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Key Points:
- Kyoto *Dst* index underestimates the solar cycle variation of magnetic activity
- Long-term averages of the Kyoto *Dst* index should be used with caution
- Quiet time currents produce a depression of the surface equatorial magnetic field of 15–30 nT

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The *Dst* index underestimates the solar cycle variation of geomagnetic activity

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Abstract It is known that the correction of the Kyoto *Dst* index for the secular variation of the Earth's internal field produces a discontinuity in the Kyoto *Dst* index at the end of each year. We show that this secular correction also introduces a significant baseline error to the Kyoto *Dst* index that leads to an underestimate of the solar cycle variation of geomagnetic activity and of the strength of the ring current as measured by the Kyoto *Dst* index. Thus, the average value of the Kyoto *Dst* index would be approximately 13 nT more negative for the active year 2003 compared to quiet years 2006 and 2009 if the Kyoto *Dst* index properly measured the effects of the ring current and other currents that influence the *Dst* observatories. Discontinuities in the Kyoto *Dst* index at the end of each year have an average value of about 5 nT, but the discontinuity at the end of year 2002 was approximately 12 nT, and the discontinuity at the end of year 1982 may have been as large as 20 nT.

1. Introduction

The Kyoto *Dst* index is widely used as an indicator of geomagnetic activity. For example, storm types have been defined based on the magnitude of the *Dst* index: minor storm ($-30\,\text{nT} > Dst > -50\,\text{nT}$), moderate storm ($-50\,\text{nT} > Dst > -100\,\text{nT}$), intense storm ($Dst < -100\,\text{nT}$), and great storm ($Dst < -250\,\text{nT}$) [e.g., *Gonzalez et al.*, 1999]. The *Dst* index is designed to be a measure of the magnetic perturbation near the equator from currents flowing above the ionosphere. As such, it is adjusted for the *Sq* dayside ionospheric current system and for the secular variation due to changes in the internal magnetic field of the Earth. The Kyoto *Dst* index baseline is corrected for the secular variation of the Earth's internal magnetic field by making a quadratic fit to each of the four *Dst* observatories by using the last 5 years of magnetic data from that observatory. Each year's contribution to the quadratic fit is based on the five quietest days of each month of that year. (The five quietest days of each month produce sixty values for that year, which are then averaged to produce a single value for that year. Then a quadratic fit is made to those five values. In a second step an additional point is added whose value is the baseline value at the end of the current year as determined in the first step, and then a second quadratic fit is done using this additional point [*Sugiura and Kamei*, 1991]). This introduces two problems. Since the baseline for each year is determined using a different set of years, a discontinuity occurs at the end of each year and because quiet days during solar maximum may not be as quiet as quiet days during solar minimum, the average *Dst* value may underestimate the change in magnetospheric activity between solar maximum and solar minimum. The main point of this report is that this is the case: the Kyoto *Dst* index underestimates the solar cycle variation of magnetic activity.

We have previously developed a model of the Kyoto *Dst* index based solely on the solar wind [*Temerin and Li*, 2002, 2006]. This model does a good job of duplicating the Kyoto *Dst* index for the years 1995–2002 using the solar wind magnetic field, velocity, and density as input. The model also had a baseline correction with a single discontinuity at the end of 1999 as we were not then aware that there was in fact a discontinuity at the end of each year in the Kyoto *Dst* index.

We have now extended the model to years 1995–2009 using OMNI solar wind data (instead of using solely Wind and ACE satellite data), added effects based on the $F_{10.7}$ index and effects using all three components of the solar wind velocity instead of just the V_x component. These additions produce interesting though minor improvements to the model. We intend to report on these improvements later. Here we report on the effect of changing the baseline correction to the model.

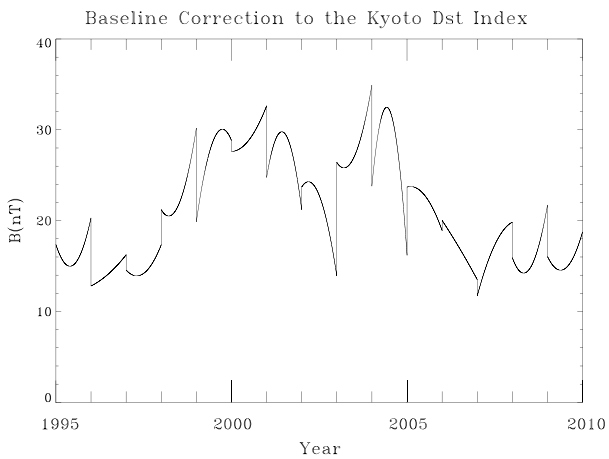

Figure 1. The baseline correction added to the model. The baseline correction uses a separate quadratic expression for each year. The three coefficients in each quadratic expression are found by minimizing the RMS difference between the model and Kyoto *Dst* index.

1.1. Effect of Baseline Correction

To find the baseline correction in the model we have made a quadratic fit to each year separately. The coefficients of each year's quadratic fit are found by minimizing the RMS error between the model and the final Kyoto *Dst* index. The resulting baseline correction in our model is shown in Figure 1. The baseline correction generally follows the solar cycle. The solar cycle has a minimum based on the sunspot number and the $F_{10.7}$ index in 1996 and again in 2008 and 2009 and a maximum in 2000 and 2001. Geomagnetic activity has a double peak in 2000 and an even larger peak during the declining phase of the solar cycle in 2003.

Figure 1 shows the baseline correction added to the model to minimize the RMS difference between the model and the Kyoto *Dst* index. In particular, notice the large discontinuity of about 12 nT at the end of 2002. Conversely, the values in Figure 1 can be regarded as the values that need to be subtracted from the Kyoto *Dst* index to make it agree with the model.

Figure 2 shows that the model with the baseline correction agrees well with the Kyoto *Dst* index.

Figure 3 (top) shows the model error without the baseline correction for the same time period. A large change in the error occurs at midnight on 31 December 2002. Figure 3 (bottom) shows the model error after the baseline correction is applied. Note that now the error has no apparent discontinuity. The error is the difference between model output and the Kyoto *Dst* index. (The Kyoto *Dst* index itself changes from −16 nT from the last hour of 2002 to −4 nT for the first hour of 2003.)

Figure 4 (top) shows the 27 day running average of the Kyoto *Dst* index and of the model if no baseline correction is applied. Note that there is less solar cycle variation in the averaged Kyoto *Dst* index than in the modeled *Dst* index. There is substantially more solar cycle variation in the modeled *Dst* index when no baseline correction is applied. Since the Kyoto *Dst* index is corrected using quiet days and since quiet days during solar maximum are likely to be less quiet than during solar minimum, the baseline correction we apply to our model to make it agree with the Kyoto *Dst* index removes much of the solar cycle variation in the averaged data. The modeled *Dst* with no baseline correction, however, does not remove the solar cycle variation in the process of removing the secular variation.

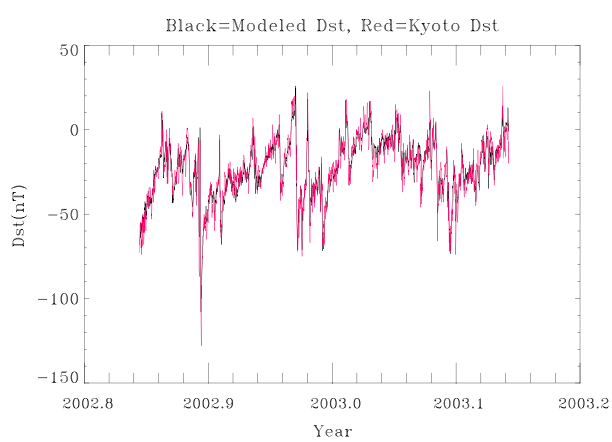

Figure 2. A comparison of the model output with the Kyoto *Dst* index for 3.5 months around the end of the year 2002. The baseline correction was applied to the model. The point of the figure is to show the good agreement between the model and the Kyoto *Dst* index.

Figure 4 (bottom) compares the 27 day moving averages once the baseline correction is applied to the model. Now the agreement between the model and the Kyoto *Dst* index is very good (correlation coefficient = 0.981). (Except for the baseline coefficients, the coefficients of the model were optimized using only data from the years 1995–2002.)

In addition, we have looked at all the year end final Kyoto *Dst* data between

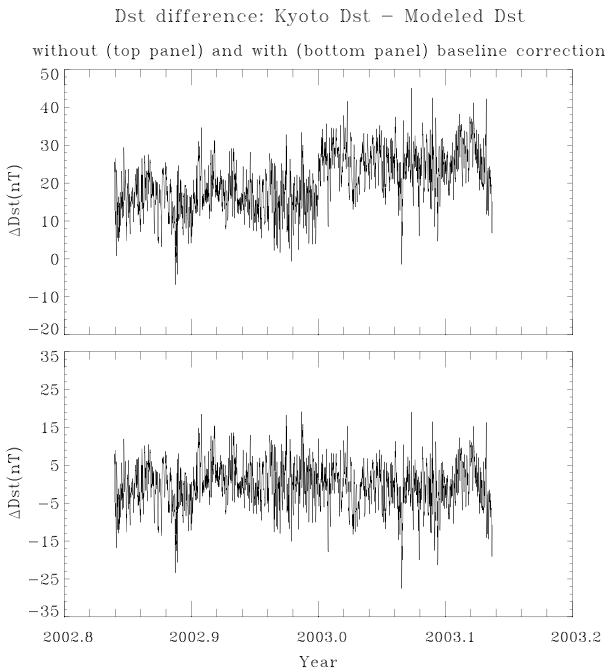

Figure 3. (top) The difference (i.e., the error) between the model and the Kyoto *Dst* index when the baseline correction is not applied to the model for the period shown in Figure 2. Note the discontinuity in the difference exactly at the end of the year 2002. (bottom) The difference once the baseline correction is applied to the model. The point of the figure is to demonstrate that the Kyoto *Dst* index can have significant discontinuities.

1957 and 2009 and found that the average change at the end of the year (5.9 nT) is more than twice as large as in each of the 2 h before and after (2.5 nT) the end of the year, implying an average discontinuity in the Kyoto *Dst* index of between 5 and 6 nT at the end of each year. (Recall that errors add quadratically rather than linearly.) The largest discontinuity appears to have occurred at the end of 1982 when the Kyoto *Dst* index decreased by 20 nT for no apparent reason. For any individual year it is not possible to determine the discontinuity by the change at year's end since some of the change can be physical. But by comparing the model with the *Dst* index as in Figure 3, it can be estimated well.

We conclude that the process of removing the secular variation from the Kyoto *Dst* index inadvertently removes some of the solar cycle variation. Thus, the average value of the Kyoto *Dst* index underestimates the modulation effects of the solar cycle on magnetospheric activity and in particular on the ring current. Conversely, if one uses the Kyoto *Dst* index to remove the magnetospheric current contribution to the magnetic field to determine the secular variation of the magnetic field, one will also get an incorrect result for the secular variation.

2. Discussion

It is our claim that the baseline as determined by the standard procedure used to remove the secular variation from the Kyoto *Dst* index results in significant offsets (errors) so that the Kyoto *Dst* index and especially its longer-term average do not accurately represent the magnetic effects near the equator of the Earth of currents flowing above the ionosphere and that the offsets determined by our model are more accurate.

The first part of this claim is clear. There are discontinuities in the Kyoto *Dst* index at the end of each year, which are typically larger during solar maximum and which, it is important to note, affect the level of the Kyoto *Dst* index for the rest of the year with respect to the previous year. In addition to the discontinuity at the end of each year, a different quadratic function determines the Kyoto *Dst* index baseline during that year.

The second part of our claim, that our model provides a better baseline offset, is maybe less clear. It is based on the fact that the model (without its own offset term) has no discontinuities at year's end and generally accurately reproduces the Kyoto *Dst* index based on the solar wind and now also on the $F_{10.7}$ index. It is however possible that if there are additional differences, not captured by the model, in the response of the magnetosphere between solar minimum and solar maximum, that some of the baseline correction determined by the model are corrections to the model's own incorrect response to the solar wind and the $F_{10.7}$ index. However, we can think of no reason this should be a large effect.

Laying aside the above concern we can say that the average value of the Kyoto *Dst* index should be approximately 13 nT more negative for the active year 2003 compared to quiet years 2006 and 2009 (since the values in Figure 1 should be subtracted from the *Dst* index to make it agree with model) and by

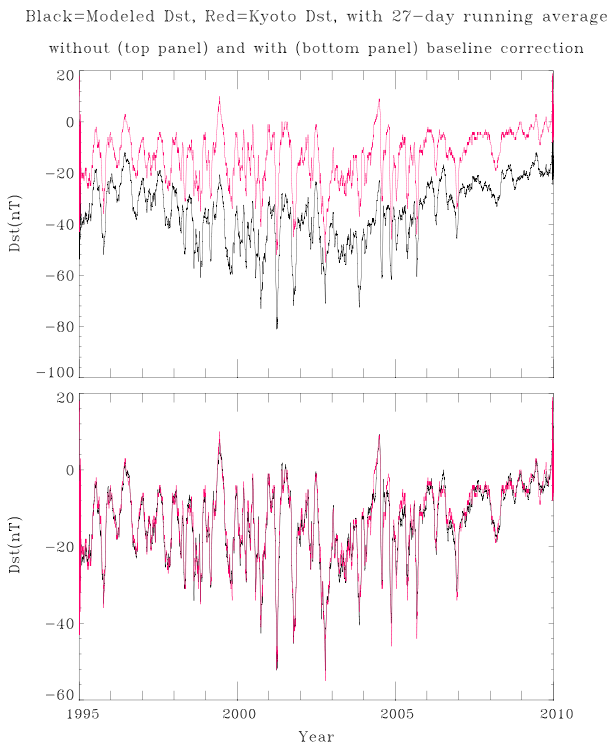

Figure 4. (top) A comparison of the 27 day running average of the Kyoto *Dst* index with the model with no baseline correction applied. The model with no correction shows a larger solar cycle variation. (bottom) The good agreement between the 27 day running averages when the baseline correction is applied to the model. It is important to note that our point is that the model without the baseline correction is a far more accurate representation of the effects of magnetospheric currents that affect the magnetic field at *Dst* observatories than the Kyoto *Dst* index.

implication, although we have not modeled other solar cycles, it is likely that the Kyoto *Dst* index more generally underestimates the solar cycle modulation of the surface magnetic field due to currents flowing above the ionosphere. The model also suggests that in addition to underestimating the solar cycle variation, the solar minimum-quiet baseline of the Kyoto *Dst* index should be around −15 nT as is clear from Figure 1 while the baseline during solar maximum can vary between about −20 nT and more than −30 nT. That is to say during solar minimum when the Kyoto *Dst* index reads 0 nT, currents flowing above the ionosphere produce a negative depression of the surface equatorial magnetic field of about −15 nT while during solar maximum when the Kyoto *Dst* index reads 0 nT such currents produce a negative depression of the surface equatorial magnetic field between −20 and −30 nT.

We care more about the relative change in the baseline offset between solar minimum and solar maximum than we do about its average value. The relative change is much less sensitive to changes in the model parameters than the average value. Nevertheless, we note that our baseline offset has an average value of 21.2 nT (23.0 nT if only the first 11 years are used to avoid two solar minima). This is very similar to the 20 nT constant in the Burton equation [*Burton et al.*, 1975], which is based on a much simpler model of the response of *Dst* to the solar wind. *Jorgensen et al.* [2004], using CRRES satellite magnetometer data, also conclude that "there is an offset in the *Dst* index so that *Dst* = 0 actually corresponds to a ring current that would create a 20 nT depression." Thus, our average baseline offset corresponds well to the effect of the quiet time ring current as determined by others.

Our results have significant implications for statistical studies of geomagnetic storms. In such studies, thresholds are often set; such that, for instance, a *Dst* value of less than −30 nT is considered an indication of a geomagnetic storm [e.g., *Gonzalez et al.*, 1999] and that a period when *Dst* remains above −30 nT is regarded as nonstorm [e.g., *Schiller et al.*, 2014]. Since *Dst* can differ by over 10 nT from nonphysical baseline corrections, threshold values should be carefully considered.

We like the Kyoto *Dst* index. After making our baseline correction we get a correlation coefficient of 0.965 between our model and the Kyoto *Dst* index for the years 1995–2002 using only the solar wind and the $F_{10.7}$ index (a good but not perfect [e.g., *Chen et al.*, 2011] proxy for the solar EUV flux and thus for the ionization of the ionosphere) as input to our model. Such a good correlation would not be possible if the Kyoto *Dst* index had large random components. Still, no index is perfect, and others have also tried to remove its defects, both real and imaginary. *Karinen and Mursula* [2005] have created a new index they call *Dxt*. The index is created in the same manner as the Kyoto *Dst* but extends back to 1932 and corrects a few technical issues with the Kyoto *Dst* index. Since the secular variation in the *Dxt* index is removed in the same manner as in the Kyoto *Dst* index, the problem that we have identified here remains in the *Dxt* index. *Karinen and Mursula* [2005] then use annual averages of the *Dxt* index to study the long-term and solar cycle variations of the *Dxt* index. Given that the correction for the secular variation can introduce

both random and systematic variations in the annual average of *Dst* and *Dxt*, the results of such studies should be accepted with care.

Mursula and Karinen [2005] and *Karinen and Mursula* [2006] have also created another index that they call *Dcx*, which they say removes the excessive semiannual variation in the *Dst* index related to the semiannual, nonstorm time behavior of the *Dst* index. We have not noticed an "excessive" semiannual variation in Kyoto *Dst* index and suggest that in the same manner that quiet days during solar maximum are on average less quiet than quiet days during solar minimum, quiet days around the equinoxes are less quiet than quiet days around the solstices.

Love and Gannon [2009] have created another index that they call $Dst^{5807\text{-}4SH}$. This index removes much of residual *Sq* current system variation that remains in the Kyoto *Dst* index. The residual *Sq* current system variation is indeed a problem with the Kyoto *Dst* index and can dominate the error in our model during quiet times [*Temerin and Li*, 2006]. (Much of the high-frequency error seen in Figure 3 is probably due to this.) However, $Dst^{5807\text{-}4SH}$ also removes other regular variations including the excessive semiannual variation and even perhaps some of the solar cycle variation. Also, the magnetosphere has a real diurnal variation since the reconnection rate can depend on the angle between the dipole axis and the solar wind velocity that can also be removed when effects of the *Sq* current system are removed. *Svalgaard* [2005] has suggested using another index (*Dsv*) that depends only on nighttime observations to avoid problems with the *Sq* current system that mostly affects daytime observations.

The creation of both the *Dcx* and $Dst^{5807\text{-}4SH}$ indices seems motivated by a desire to remove the nonstorm component of the *Dst* index. We think that making a hard distinction between storm and nonstorm or quiet times in the *Dst* index is not useful. The *Dst* index and the magnetospheric currents that it reflects are constantly changing in response to the changing solar wind. For instance, it is impossible to find something corresponding to a "quiet" level in the 3.5 months of data shown in Figure 2, and the number of magnetic storms during this interval depends on ones arbitrary threshold for determining storms: there are number of excursions of the *Dst* index below −50 nT and even more below −30 nT.

3. Summary

We have shown that the average value of the Kyoto *Dst* index should be approximately 13 nT more negative for the active year 2003 compared to quiet years 2006 and 2009 and that discontinuities in the Kyoto *Dst* index at the end of each year have an average value of about 5 nT but may be as large as 20 nT. This implies that the Kyoto *Dst* index underestimates the solar cycle variation of currents above the ionosphere that affect the surface equatorial magnetic field. Our study also implies that quiet time currents above the ionosphere produce a negative depression of the surface equatorial magnetic field of at least −15 nT even during solar minimum and as much as −30 nT during solar maximum.

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