# A new model for the prediction of *Dst* on the basis of the solar wind

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Received 10 May 2001; revised 27 December 2001; accepted 27 December 2001; published 24 December 2002.

[1] An explicit model for predicting *Dst* based on solar wind data for the years 1995–1999 gives a good fit with a prediction efficiency of 88%, a linear correlation coefficient between the *Dst* index and the model of 0.94, and a RMS error of 6.4 nT. The same model applied to the first half of 2000 gave a prediction efficiency of 91%, a linear correlation coefficient of 0.95, and a RMS error of 7.9 nT. The modeled *Dst* is a sum of three terms that have growth and decay, a dynamic pressure term, an interplanetary magnetic field term, and some offset terms. The main innovations are that the decay terms have different time constants ranging from 5 days to 1 hour and that all the terms except the offsets depend on the angle of the Earth's dipole with respect to the solar wind velocity. This result shows that the magnetosphere is highly predictable and that chaotic behavior within the magnetosphere has little influence on the large-scale currents that determine *Dst*. *INDEX TERMS:* 2788 Magnetospheric Physics: Storms and substorms; 2778 Magnetospheric Physics: Ring current; 2722 Magnetospheric Physics: Forecasting; *KEYWORDS:* *Dst* prediction, ring current, space weather

**Citation:** Temerin, M., and X. Li, A new model for the prediction of *Dst* on the basis of the solar wind , *J. Geophys. Res.*, *107*(A12), 1472, doi:10.1029/2001JA007532, 2002.

## 1. Introduction

[2] The *Dst* index is based on measurements from four magnetometers near the equator [*Sugiura and Kamei*, 1991]. Ideally, the *Dst* index should be a measure of the magnetic perturbation at the center of the Earth's dipole in the direction of the Earth's dipole due to currents in space above the ionosphere. To approach this ideal, the four magnetometers are widely spaced in longitude and also located somewhat away from the equator to avoid the magnetic perturbations from the equatorial electrojet. They are adjusted to remove the quiet time *Sq* ionospheric current perturbations and the secular variation of the magnetic field due to changes in the internal currents of the Earth. Currently, the *Dst* index is calculated every hour and is available on the web in near real time, provisional, and, after about a year and half, final versions [*World Data Center for Geomagnetism*, *Kyoto*, 1995–1999], and thus we also refer to it as the "Kyoto *Dst*." The *Dst* index is the main measure used to indicate magnetic storms with a value of less than −50 nT often used to indicate that a magnetic storm is in progress. The *Dst* index is also often used as a measure of the strength of the ring current. However, all magnetospheric current systems affect *Dst*, and the relative contribution of the ring current to *Dst* remains uncertain [*Feldstein et al.*, 2000; *Turner et al.*, 2000] though the ring current is certainly an important contributor during magnetic storms [*Gonzalez et al.*, 1994].

[3] It has been known since the work of *Burton et al.* [1975] that the *Dst* index can be well modeled using the solar wind as input. The Burton method specifies the change in *Dst* due to a driver term and a decay term. The driver term is a function of only the interplanetary $E_y$ electric field and gives (a negative) contribution to the change in *Dst* if the interplanetary $E_y$ electric field exceeds 0.5 mV/m, which is equivalent to a $b_z$ interplanetary magnetic field (IMF) component of less than 1.0 *nT* for a solar wind velocity of 500 km/s. The decay term gives a constant decay rate of about 7 hours. The changes in *Dst* are then integrated to find *Dst* to which a constant and a term proportional to the square root of the solar wind dynamic pressure is added to give the predicted *Dst*.

[4] Following Burton et al., others have tested, improved, or attempted to improve the prediction by either modifying the driver and decay terms [*Gonzalez et al.*, 1994; *Murayama*, 1986; *Thomsen et al.*, 1998; *Klimas et al.*, 1998; *O'Brien and McPherron*, 2000] or by using other methods such as neural networks [*Wu and Lundstedt*, 1996, 1997] or other innovative techniques [*Vassiliadis et al.*, 1999]. The motivation for attempting such improvements is usually a combination of a practical desire to make a better prediction (*Dst* is an important space weather parameter since it is the main indication of magnetic storms), a desire to learn which features of the interaction between the solar wind and the magnetosphere are most important in producing magneto-


0148-0227/02/2001JA007532$09.00

spheric activity, and a desire to learn how predictable the magnetosphere is or in other words to what extent the magnetosphere is directly driven by the solar wind. These are also our motivations.

[5] We have modeled 5 years of the *Dst* index (1995–1999, except for times when there are gaps in the solar wind data and the last 45 days of 1999, a total of 40,433 hours) using solar wind data from Wind and ACE as input [*Lin et al.*, 1995; *Lepping et al.*, 1995; *Smith et al.*, 1999; *McComas et al.*, 1998]. The RMS error in our model of *Dst* is 6.44 nT which corresponds to a prediction efficiency (defined as [1-(variance of the residual)/(variance of the *Dst* index], where the residual is the difference between the *Dst* index and the prediction) of 88.1%, and a linear correlation coefficient between the *Dst* index and the model of 0.939. For active times, defined as a measured *Dst* of less than −50 nT (1624 hours of data), the RMS error is 12.5 nT, but the corresponding prediction efficiency was greater at 95.8% because of the much larger variance in the *Dst* index. Figure 1 shows a comparison of the model and the data for 1998, a year which had no significant solar wind data gaps. These results can be contrasted with the Burton model, which, with the best fit parameters for this 5-year period, gives a RMS error of 10.6 nT and a prediction efficiency of 67.6%. (Using the original Burton parameters gives an RMS error of 11.8 nT and a prediction efficiency of 59.7%.)

[6] There are several implications of these results: (1) The magnetosphere is very strongly controlled by the solar wind and thus chaotic or other unpredictable behavior has little influence on its large-scale currents. (2) *Dst* and thus magnetic storms are highly predictable from solar wind measurements. (3) The seasonal behavior of the magnetosphere (stronger activity during the equinoxes) is strongly influenced by the angle of the dipole with respect to the solar wind velocity as has also recently been argued [*Cliver et al.*, 2000]. (4) There are at least three current systems within the magnetosphere that make a significant contribution to *Dst*.

## 2. Model Description

[7] Our calculated *Dst* is a sum of several terms: *Dst* = *dst*1 + *dst*2 + *dst*3 + (pressure term) + (direct IMF $b_z$ term) + (offset terms that do not depend on solar wind). The terms *dst*1, *dst*2, and *dst*3 are all calculated in a similar way: $dstx(t + dt) = dstx(t)$ + (driver term) − (decay term). The pressure term and the direct IMF $b_z$ term are calculated directly from the solar wind.

[8] These terms are added with appropriate time shifts. Most of the solar wind data is from the Wind satellite, but in 1998 and 1999 we used ACE data to fill gaps in the Wind data. The solar wind coordinate system is GSM. The time of solar wind is changed to $t_e = t_{wind} - x/v_x$ to take into account the propagation of the solar wind to the Earth. The solar wind IMF has also been rotated to take into account the change in the GSM coordinates between the time of the solar wind measurement and the time of impact on the Earth though this gives only a small improvement. In our calculation we have used solar wind data interpolated to a constant 10-min interval.

[9] The *dst*1, *dst*2, and *dst*3 terms are similar in that their driver terms depend strongly on a negative IMF $b_z$ component. They differ most strongly in their decay terms. The *dst*1 term decays more slowly than *dst*2 which decays more slowly than *dst*3. The *dst*3 term has a decay time constant of 59 min. Both *dst*1 and *dst*2 are nonlinear, and so their decay times depend on their values with faster decay for larger absolute values. For typical values of −20 nT, *dst*2 has a decay time constant of 11.4 hours, and *dst*1 has a decay time constant of 5.1 days.

[10] A discussion of the each term is provided below. It has been our practice to optimize the model by finding the functions and values of the free parameters in the functions that minimize the RMS error between the model and the measured *Dst*. These functions are typically simple with some multiplicative factor or power being varied. Because of the large number of free parameters, there can be no assurance that the quoted parameters represent an absolute minimum for the assumed functional forms. Also, there can be quite a bit of uncertainty in the values of the individual parameters because of various trade-offs. For instance, a larger solar wind density gives a larger *Dst* through the pressure term but a smaller *Dst* through its effects on the driver terms. Thus a "mistake" in the value of density parameter in the pressure term can be partly offset by a "mistake" in the value of density parameter in the driver terms with the result that the sum (i.e., the prediction) is better than its individual parts.

[11] The pressure term is usually taken [e.g., *Burton et al.*, 1975] to be proportional to the square root of the dynamic pressure of the solar wind, $(nv^2)^{\frac{1}{2}}$, where $n$ is the solar wind density (cm$^{-3}$) and $v$ the solar wind velocity (km/s). This term is usually assumed to represent the magnetopause currents.

[12] We have complicated this by including the IMF magnetic pressure and a term proportional to the solar wind density that we hoped would serve as a proxy for the solar wind thermal pressure (it is not, in fact, since the temperature of the solar wind is well correlated with the solar wind velocity) and a correction for the dipole angle and then did a least squares fit to find the best parameters with the result that

$$\text{pressure term} = \left[p_1 \cdot b^2 + n \cdot \left(\frac{p_2 \cdot v^2}{\sin^{2.52}(\phi)} + p_3\right)\right]^{\frac{1}{2}}, \qquad (1)$$

where $b$ is IMF magnitude and $\phi$ is approximately the angle between the dipole and the solar wind velocity, $p_1 = 0.90$, $p_2 = 2.18 \cdot 10^{-4}$, $p_3 = 14.7$. Using typical values of $b = 5$ nT, $v = 425$ km/s, $\phi = 90°$, and $n = 7$ cm$^{-3}$ gives pressure term = $[22.5 + 7 \cdot (39.4 + 14.7)]^{12} = 20.0$ nT.

[13] Explicitly $\sin(\phi) = (1 - \cos^2(\phi))^{0.5}$ where

$$\cos(\phi) = \sin(tt + \alpha)*\sin(ttt - tt - \beta)*9.58589 \cdot 10^{-2} + \cos(tt + \alpha)*(0.39 + 0.104528*\cos(ttt - tt - \beta)), \qquad (2)$$

where $tt = 2\pi t/\text{year}$, $ttt = 2\pi t$, $\alpha = 0.078$, $\beta = 1.22$, and $t$ is time in days from the beginning of 1995 and year = 365.24 days.

[14] In the above the contribution from the IMF and density, though still smaller than the dynamic pressure contribution, is much larger than the ratio of magnetic field and thermal pressures of the solar wind to the dynamic pressure of the solar wind

$$\text{direct IMF } b_z \text{ term} = 0.478 \cdot b_z \cdot \sin^{11.0}(\phi). \qquad (3)$$

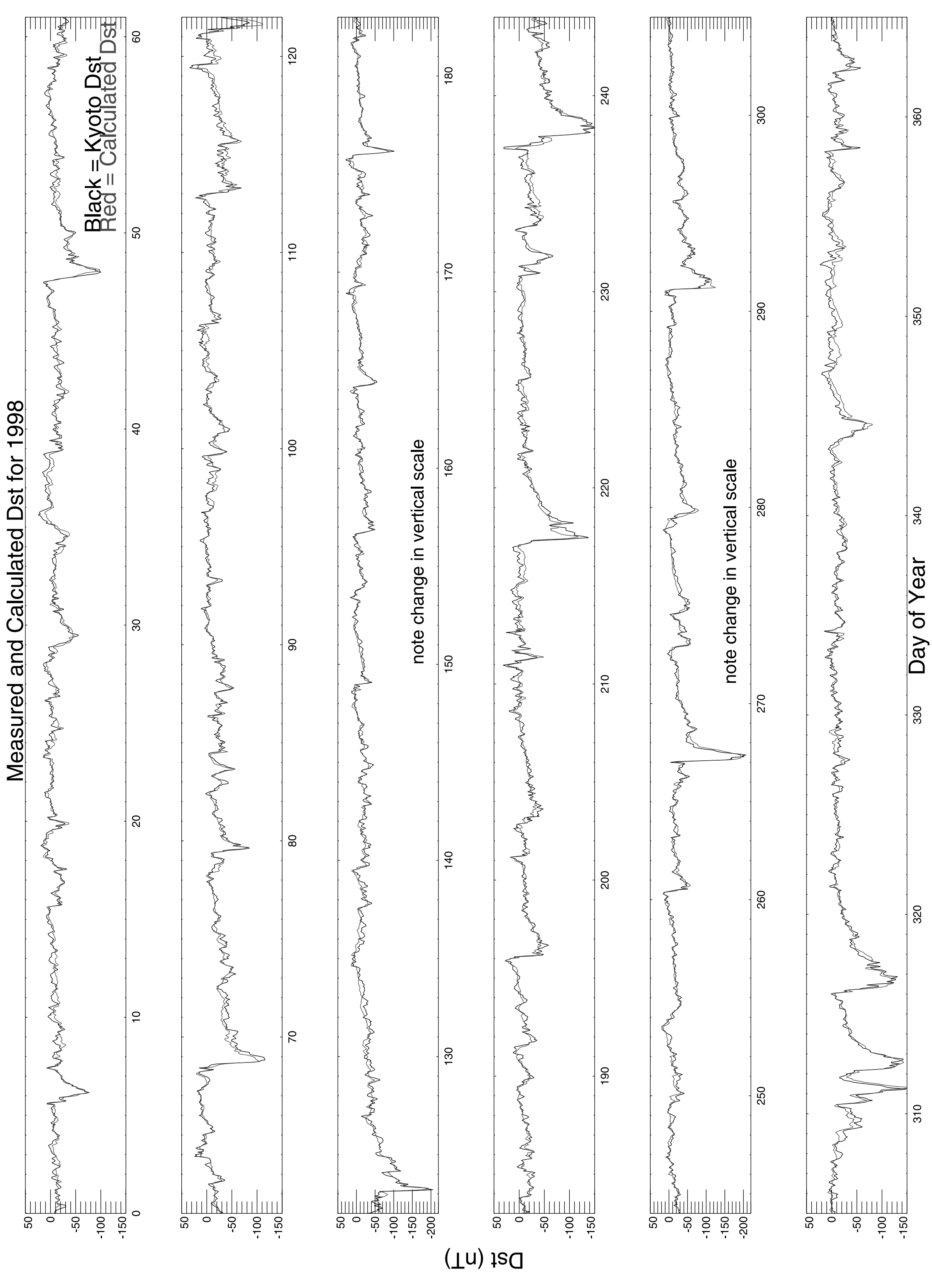


**Figure 1.** A comparison of the *Dst* index with the prediction for 1998. See color version of this figure at back of this issue.

The direct IMF $b_z$ term is a small term with an average magnitude of only 0.71 *nT* but sometimes over 10 nT. It has a strong dependence on the angle of the dipole with respect to the solar wind velocity. "Offset terms"

$$\text{offset} = s_1 + s_2 \cdot \sin(2\pi t/yr + s_3) + s_4 \cdot t + s_5 \cdot t^2, \quad (4)$$

where $s_1 = -2.788$, $s_2 = 1.44$, $s_3 = -0.92$, $s_4 = -1.054 \cdot 10^{-2}$, $s_5 = 8.60 \cdot 10^{-6}$. This term may compensate for a portion of the secular variation that may not have been removed in the *Dst* index and for an annual variation.

[15] The *dst*1, *dst*2, and *dst*3 terms are calculated as follows:

$$dst1(t+dt) = dst1(t) + \left\{ a_1 \cdot [-dst1(t)]^{a_2} + fe1(t) \cdot \left[1 + \frac{a_3 \cdot dst1(t-\tau_1) + a_4 \cdot dst2(t-\tau_1)}{1 - a_5 \cdot dst1(t-\tau_1) - a_6 \cdot dst2(t-\tau_1)}\right] \right\} dt \quad (5)$$

$$dst2(t+dt) = dst2(t) + \left\{ b_1 \cdot [-dst2(t)]^{b_2} + fe2(t) \cdot \left[1 + \frac{b_3 \cdot dst1(t-\tau_2)}{1 - b_3 \cdot dst1(t-\tau_2)}\right] \right\} dt \quad (6)$$

$$dst3(t+dt) = dst3(t) + \left\{ c_1 \cdot dst3(t) + fe3(t) \cdot \left[1 + \frac{c_2 \cdot dst3(t-\tau_3)}{1 - c_2 \cdot dst3(t-\tau_3)}\right] \right\} dt, \quad (7)$$

where $a_1 = 6.51 \cdot 10^{-2}$, $a_2 = 1.370$, $a_3 = 8.4 \cdot 10^{-3}$, $a_4 = 6.053 \cdot 10^{-3}$, $a_5 = 1.21 \cdot 10^{-3}$, $a_6 = 1.55 \cdot 10^{-3}$, $\tau_1 = 0.14$ days, $b_1 = 0.792$, $b_2 = 1.326$, $b_3 = 1.29 \cdot 10^{-2}$, $\tau_2 = 0.18$ days, $c_1 = -24.3$, $c_2 = 5.2 \cdot 10^{-2}$, $\tau_3 = 9 \cdot 10^{-2}$ days, $fe1 = -4.96 \cdot 10^{-3}\,(1 + 0.28 \cdot dh)[2 \cdot exx + \text{abs}\,(exx - th1) + \text{abs}\,(exx - th2) - th1 - th2] v_x^{1.11} n^{0.49} \sin^{6.0}(\phi)$, $fe2 = 2.02 \cdot 10^3 \cdot \sin^{3.13}(\phi) \cdot df2/(1 - df2)$, $df2 = -3.85 \cdot 10^{-8} \cdot v_x^{1.97} b_t^{1.16} \sin^{5.7}(\theta) \cdot n^{0.41} \cdot (1 + dh)$, $fe3 = 3.45 \cdot 10^3 \cdot \sin^{0.9}(\phi) \cdot df3/(1 - df3)$, $df3 = -4.75 \cdot 10^{-6} \cdot v_x^{1.22} \cdot b_t^{1.11} \sin^{5.5}(\theta)\, n^{0.24}(1+dh)$, $exx = 10^{-3} \cdot v_x \cdot b_t \sin^{6.1}(\theta)$, $\theta = -(\text{acos}(-\frac{b_z}{b_t}) - \pi)/2$, $b_t = (b_y^2 + b_z^2)^{\frac{1}{2}}$, $th1 = 0.725 \sin^{-1.46}(\phi)$, $th2 = 1.83 \sin^{-1.46}(\phi)$, $dh = b_p \cdot \cos(\text{atan}(b_x, b_y) + 6.10)(3.59 \cdot 10^{-2} \cos(2\pi t/yr + 0.04) - 2.18 \cdot 10^{-2} \sin(2\pi\, t - 1.60))$, and $b_p = (b_y^2 + b_z^2)^{\frac{1}{2}}$. Time (*t*,*dt*) is in days, magnetic field in *nT*, solar wind velocity in km/s and density in $cm^{-3}$. Here $v_x$ is the magnitude of *x* component of the solar wind velocity.

[16] The *th*1 and *th*2 constants are threshold values that *exx* needs to exceed before there is any growth in *dst*1. This is similar to the Burton formula where the solar wind $E_y$ has to be greater than 0.5 mV/m before there is any growth. Here the threshold is effectively larger, giving a threshold of about 1.0 mV/m. However, *dst*2 and *dst*3 have no thresholds. Here also the threshold for *exx* in *dst*1 has been divided into two steps (*th*1 and *th*2) in order to explore whether a sudden threshold is realistic. This division gives only a marginal improvement confirming that there is in fact a threshold-like behavior in this term.

[17] The angle "θ" is the IMF clock angle used in Akasofu's epsilon parameter [*Perreault and Akasofu*, 1978], but the sine term is raised to powers of 5.5 to 6.0 instead of the fourth power making it a stronger function of the clock angle. In addition, there are solar wind velocity and density terms in *fe*1, *fe*2, and *fe*3 and a dependence on the dipole angle with respect to the solar wind velocity.

[18] The change of *dst*1 also depends on the value of *dst*1 and *dst*2 about three hours earlier; the change of *dst*2 also depends on the value of *dst*1 about 4 hours earlier; and the change of *dst*3 also depends on the value of *dst*3 about 2 hours earlier. These effects may be related to the convection of plasma out of the magnetosphere [*Takahashi et al.*, 1990; *Liemohm et al.*, 1999]. The *dh* term gives a dependence on $b_y$.

[19] The *dst*1, *dst*2, and *dst*3 terms had average values of −15.5 *nT*, −13.7 *nT*, and −1.9 *nT*, respectively, and are always negative. The *dst*1, *dst*2, *dst*3, (pressure term), (direct IMF $b_z$ term), and (offset terms) are added (after interpolations) with time delays of 7.1, 21.0, 43.4, 2.0, 23.1 and 7.1 min, respectively, for comparison with the "Kyoto *Dst*." Figure 2 illustrates the relative magnitude and behavior of these terms and how they add to produce the modeled *Dst*.

[20] This is an important but difficult paragraph, so pay attention: All of the terms (except offset) have a significant dependence on ϕ, which is approximately the angle of the magnetic dipole with respect to the solar wind velocity, such that *dst*1, *dst*2, *dst*3 and the direct IMF $b_z$ term have a minimum coupling with the solar wind near the solstices and a maximum coupling near the equinoxes. This results (together with the larger positive contribution from the pressure term near the solstices) in a significant seasonal dependence in *Dst*. Because of the motion of the Earth around the Sun, the solar wind appears to come from a direction slightly away from the Sun. The exact angle depends on the solar wind velocity but for an average solar wind velocity of 425 km/s; this direction results in a "solar wind solstice" (the time when the angle between the rotation axis of the Earth and the solar wind is minimum) that occurs 4 days after the normal solstice or on about 26 December for the winter solstice. (The summer "solar wind solstice" and "solar wind equinoxes" are also delayed 4 days of course.) In our model the time of the solstice is actually a free parameter (α in equation (2)) which is found by minimizing the least squares error. This value of α gives a minimum for ϕ on 27 December or within 1 day of the expected value. Because of the offset of the magnetic dipole with respect to the rotation axis there is also a diurnal variation of the angle of the dipole with respect to the solar wind velocity. The phase of this variation depends on the geographic longitude of the dipole. This longitude is known but in our model was also treated as a free parameter (β in equation (2)). The value found is equivalent to a longitude of 280.5°E. The known value is 289°E for the direction of the dipole based on the 1995 IGRF model. Thus the agreement is within 9°. The relative amplitude in the diurnal variation of the coupling with respect to the seasonal variation is determined by the latitude of the offset of the magnetic dipole from the geographic pole, which is 11°. Again this was treated as a free parameter (hidden in the numbers in equation (2)). The best value was found to be 6°. This implies that the diurnal variation is substantially less than expected given the seasonal variation. We believe

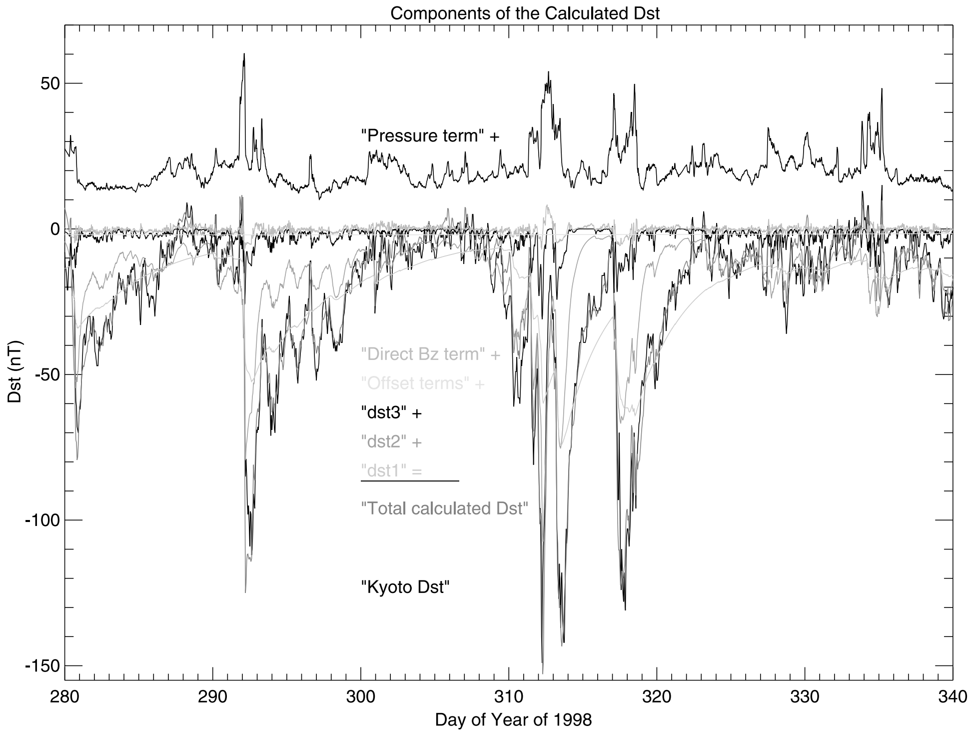


**Figure 2.** The calculated *Dst*, the components of the calculated *Dst*, and the *Dst* index for 60 days in 1998. See color version of this figure at back of this issue.

this may be due, at least in part, to the adjustment that is made to the magnetometer data used to calculate *Dst*: The removal of the quiet time *Sq* ionospheric daily variation may also remove real diurnal magnetospheric effects. The effect of $\phi$ should not be confused with the dipole tilt effect commonly referred to as the Russell-McPherron effect [*Russell and McPherron*, 1973]. The Russell-McPherron effect is automatically included in the model from our use of GSM coordinates for the solar wind measurements but gives a smaller seasonal effect [*Cliver et al.*, 2000]. If $\phi$ is removed from the model, the RMS error increases to 7.34 nT, and the prediction efficiency decreases to 85%. This model has already been applied [*Li et al.*, 2001b] to describe the seasonal variation of magnetic activity as measured by *Dst*.

[21] In the Burton model, the state of the magnetosphere is described by one parameter, the pressure-adjusted *Dst*, which can be determined from the solar wind pressure and the current *Dst* measurement. Given this parameter, the change in *Dst* can be calculated from solar wind measurements. In our model, the state of the magnetosphere is described by seven parameters: $dst1(t)$, $dst2(t)$, $dst3(t)$, $dst1(t - \tau_1)$, $dst1(t - \tau_2)$, $dst2(t - \tau_1)$, and $dst3(t - \tau_3)$, and knowledge of the current *Dst* measurement and the current solar wind is not sufficient to allow one to integrate the value of *Dst* forward in time. Rather it is necessary first to determine the various values of *dstx* by integrating the equations forward in time using the solar wind as a driver. One can do this in practice by making reasonable initial assumptions for these values. The *dst*2 and *dst*3 contributions, because of their fast decay, quickly lose memory of their initial values, and this allows for a calculation of *dst*1. So in practice only about a day's worth of solar wind data should be necessary to properly initiate the integration.

## 3. Errors

[22] The error between the prediction and the measurement can be divided into four factors.

[23] Factor 1 is inaccurate or inappropriate solar wind measurements. Most of the solar wind measurements were made by the Wind satellite at various distances. It is known [*Collier et al.*, 1998] that such measurements do not correspond exactly to the solar wind as it strikes the magnetosphere. This is especially true for smaller scale features.

[24] Factor 2 is inaccuracies in the measurement of *Dst*. The "official Kyoto *Dst*" is derived from only four stations near but not at the magnetic equator. The secular variation and diurnal variations from the ionospheric currents are removed, but this removal is not perfect and may also remove actual magnetospheric currents as we have suggested. For 1995–1998 we have used the "final" *Dst*. For 1999 we have used the "provisional" *Dst*. For 1998, there were large differences (bigger than our average error) between the provisional and final *Dst*. The use of four stations can lead to different signals for exactly the same magnetospheric current depending on the local time of the station. (Note that the final *Dst* for 1999 is now available as of the time of the revision of this paper. Using the final *Dst* for 1999 gives 6.37 nT for the RMS error, a prediction efficiency of 88.4% and linear correlation coefficient of 0.941 without any change in the parameters. Some small further improvement can be achieved by further adjustment of the parameters.)

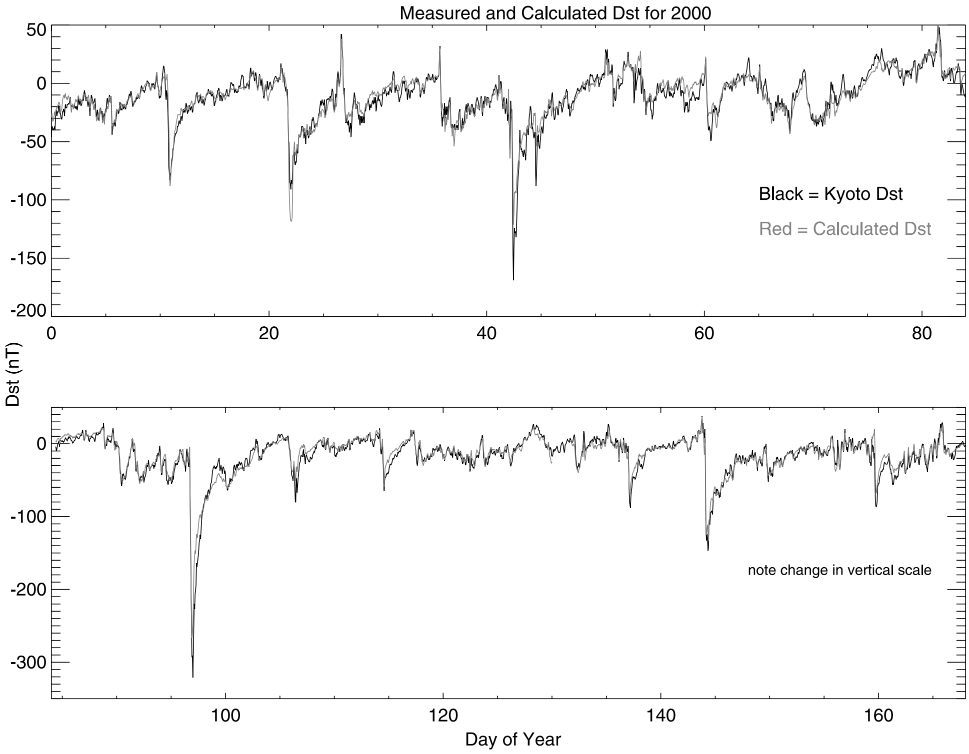


**Figure 3.** A comparison of the calculated *Dst* with the provisional *Dst* for the first 6 months of 2000. See color version of this figure at back of this issue.

[25] Factor 3 is inaccuracies in our model. Our model is far more complicated than some other models (e.g., the Burton model), but it is far simpler than the magnetosphere. The driver terms in our model enter as a product of solar wind parameters to some power or as the sine of some angle to some power. Such effects as the detailed previous history of the magnetosphere or the effect of solar cycle variations on the ionosphere (the *F*10.7 proxy for solar UV is often used to model this) are not included.

[26] Factor 4 is the inherent chaotic or complex behavior of the magnetosphere. There is currently a great deal of interest in this topic [*Klimas et al.*, 1996; *Chang*, 1999]. Because of the accuracy of our model despite factors 1, 2, and 3 above, we believe there is very little room for "chaotic or complex behavior of the magnetosphere" to play a major role in the large-scale currents that affect *Dst*.

[27] We have not done a detailed analysis of these errors. It would be relatively easy to determine the error due to factor 1 by comparing different upstream solar wind monitors. Factor 2 is somewhat more difficult to determine. A casual comparison of the "Kyoto *Dst*" with another measurement of "*Dst*," the "Amie *Dst*," [*Lu et al.*, 1998], for several storm periods, shows that different ways of measuring *Dst* differ from one another as much or more than our model differs from the "Kyoto *Dst*" and thus leads us to believe that the largest error is due to factor 2.

[28] A common comment is that with enough free parameters one can fit anything and we may appear to have many parameters. This is in fact not a significant criticism since we have far more data than parameters. (In fact, we believe that we do not have enough free parameters and that the physics is still more complicated than our model, or why do MHD simulations?) Still the best way to address this concern is to apply the model to data not used in determining the parameters. Figure 3 shows the model applied to first half of 2000 with the same parameters except for the offset terms. For this period the model gave a prediction efficiency of 91%, a linear correlation coefficient of 0.95, and a RMS error of 7.9 nT. The larger error but also larger prediction efficiency and correlation is consistent with a more active period and our already known result that during active times the error and prediction efficiency both increase. There is great opportunity for further improvement, discussion, and investigation. Much has not yet been mentioned: errors of the various terms, the physical significance of the various terms and their functional forms (i.e., does the direct IMF $b_z$ term really imply a direct penetration of the IMF into the magnetosphere?). Rather than investigate all this before publishing, we have decided to submit what we have, imperfect as it is. Our basic goal has been to describe the model in enough detail so that the interested reader may be able to duplicate and improve.

[29] The next three paragraphs have been added in response to one of the referees of this paper. One of the referees has asked that "the procedure for each parameter determination and discussion on the physical meaning of each term" be described in the text. The procedure for each parameter determination has already been mentioned: We have minimized the root square error (RMS error) between the prediction and the data to find the parameters. We have done the root square minimization "by hand." That is, we have run an IDL program that calculates solar wind based *Dst* and the RMS error. We then changed parameters in the program and calculated a new RMS error and so forth. We

also often tried different functional forms and after a few months of work have come up with the present results. We do not claim these are the best results. We know already from subsequent experimentation after including the final *Dst* for 1999 that the best parameters change. This is not surprising since incorrect inputs will lead to incorrect parameters, and neither the measured solar wind nor even the "final" Dst is an ideal parameter as has already been discussed above. The physical meaning of each term is not possible for us to describe since we do not understand the physical meaning of every term and regard that as a subject for further investigation. The terms we least understand are the direct IMF $b_z$ term, the additional terms in the pressure term, and the $b_y$ contribution to the *dst*1, *dst*2, and *dst*3. The pressure term in general is understood as due to the magnetopause currents.

[30] We have found all the terms by starting with the Burton formulation and then tried to improve it by adding additional solar wind parameters as has also been done by others [*Gonzalez et al.*, 1994]. In addition, we found that dividing the driver term into two parts (*dst*1 and *dst*2) gave a dramatic improvement. A further smaller improvement was then achieved by adding the *dst*3 term. The *dst*1 term undoubtedly represents to main ring current. The physical meaning of *dst*2 and *dst*3 is less clear but probably represents some combination of the so-called partial ring current and the tail currents. The basic physical interpretation of *dst*1, *dst*2, and *dst*3 is similar to the interpretation of the Burton equation: The solar wind through reconnection drives currents in the magnetosphere that then decay when the driver is removed or becomes less efficient. The form of the driver term then represents the efficiency of reconnection together with the effect of such reconnection in driving magnetospheric currents.

[31] It should, however, be understood that minimizing RMS error between the prediction and the data to find the best parameters does not lead to the best physical model or even the best physical parameters in any model but only to some approximation to such parameters. Consider the hypothetical case of the response of the magnetosphere to small-scale pressure pulses in the solar wind. A real upstream solar wind monitor will see only some fraction of the pulses that actually impinge on the magnetosphere and will see some pulses that will not in fact impinge on the magnetosphere (because the pulses are, by hypothesis, small-scale). Suppose further that the actually response of the magnetosphere to such pulses is known. We could then compare the actual response to that found by minimizing the RMS error. The two responses would be different. If, for instance, only half the pulses that impinge on the magnetosphere are seen by the upstream monitor and half the pulses seen by the upstream monitor do not in fact impinge on the magnetosphere, then the magnitude of the response found by the minimizing the RMS error will be about half the correct response.

## 4. Conclusion

[32] The dipole tilt with respect to the solar wind velocity has an important effect on the coupling efficiency of the magnetosphere with the solar wind. The currents that contribute to *Dst* have at least three distinct timescales. The magnetosphere is highly predictable, and chaotic behavior within the magnetosphere has little influence on the large-scale currents that determine *Dst*. The predictability of the magnetosphere has also recently been emphasized by *Li et al.* [2001a], who have shown that the variation of relativistic electrons at geostationary orbit can be well modeled using the solar wind as input.

[33] **Acknowledgments.** We appreciate the effort by the science teams (WDC for Geomagnetism, Kyoto, Wind/3D, Wind/Mag, ACE/SWEPAM, ACE/Mag) for making the data available. This work was supported by NSF grant ATM-9909358, 0101351 and NASA grant NAG5-9421, 10473.

[34] Hiroshi Matsumoto thanks the referees for their assistance in evaluating this paper.

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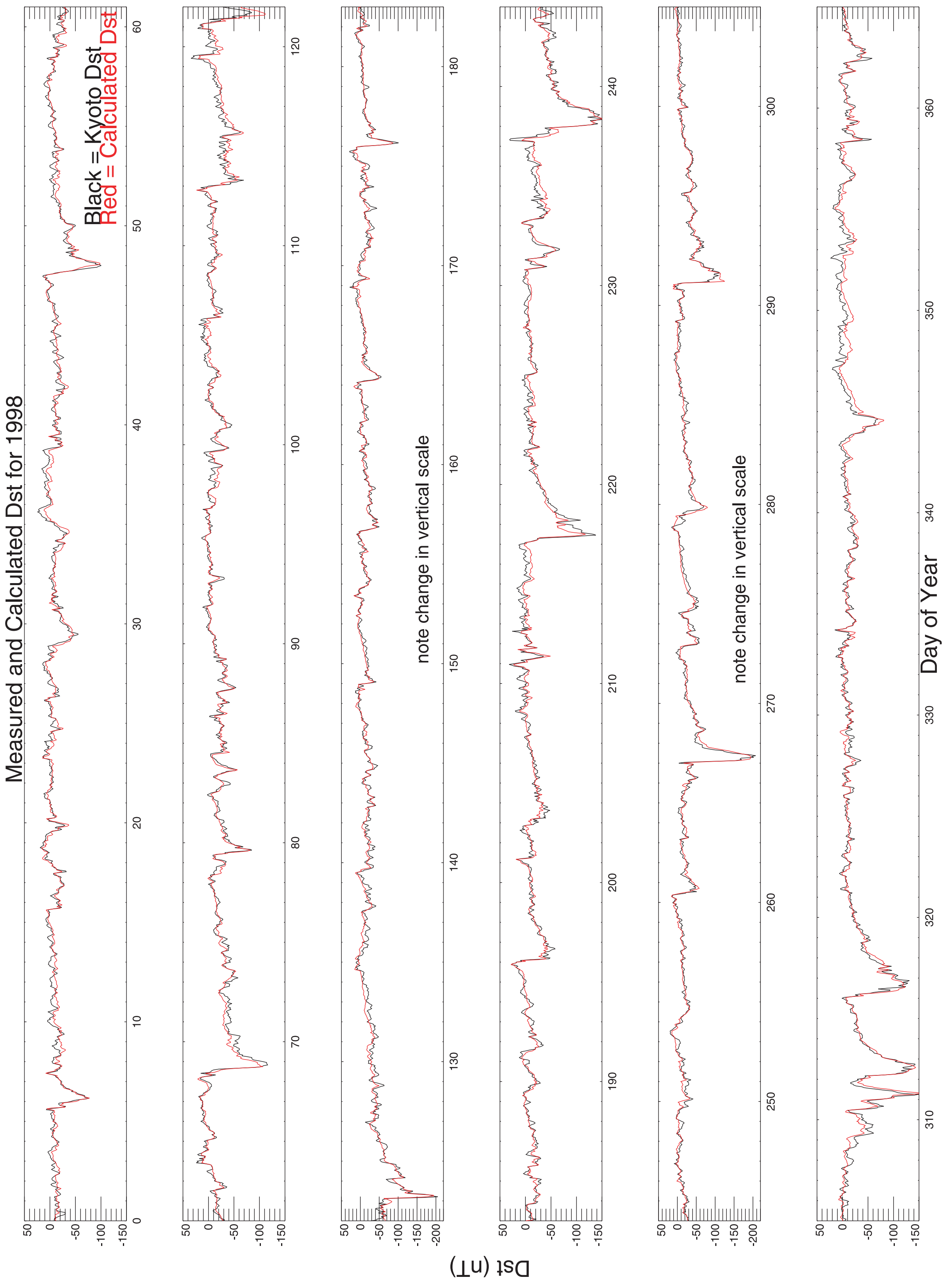


**Figure 1.** A comparison of the *Dst* index with the prediction for 1998.

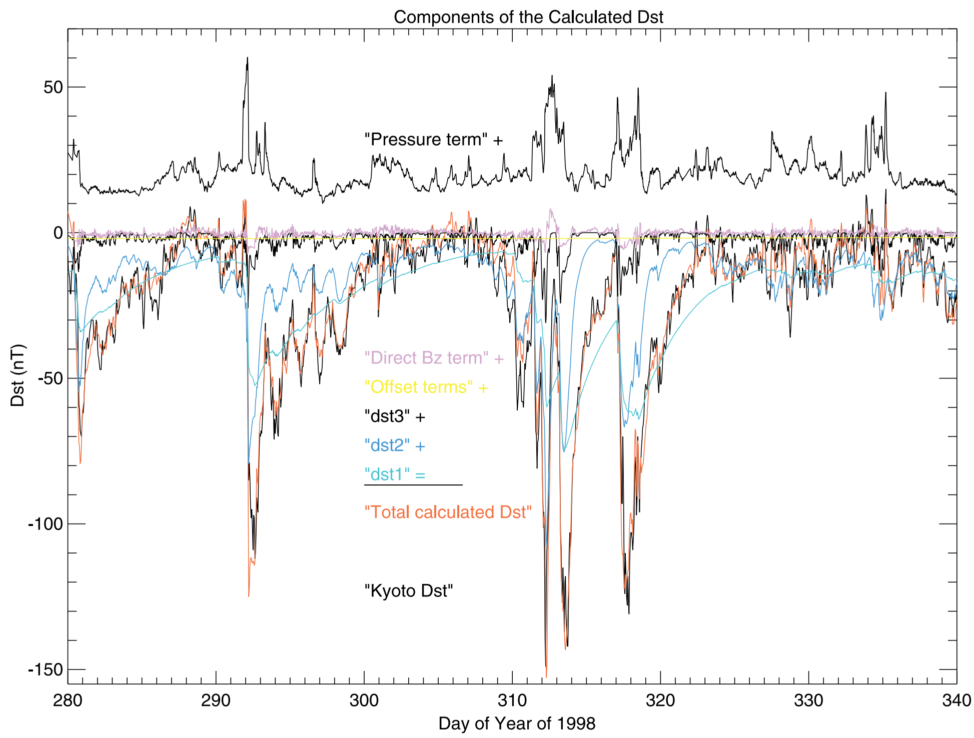


**Figure 2.** The calculated *Dst*, the components of the calculated *Dst*, and the *Dst* index for 60 days in 1998.

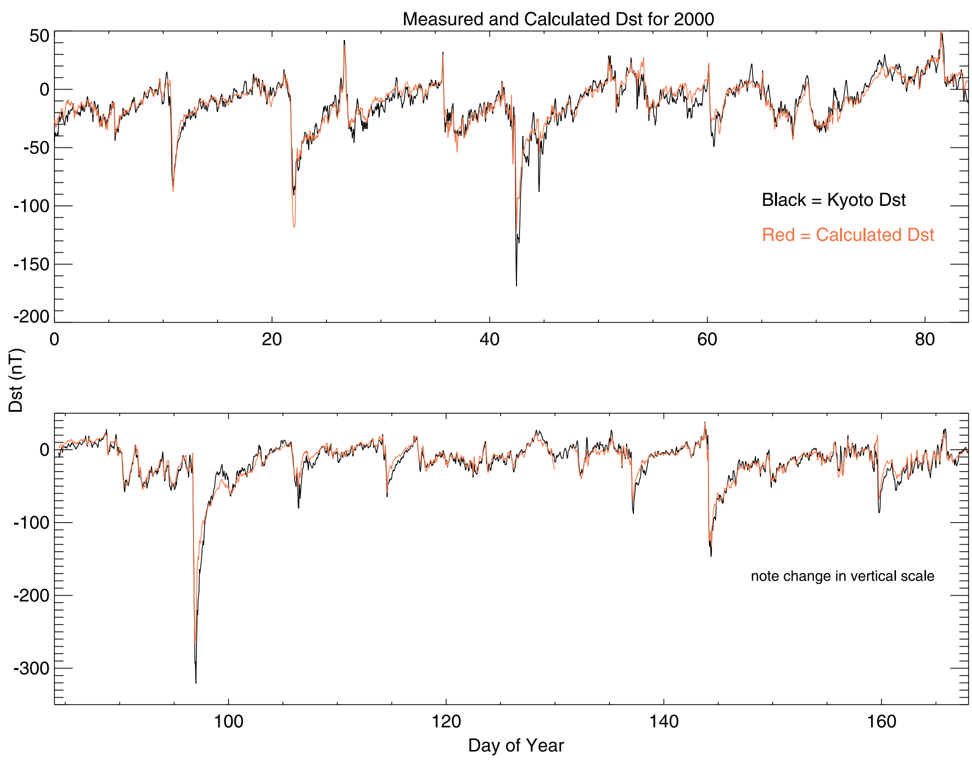


**Figure 3.** A comparison of the calculated *Dst* with the provisional *Dst* for the first 6 months of 2000.