uniform in Y. This region, shown in Figure 1, was selected based on current profiles from the models. The curl was then taken to calculate the currents flowing through the box, and the effects of these currents were then subtracted from each ground station before the *Dst* calculation was made. It is important to note that the tail current contribution was also subtracted from the quiet day baseline calculation for the *Dst* so that the results reflect the net change in *Dst*, rather than simply the total change felt on the ground due to the tail currents.

3. January 1997 Storm

The model *Dst* was calculated for the January 1997 storm interval. This storm has been studied in detail by *Lu et al.* [1998] and *Baker et al.* [1998]. Figure 2 shows the solar wind B_Z, proton density, and measured *Dst* for this interval, as well as the *Dst* as modeled by the Tsyganenko 1996 model. Note that early on January 11, shortly after 1100 UT, there was a pressure pulse in the solar wind. Since the Tsyganenko magnetic field model is an empirical model, it cannot model the detailed features in such rare events. Therefore, results from the model during this period are not valid. The modeled *Dst* shown in Figure 2 agrees well with the

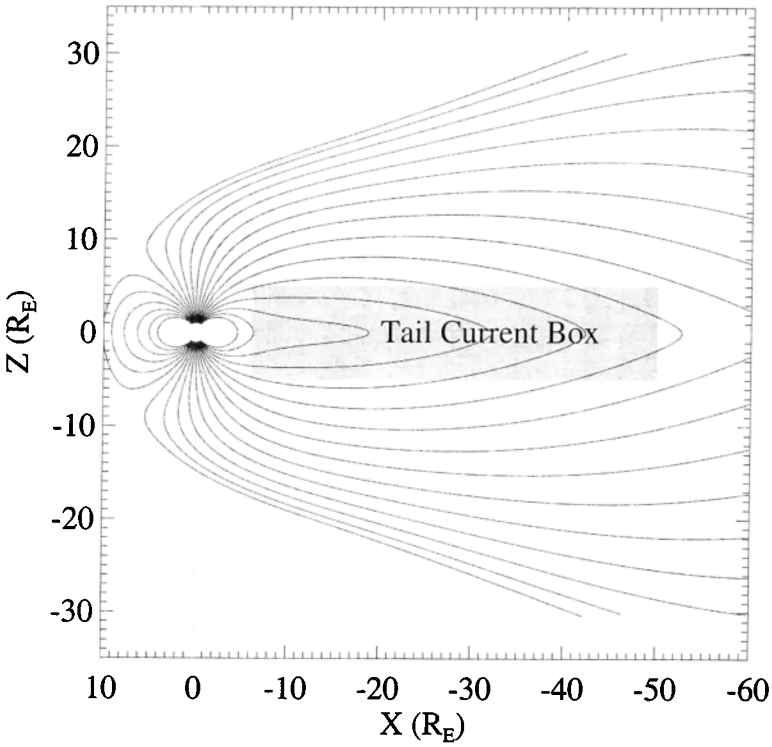

Figure 1. Tail current box used to model and remove the effect of the magnetotail current systems.

measured *Dst*, with the exception of the time of the pressure pulse which is out of range.

Figure 3 shows the modeled *Dst* with and without the influence of tail currents. The differences between these two are modest (~ 5 nT) during quiet times, and reach a peak during the most disturbed time period of the storm. Figure 3b shows the measured *Dst* during this time, and Figure 3c shows the difference between the modeled *Dst* with and without the tail currents. There is a peak in this plot when the model was out of range. A more reliable peak occurred at ~ 1025 UT; this reveals a tail current influence on *Dst* of 22 nT out of the total 78 nT disturbance.

4. Storm-Time Substorm

Another modeled event was a storm-time substorm that occurred on May 3, 1986. This CDAW-9 Event C substorm took place during an 80 nT magnetic storm, which initiated around 0400 UT on May 2, 1986. The storm main phase was characterized by strong *AL* activity with maximum disturbances reaching to 1500 nT in *AL* and around 2000 nT in *AE*. The substorm under consideration took place during the peak activity, and was associated with ~ 1500 nT disturbance in *AE*. Figure 4 shows an overview of the storm-time *Dst* and AU/*AL*. Figure 4c shows the *AU*/*AL* during the substorm early on May 3, 1986. The substorm has been studied in detail by *Pulkkinen et al.* [1991, 1992] and by *Baker et al.* [1993]. Because the T89 model was modified to match data for specific points in time, the full time series for the storm interval was not calculated.

The substorm event was modeled using the modified T89 model as described by *Pulkkinen et al.* [1992]. The contribution from the tail currents to *Dst* was evaluated at the end of the growth phase, when a thin and intense current sheet formed quite close to the Earth [*Pulkkinen et al.*, 1992; *Baker et al.*, 1993]. This is assumed to be the time when the substorm-time tail current contribution to *Dst* is largest. Calculating the model *Dst* with and without the tail currents revealed a difference of 25.8 nT.

The results indicate that during storm-time substorms the tail current intensification during the growth phase can contribute around 26 nT to the *Dst* index. Because the tail current is disrupted and the field is dipolarized after the expansion onset, the contribution to the *Dst* index from the tail currents during the expansion phase becomes increasingly less important. As the *Dst* indices were about the same magnitude during this and the January 1997 storm (i.e., ~ 80 nT *Dst*), these results are quite consistent with one another.

5. Substorms

Several isolated substorms were also analyzed. These events occurred on April 29, 1986, December 10, 1996, March 4, 1979, and March 22, 1979. The indices *AU*/*AL* and *Dst* for these events may be found in Figures 5 - 8. The *AU* and *AL* indices were unavailable

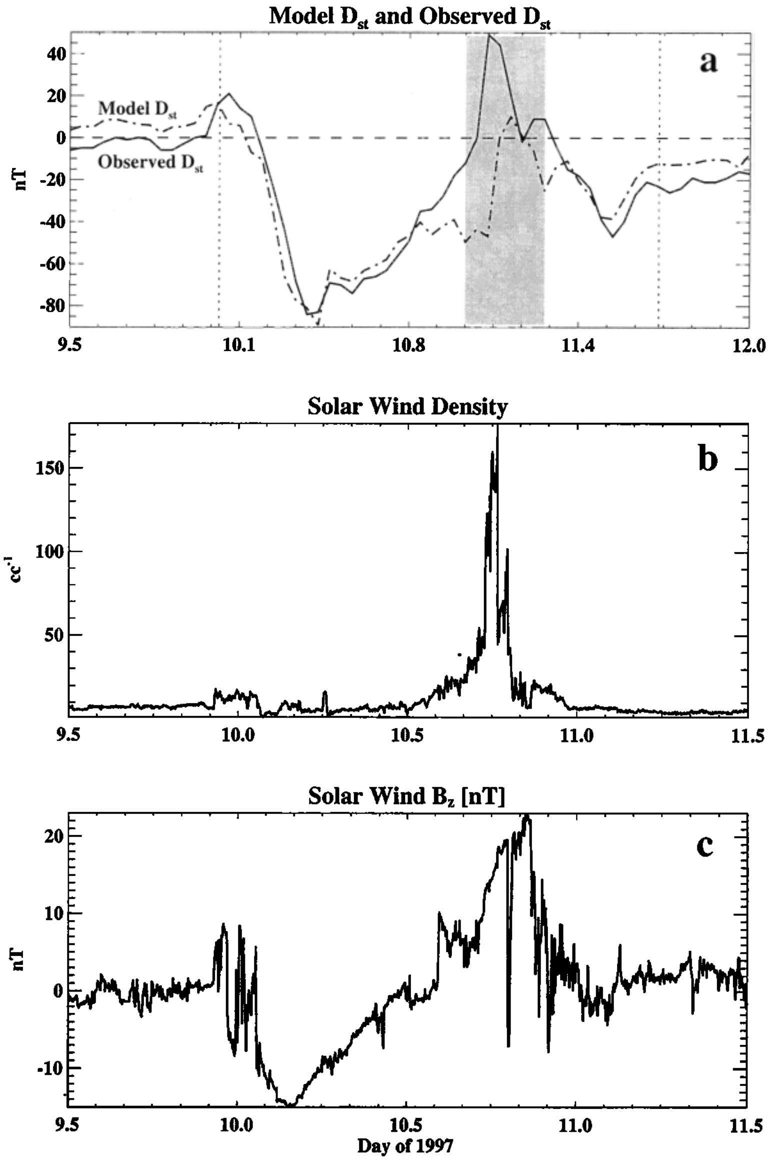

Figure 2. (a) Modeled and observed *Dst* (not pressure-corrected) for January 9-12, 1997; (b,c) solar wind conditions. The shaded region is during a solar wind pressure pulse which is out of range for the model.

for the December 10, 1996 event, so the CANOPUS *CU*/*CL* is shown. The April 1986 event produced only a 7 nT variation in *Dst*, though the *AL* for this event reached a minimum of ~ 400 nT. The March 22, 1979 substorm produced a 36 nT *Dst* and over 1000 nT in *AL*. The event on March 4, 1979 resulted in a 600 nT *AL* and a 44 nT *Dst*. The December 10, 1996 substorm caused a drop of ~ 900 nT in *CL*, and 31 nT in *Dst*. The substorms were modeled the same way as the storm-time substorm: a modified version of the T89 model was used which, in each case, had been optimized to fit spacecraft data in the tail for the event being modeled.

When all the events were combined, the correlation between *Dst* and the tail current contribution to *Dst* was nearly linear. The best fit tail current contribution for these substorms was (5 ± 1) nT $-(24 \pm 2)\%$ of *Dst*. When the storm and the storm-time substorm are included in this average, the tail current contribution is similar, but with larger uncertainties: (5 ± 2) nT $-(24 \pm 3)\%$ of *Dst*. Figure 9 shows the tail contribution for all of these events. The substorms are shown as circles, the storm is represented by a diamond, and the storm-time substorm is indicated with an asterisk.

6. Discussion

In both the storm-time substorm and the geomagnetic storm events, the measured *Dst* had a minimum of ~ 80 nT, and the tail current contribution is estimated to be in the 20 - 25 nT range. This suggests that while the tail current contribution is significant, it

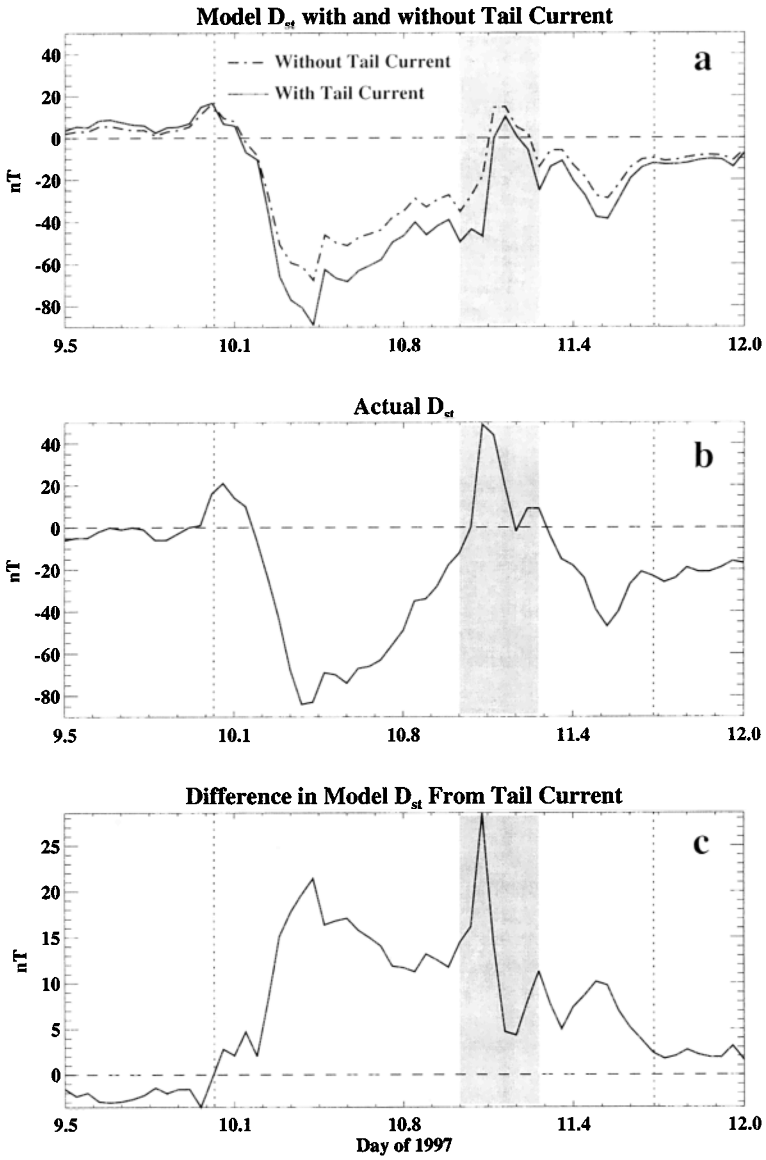

Figure 3. (a) Modeled *Dst* with and without the tail current, (b) measured *Dst*, and (c) the difference in *Dst* due to the tail current. The shaded region is during a solar wind pressure pulse which is out of range for the model.

is not the dominant effect, as has been argued by some research groups.

Overall, there was a clear correlation between the magnitude of *Dst* and the tail current contribution for both storms and substorms. In the case of substorms the relationship was nearly linear, with the tail current systems contributing approximately one fourth of the observed variation. Given that the ring current is known to contribute significantly to *Dst*, this implies a relationship between the magnitude of the ring current and the tail current systems.

Since the *AU*/*AL* index is an indicator of substorm activity, this index was also compared with the tail current contribution to *Dst* for the substorms in the study. This initial comparison showed less of a correlation than for *Dst*. However, since *AU*/*AL* was unavailable for one substorm, this left only three modeled substorms, so no firm conclusions regarding *AU*/*AL* could be drawn.

In addition to the January 1997 event, six other storms were analyzed using the T96 model. These storms occurred in January, February, March, April, June, and October 1998. The tail current contribution for these storms (with *Dst* ranging from -68 to -115 nT) was between 20 and 30%, averaging $(26 \pm 3)\%$ of measured *Dst*. This result is very consistent with the other event analyses discussed in this paper. However, because the modified T89 models have been matched to actual spacecraft data for each event, these are consid-

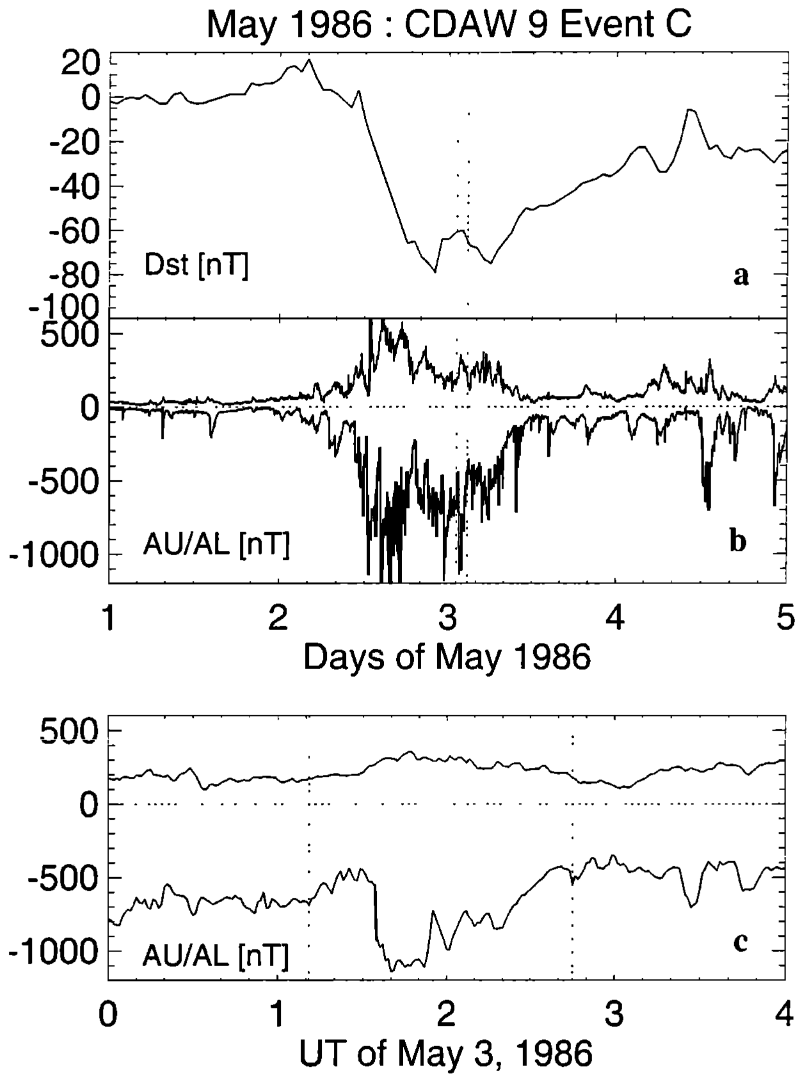

Figure 4. Storm development in May 1986 event: (a) *Dst*, (b) *AU/AL*, and (c) a close-up of *Dst* during a storm-time substorm.

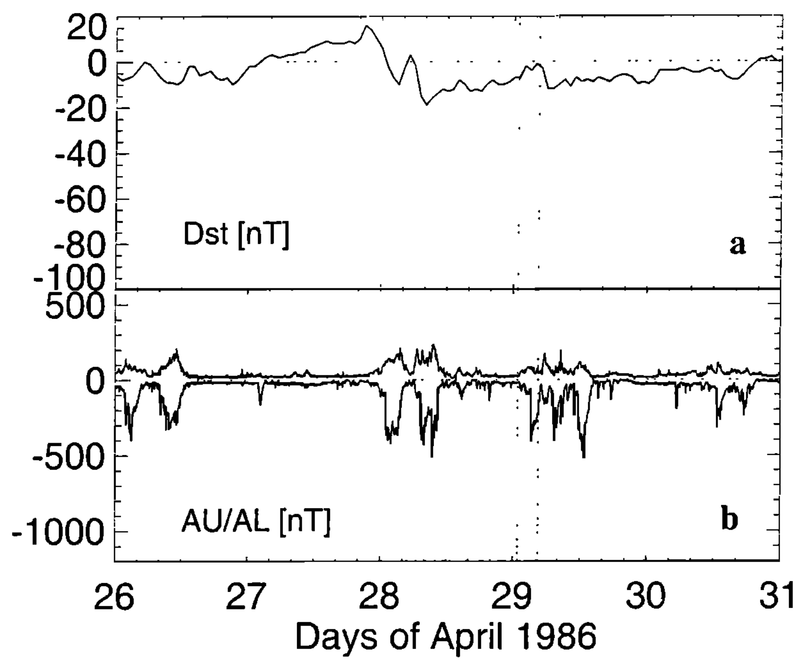

Figure 5. Substorm on April 29, 1986, event: (a) *Dst* and (b) *AU/AL*.

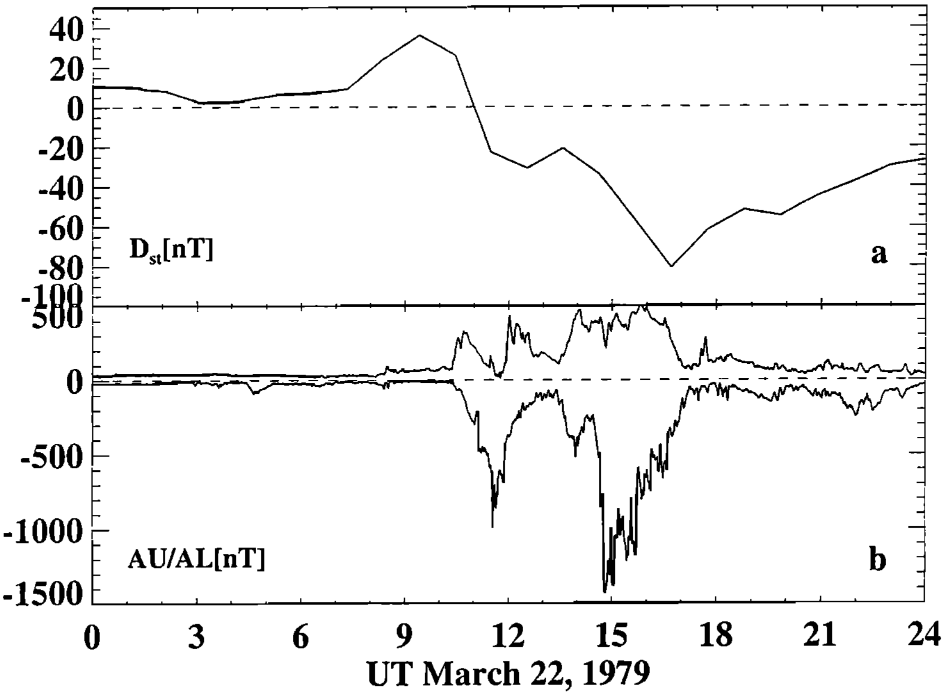

Figure 6. Substorm on March 22, 1979, event: (a) *Dst* and (b) *AU/AL*.

ered to give a more reliable result than the T96 model alone. Thus, the detailed analyses using T89 have been predominantly relied on for the overall conclusions of the paper. It would be an interesting study, in the future, to put together a larger collection of these models which have been modified to match spacecraft data in the magnetotail, in order to provide a more statistical study of the tail current contribution to *Dst*. However, at this time, only a limited number of such models exist, and we have made use of all that were available. Further

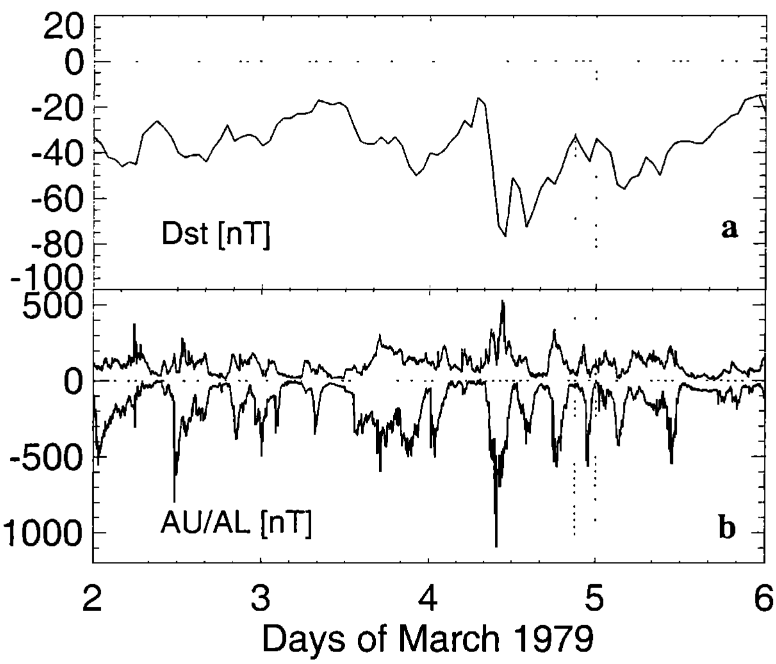

Figure 7. Substorm on March 4, 1979, event: (a) *Dst* and (b) *AU/AL*.

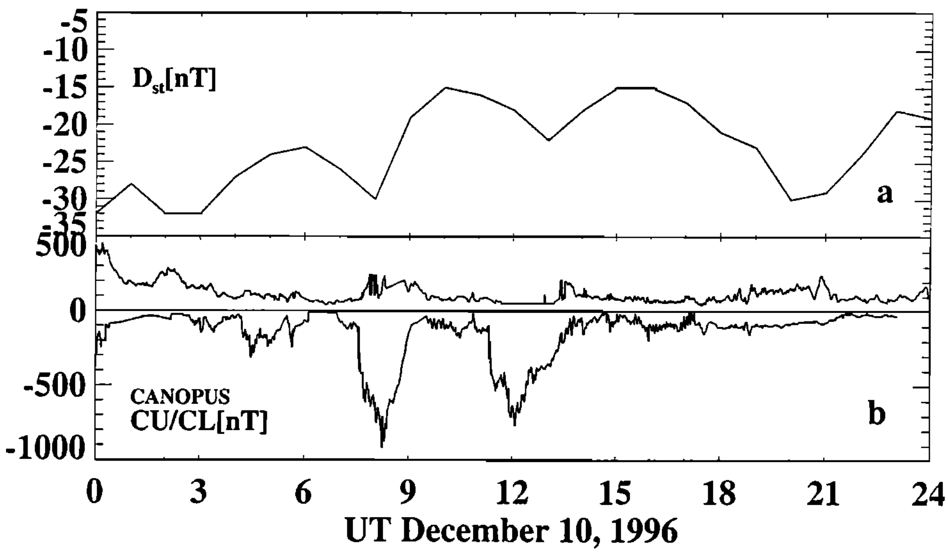

Figure 8. Substorm on December 10, 1996, event: (a) *Dst* and (b) *CU/CL*.

work with larger storms was not undertaken because it would be outside the validity range of the Tsyganenko models.

7. Conclusion

While *Dst* is often assumed to represent the magnitude of the ring current, much work has shown that other current systems contribute as well. This modeling result shows that the tail current contribution is significant, though not dominant, both during storms and substorms. In each case this contribution is ~ 25% of the measured *Dst* variation.

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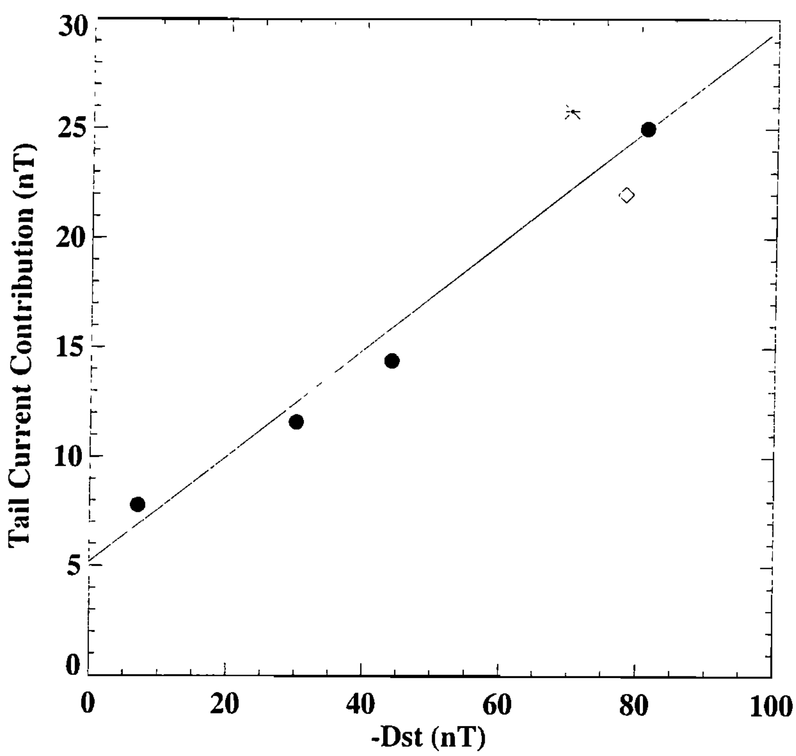

Figure 9. Measured *Dst* versus modeled tail current contribution for all events in this study. The diamond indicates the January, 1997 storm; the asterisk indicates the May 1986 storm-time substorm; the circles indicate substorms. The line shown is a best fit for all events.

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