SuperMAG-based partial ring current indices

P. T. Newell¹ and J. W. Gjerloev²

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[1] Using the extensive set of stations in the SuperMAG collaboration, we introduce partial ring current indices, which provide new insights into ring current development. The indices are labeled SMR-00, SMR-06, SMR-12 and SMR-18 for their center local time range. These indices incorporate data from 98 mid and low latitude stations. The behavior of these local time indices during storms and substorms, on both an individual and superposed epoch basis, produces consistent patterns. The initial positive spike before a storm, which results from solar wind pressure enhancements, is seen simultaneously at all local times. Once the main phase of the storm begins, however, SMR-18 nearly always drops fastest and furthest in magnitude, while SMR-06 drops more slowly (i.e., has weaker ring current signatures), and never as far. Symmetry is, in fact, not reached until storm recovery is well underway, with a typical symmetry point of about 20–25 h after onset. If the main phase continues to new depths (larger magnitude negative SMR) over a longer time period, the SMR-18 sector will continue to lead, and SMR-06 to lag. There has been controversy over the extent to which substorm auroral and cross-tail currents perturb Dst and SYM-H signatures. The signature of substorms can be seen very clearly as a positive spike of roughly 10 nT magnitude in SMR-00, and only to a much lesser extent elsewhere. The SMR global index, and thus also SYM-H, experiences only a small immediate perturbation from a substorm onset, ending with a net drop of a few nT. Since there are typically only 1–2 substorms in a main phase, substorms are a minor factor in the development of the storm time ring current. Indeed, because even the peak perturbation of substorm currents in the most affected sector (which is midnight) is nearly an order of magnitude smaller than the storm perturbation (about 10 nT versus 80 nT), fluctuations in the cross-tail and field-aligned currents in general are not a major influence over SMR. The pattern of LT substorm responses, with a strong positive SMR-00 effect, weak positive SMR-06 effect, and negative SMR-18 effect implies it is field-aligned currents and not the cross-tail currents which create modest perturbations in the putatively ring current indices.


1. Introduction

[2] Dst is often regarded as the geomagnetic index having the clearest physical interpretation [Dessler and Parker, 1959; Skopke, 1966], while also being the easiest to predict purely from solar wind observations [Burton et al., 1975; Temerin and Li, 2006]. The simple – and we will herein conclude, largely correct – view is that Dst represents the energy of the suprathermal ions circulating about the Earth, and is produced by energization of plasma sheet ions by solar wind driving. But, as is typical in the messy field of space physics, complications abound.

[3] The extent to which alternate current sources affect Dst and its higher time resolution twin SYM-H (symmetric horizontal component of a low or midlatitude magnetometer station) has been much mooted. We regard Dst and SYM-H as essentially the same measurement at different time resolution, as in fact was explicitly verified by Wanliss and Showalter [2006]. For example Fukushima and Kamide [1973] argued that field-aligned Birkeland currents play a major role in affecting Dst, and were largely responsible for the apparent local time variations sometimes reported for ground magnetometers. More recently the emphasis has been placed on the possible effect of the cross-tail current on Dst, especially from a global magnetic field modeling perspective [e.g., Alexeev et al., 1996; Kalegaev et al., 2005]. Likewise, the effects of substorms on the ring current has been variously reported, with many arguing for an absence
of a significant relationship [e.g., Kamide et al., 1998] while Ohtani et al. [2005] has actually suggested that substorms (or at least dipolarizations) actually reduceDst magnitude and the number of energetic ions in the ring current.

[4] A key aspect of the puzzle is that the simplifying assumption of an azimuthally invariant $H$-perturbation as observed from low or midlatitude ground stations is often far from correct. Instead, strong local time variations can be seen in the $H$ component of midlatitude stations. This observation early on led to speculation of a partial ring current formation, with the dusk-to-midnight sector typically considered to be the formation site (or, at any rate, to have the stronger depressions inSYM-H). Some authors, such as Fukushima and Kamide [1973] concluded that other current systems, notably the Birkeland currents, are responsible for this local time asymmetry, and that the actual ring current was largely symmetric. Contrary to that view, in situ measurements have convincingly shown the reality of significant local time variations in the ring current [De Michielis et al., 1997; Greenspan and Hamilton, 2000]. Given that ion injection must occur in local times in contact with the nightside plasma sheet, and that ions are lost through charge exchange, precipitation, and contact with the frontside magnetopause as they drift westward toward dawn, most researchers today accept that significant local time variations do exist in the ring current. However, it is difficult to monitor this systematically. Even with the impressive advances from global imaging with IMAGE [DeMajistre et al., 2004; Ohtani et al., 2005; Nosé et al., 2011] and TWINS [Valek et al., 2010] it is still difficult to compare the ring current strength at different local time sectors at a time resolution comparable to the time scale to the variations observed. Meanwhile ground-based observations [Li et al., 2011] have shown that local time asymmetries arise early in a storm, and tend to disappear during the recovery.

[5] Here we take advantage of the SuperMAG collaboration, currently involving several hundred magnetometer stations including many disparate chains, to introduce the SMR index. The new index in its composite or global version is conceptually the same asSYM-H, but uses 98 low and midlatitude magnetometers rather than 6 (as is the case forSYM-H) or 4 (as is the case forDst). Because of this extended coverage, it is possible to include local time components, consisting ofSMR-00,SMR-06,SMR-12, andSMR-18, each of which is named for their respective local time center point. These new indices make it possible to track variations on a consistent and global basis. A study of the results shows that local time variations are so routine, systematic, and striking. These clearly indicate partial ring current is clearly shown to be the norm, at least until well into storm recovery. It also turns out to be possible to more clearly distinguish the effects of substorms on the indices; these prove to be more modest than often supposed.

2. Data and Methods

2.1. The SuperMAG Collaboration and Data Processing

[6] SuperMAG is a worldwide collaboration of organizations and national agencies that currently operate ~350 ground-based magnetometers. In an earlier paper introducing the SuperMAG auroral electrojet indices [Newell and Gjerloev, 2011a], we list the extensive set of collaborators, which will not then be repeated here. SuperMAG utilizes vector measurements of the magnetic field, which represent a variety of file formats, temporal resolutions, units, and coordinate systems, and are provided with or without baseline subtracted. The SuperMAG project resamples the data to 1-min temporal resolution and converts all units into nanoteslas (nT). The data is cleaned and artifacts removed by both manual and automatic procedures. Data are converted into a geomagnetic coordinate system in which the “$H$” component points toward local magnetic north. The baseline subtraction approach is an important part of created geomagnetic indices.

[7] The SuperMAG initiative requires an automated and objective baseline method, since decades of data from more than 350 stations are included. One of us therefore developed a new procedure for finding the undisturbed daily variations of the magnetic field which forms the baseline (J. W. Gjerloev, The SuperMAG data processing technique, submitted to Journal of Geophysical Research, 2012). The automated procedure removes yearly trend as well as the daily variation (including contributions from theSq current system) in two steps. Both steps use a sliding window and bin data according to magnitude, and determine a typical value. For example, the yearly trend is calculated by determining a single value for each day which is then subtracted from the 1-min data after a simple interpolation between discrete daily values (since the change from one day to the next is typically <1 nT, no more complex interpolation is meaningful). This single value is determined for day N using a 17 day window centered at day N. The 17-day window was chosen to balance the competing interests of avoiding seasonal variations, which favors a shorter window, and avoiding ring current perturbation, which favors a longer window. The value for this day is then determined by fitting a Gaussian to the distribution of the binned data, designed to pick a characteristic value, not an average value. This technique is used to avoid the inherent problems for mean, which is affected by extreme values, and for the median, which implicitly assumes a symmetric distribution.

[8] In the future (probably coinciding with the publication of this paper), the SMR local time ring current indices will be available on the SuperMAG web sites at JHU/APL and at the University of Bergen. We anticipate that all years from 1980 through 2010 should be available by roughly the time this paper is published. There are no data gaps in SuperMAG temporal coverage or indices, although the number of contributing stations does vary (and is specified in each index record).

[9] Figure 2 shows the distribution of stations contributing toSMR index, in both geographic and geomagnetic coordinates. Altogether there are 98 stations lying below 50° MLAT (in Altitude Adjusted Corrected Geomagnetic Coordinates, quite similar to invariant latitude) for which data is contributed. The most sparsely covered area is the Pacific Ocean, whereas the Americas and Europe are well represented.

2.2. Creating the SMR Local Indices

[10] Once data from all contributing stations is cleaned, and if necessary resampled into 1-min cadence, it is rotated into a common coordinate system in which the “$H$”
component tracks toward local geomagnetic north. The first estimate of a global average $H$ component then follows the outline specified by T. Iyemori, M. Takeda, M. Nose, Y. Odagi, and H. Toh (Web publication wdc.kugi.kyoto-u.ac.jp, 2010). This includes, for example, dividing by $\cos(\theta_m)$, where $\theta_m$ is the dipole latitude of each station. However, we then calculate an average "$H" component separately for each 6 h interval in LT, rather than globally. The center point for the averages define the indices, thus SMR-00 covers 2100–0300 LT. The composite global value, SMR, is taken to be the average of the four indices, rather than (as is the case for SYM-H) an average over all contributing stations. The reason is that we wish the index to be independent of the number of stations that happen to lie within a given local time sector.

3. Local Time Variations Observed in the SMR Indices

[11] If the ring current were axially symmetric, the "$H" component measured around the globe would be substantially the same, excepting perhaps for substorm produced deviations on the nightside. To test whether that is true, Figure 2 shows the correlation between the $H$ inferred by the SuperMAG stations, calculated in the same way as the Kyoto SYM-H, as a function of their spatial separation. Contrary to the simple assumption of axial symmetry, stations which are close together exhibit a high degree of correlation, while stations widely separated in longitude exhibit a much lower correlation. It should be noted that the standard SYM-H correction for latitude (refer to section 2.2) are
applied before the correlations were calculated in Figure 2. The relatively low correlations seen for very small values of $\text{SYM-H}$ (a few nT) are not particularly worrisome. However, even for $\text{SYM-H}$ large enough to represent a significant storm, say above 80 nT, only stations within less than 50 degrees longitudinal separation are highly correlated.

[12] These results suggest that dividing the globe into as many as 6–8 local time sectors could be profitable in terms of understanding the geophysical evolution of the ring current. However, the practical consideration of maintaining good coverage in each sector permits just four local time sectors. Note that at least all stations within a chosen sector index are highly correlated with the center point time (that is, no station is more than 45 degrees away from the nominal local time specified).

[13] As a first step in searching for local time variations, the probability distribution functions (PDFs) of these four sectors are plotted in Figure 3 (top). The shapes are certainly broadly similar, with modes around 0 nT, and with the expected long tails skewed toward large negative values. Noon is the LT most likely to have positive values. Pressure compression of the frontside magnetopause can move the magnetopause currents closer to the Earth, which has long been understood to be a source of such positive values for the $H$ component observed by ground stations.

Figure 3. The probability distribution functions for the 1 min values of the SMR indices. (top) Distribution of the four local time sectors. (bottom) Comparison of the SMR value (average of the sectors) versus Kyoto $\text{SYM-H}$. 
The PDF for the sector centered at 1800 MLT is larger than other sectors for large negative values, while the PDF for dawn is smallest for large negative values. Dusk is the symmetry point, since SMR-12 behaves very much like SMR-00 for any significantly negative value. 

Figure 3 (bottom) compares the PDF of the global SMR index with the SYM-H distribution downloaded from Kyoto World Data Center over the same 11 year period (1996–2007). The global behavior of these two indices is quite similar, as is expected. The PDF for SYM-H can be fitted to a distribution which is bi-normal in log(SYM-H) [e.g., Wanliss and Weygand, 2007], and it is unlikely that SMR is any different. The situation in which SMR is very similar to SYM-H is quite different from the auroral electrojet for which we introduced an SMR index predicting auroral behavior much better than does AE. The auroral currents are relatively localized, so the use of a large number of ground stations in deriving SME results in an index much more able to track auroral power and determine substorm onsets than does AE. However, the more global nature of the ring current perturbations means that a similarly large improvement in the ability to monitor the overall ring current strength is not to be expected. The main value of the SMR index is to be found in the local time variations, not the simple global average. 

These distributions are simply the 1-min values observed over 11 years, and do not reveal how these sectors differ during ring current formation and decline. Therefore in section 4, we consider how storms and substorms affect SMR regional distributions.

4. Typical Storm and Substorm Behavior

As its etymology suggests, Dst is intended to monitor storms – hence the nomenclature, which arises from “Disturbance storm time.” Since the realization that substorms can occur quite independently of storms, the influence of substorms on the Dst index, and its higher time resolution twin SYM-H, has been a source of controversy. The questions to be resolved involve both the extent to which additional current systems affect SYM-H, and the extent to which the geophysical ring current intensity is affected by substorms.

4.1. Examples of Storm Behavior

Figure 4 (top) shows the evolution of the four SMR sector indices over the course of a storm that began around minute 69100 of 2005 – or, more conventionally put, around 23:40 UT on Feb 17, 2005 (we consider the start of storms to occur only after the SMR sum goes negative, not when the initial positive spike – the sudden storm commencement or SSC – occurs). As Figure 4 (bottom) shows, an abrupt change in solar wind parameters with an increase in the merging rate calculated according to the formula proposed by Newell et al. [2007] occurred around 6.91 × 10^4 min, leading to a simultaneous positive deviation in all four SMR sectors. A series of substorms follows, with multiple further strong auroral intensifications. These substorms are responsible for the positive excursion seen in SMR-00 but not seen in the other indices. As the storm and thus ring current develops, all SMR regional indices drop, with SMR-18 leading, while SMR-06 lags.

The four sectors do not converge around minute of the year 6.98 × 10^4 (roughly 12 h after onset) by which time the storm is well into recovery. This behavior is almost universal, with symmetry established only during recovery, and never near the peak of the storm.

A careful reader might note an upward spike in the SMR-00 index around 6.915 × 10^4 minutes. This is associated with a series of recurrent substorms as identified by the SME auroral electrojet indices [Newell and Gjerloev, 2011a]. Another important point is that SMR-18 drops to the most negative values, while SMR-00 joins SMR-12 at intermediate values around the peak of the storm. SMR-06 falls the least. After convergence, the short-term additional deviations are associated with additional substorms (a large one happened just after 7.00 × 10^4 min). As the magnetosphere quiets, the convergence becomes more complete.

Figure 5 shows one of the few storms we could find which developed roughly synchronously around the globe in the early stages of negative SYM-H excursion. This storm starts about minute 193500 of 2005 (or May 15 at 0900 UT). The synchronicity for the positive spike before the storm is not unusual – indeed, it is rather the rule – but both the rapidity of the subsequent drop and its similarity at all local times. Figure 5 (bottom) shows the solar wind and IMF data associated with this event, again lagged to the magnetopause. We do not know what the distinguishing feature is that makes the initial stages of ring current development more symmetric in this event. Nonetheless, even in this example SMR-18 bottoms out at significantly more negative values than does SMR-06 (about −300 nT versus −220 nT).

We have individually examined several score storms, which evinced a variety of local time variations. Although it is impossible to characterize all the possible variety with a few figures, Figure 6 shows two more “typical” examples. In Figure 6 (top), notice that the local time index which most closely tracks SMR-18 is not SMR-00 but rather SMR-12. Again, the narrow upward spikes in SMR-00 are all coincident with substorms. Also, as is virtually always the case, local time symmetry is only established during recovery, in fact, once again about 12 h after the minimum (largest negative amplitude) was reached for SMR-18.

In Figure 6 (bottom), only the dawn sector lags in the initial drop, but it is SMR-00 which more closely follows SMR-18 (in our survey, this seemed to be more common, although the statistics do not necessarily verify that pattern, as section 4.2 will show). The deepest minimum is still eventually observed in SMR-18 alone, as is typically (albeit not universally) the case. Once again, local time symmetry is established during recovery, about 12 h after the minimum.

4.2. Superposed Epoch Analysis of Storm Behavior

We identified 125 instances of storms over the interval 1997–2007, based on a minimum Dst < −80 nT. The behavior of SMR = (SMR-00 + SMR-06 + SMR-12 + SMR-18)/4, as well as Dst and SYM-H is plotted in Figure 7 (top). All three indices exhibit essentially the same behavior, as one should expect. The expansion in the four stations used for Dst to the six used for SYM-H and even up to the 98 used for SMR does not change the fact that the ensemble average behavior over many storms of the symmetric-H component observed at low and midlatitude during a typical storm is much the same. The differences which do exist are apparently related primarily to the methodology for computing the quiet time baseline.
Figure 4. (top) A storm occurring on minute 69100 of 2005 (23:40 UT on Feb 17). The dusk sector drops the most, while the dawn sector lags. The upward spikes in SMR-00 correspond to substorms. Symmetry does not occur until recovery. (bottom) IMF and solar wind data for this event. The bottom panel is an estimator of the dayside merging rate, which spikes up as the storm starts.
Figure 5. (top) SMR indices for a storm occurring about minute 193500 of 2005 (or 15 May 0900 UT). This behavior has the best initial synchronicity of those we have examined. Nonetheless, by the time the minimum in SMR is reached, the usual dispersion exists, with dusk the most depressed and dawn (and in this case noon) the least. (bottom) Solar wind and IMF data. The bottom image shows the spike in dayside merging which occurs as the ring current develops.
However the regional indices show that large local time variations are hidden by a composite single index. Figure 7 (bottom) shows the superposed epoch variation of the four local time indices separately. This is perhaps the crucial figure for this paper. Several significant results can be seen in Figure 7 (bottom), starting with sorting the intensity of the ring current by sector. To wit, SMR-06 shows the least depression, SMR-12 and SMR-00 are roughly equal, while SMR-18 shows the largest depression. The differences are not minor; the depression in SMR-18 is close to double that of SMR-06. This sharp difference between dawn and dusk is presumably why the recent study of Li et al. [2011] focuses exclusively on the ratio between those two to study the partial ring current.

By looking at four different local time sectors we can see in Figure 7 (bottom) that the local time sector with the enhanced H component is not dusk-to-midnight, but rather approximately symmetric about dusk. In particular, the SMR-00 trace most closely matches SMR-12, not SMR-18. The time scale for ion drifts around the Earth is commensurate with the time until the dawn sector re-establishes synchronicity with the other indices. This is on the order of 12 h. Thus with minimum in SMR-18 reached about 10 h after onset, synchronicity is established about 15 more hours after that, at onset +25 h. In individual storms which take longer to reach the maximum, it still takes about another 12–15 h after the maximum for this convergence of the differing sectors to occur. These results strongly suggest that ions are not as easily introduced into the ring current on the dawn side as other local times, but instead require ion drift to reach approximate symmetry. Indeed, much of the H-component perturbation that is observed in the dawn sector might well arise from the influence of the partial ring current at other local times.

Figure 6. Two more storms showing the variety of LT variations. (top) Notice that noon tracks dusk fairly closely, while both SMR-00 and SMR-06 drop less. (bottom) The most typical pattern, with dawn dropping the least, dusk the most. In the early stages, midnight tracks closely with dusk.
4.3. Example of Substorm Behavior

The effects of substorms on the ring current (and, somewhat separately, on the ring current indices) has been much debated. To separate out how a substorm impacts the symmetric-\(H\) indices, it is helpful to consider cases which occur outside storm times. Figure 8 shows a typical series of substorms, which were previously identified using SML, the SuperMag generalization of \(AL\) [Newell and Gjerloev, 2011b]. In Figure 8, each substorm onset is marked by a vertical dashed line. The obvious feature is that \(SMR\)-00 shows a sharp but brief spike of roughly 15 nT (occasionally more) commencing at onset. The rise reverses after about 10–20 min, shorter than the superposed epoch time for substorm recovery. For example, both hemispheric auroral power [Newell et al., 2010] and the SME index [Newell and Gjerloev, 2011a] take about 35–50 min to peak, and more than 2 h to recover. However, in case studies, such as this, recovery is quicker (superposed epoch studies are always more blurred, and include the possibility of subsequent onsets).

Based on a limited set of case studies, the signature in the \(SMR\)-00 index is reliable, and could be worth investigating as a substorm onset indicator in its own right. Despite this perturbation in \(SMR\)-00, there is very little effect on the overall ring current indices. In particular, the \(Dst\), \(SYM-H\), and \(SMR\) indices are not greatly affected by this series of substorms. For brevity, the next section (4.4) will show only the superposed epoch versions of the latter.

Figure 7. A superposed epoch study of 125 storms. (top) \(SMR\), \(SYM-H\) and \(Dst\). (bottom) The four regional \(SMR\) indices.
4.4. Superposed Epoch Substorm Behavior

[30] Figure 9 (top) shows how the four local time SRM sector indices vary over the course of 23436 substorms from 1997 to 2007. Although the plot has a synchronized \( t = 0 \) based on onset, this synchronization is never perfect, and each substorm behaves a bit differently. As a result, the rise in SMR-00 is somewhat smaller in magnitude and somewhat more spread out in time compared to the observations of individual substorms. Nonetheless, the essential features are the same: the largest perturbation occurs in SMR-00, has a risetime scale of tens of minutes, and a recovery time less than 2 h. The SMR-18 index sometimes moves the opposite direction during substorms, although with a smaller amplitude (as does SMR-12). Overall, Figure 9 (top) quantifies the effects substorms have on the ring current related indices: small, but negative. Notice that all four of the individual LT sector indices end a few nT lower than they started. This is not because of increased solar wind driving, incidentally, since actually solar wind driving is reduced just before onset and drops thereafter [Newell and Liou, 2011]. Therefore the substorm itself does create a small (a few nT) negative net change.

[31] The question naturally arises as to the source of these substorm induced perturbations in the putatively ring current indices. It seems that the cross-tail currents can be ruled out. If the cross-tail current is taken to lie 10 or more \( R_E \) down-tail, all LT sectors on Earth should experience roughly the same perturbation. However, the substorm current wedge should create a strong positive response in the midnight sector. The overall pattern of Figure 9 strongly suggests that field-aligned currents are the main source of perturbations to the SMR indices. Any effect of the cross-tail current disruption, would affect all LT approximately equally.

[32] Figure 9 (bottom) shows how the summary indices vary. Because of the relatively short time scales involved, we plot only SMR and SYM-H, not the hourly \( Dst \) value (though it, too, has an average net change of a few nT negative around substorm onset). The global indices show much less variation than do the local indices, with only a very small (1–2 nT) short-lived positive excursion around onset, followed by a decline to a few nT less than before the substorm. The tiny short-lived variation in all four indices around onset may be due to variation in the cross-tail current. The longer term variation, which is still small, may be the net effect of substorms on actual ring current. These figures show that substorms do appear to contribute to the ring current, but only slightly. The storms we selected reach \( Dst \) of \(-80\) nT. Typically there are a very small number of substorms during the development of the storms. Since the net effect of each substorm is only a few nT or less, it seems unlikely that substorms contribute significantly to ring current development. Conversely, it is not true that substorms have no effect on the ring current: each substorm does produce a net \(-2–3\) nT drop around onset in SMR and SYM-H.

[33] The consistency between the individual cases and the statistical pattern is quite good, except that in individual cases the magnitude of the SMR-00 deviation is somewhat larger, and one or more of the other components often participates to a lesser extent.

5. Discussion

5.1. Reconciliation With In Situ Observations

[34] In recent years, there seems to be increasing agreement that the ring current can be “partial,” with the dawn sector statistically weaker [e.g., De Michelis et al., 1997; Greenspan and Hamilton, 2000]. Early results from the SMR sector indices go a step further and show that, in fact, the ring current is rarely axially symmetric, except well into the recovery stage of a storm. The dawn sector does have the least perturbation of the SYM-H component, so there is agreement between the high-altitude equatorial observations.
and the ground stations (for that matter, global MHD simulations also show the dawn sector having the smallest ring current, mostly because of particle loss, through process such as intersection with the magnetopause). The major putative discrepancy between the magnetometer observations and the in situ ring current observations arises from the fact that the latter indicate the midnight or dusk-to-midnight sector has the most intense ring current, while the SMR index shows noon and midnight are about comparable, with both below $SMR_{-18}$.

[35] It is beyond the scope of this paper to attempt a simulation of a realistic complete ring current and reproduce the expected effects on the ground. But we can demonstrate at least that the observation on the ground of similar sized $SMR_{-00}$ and $SMR_{-12}$ does not disagree with the in situ observations of a much stronger midnight ring current. Figure 10 shows what is happening schematically. On the right is a plot of the radial profile of azimuthal current ($J_{\text{perp}}$) inferred for moderate conditions by De Michelis et al. [1997]. Between 3 $R_E$ and about 4.25 $R_E$, the current is actually eastward. Thereafter, out to the limit of measurement, about 8 $R_E$, the current is the familiar westward current associated with the ring current. Notice that both magnetometers in the $SMR_{-12}$ and in the $SMR_{-00}$ region are affected by this midnight current. In fact, the plots given by De Michelis et al. [1997] show a weak enough current at

![Superposed Epoch Substorm (Isolated) SMR LT Variation](image1)

![SMR and SYM-H Superposed Epoch Variation](image2)

**Figure 9.** Superposed epoch variation of (top) $SMR$ regional indices and of (bottom) the global $SMR$ and $SYM-H$ around the onset of isolated substorms. Only the $SMR_{-00}$ index shows a significant variation on an ensemble basis. Notice that the global indices are barely perturbed by substorms, somewhat contrary to some expectations.
noon that even \( SMR-12 \) will experience mainly the effects of the midnight ring current. Now the strength of a line current varies as

\[
\Delta H = 0.2^*\frac{I}{x} \quad (H \text{ in Gauss}, \ x \text{ in cm}, \ I \text{ in Amperes}). \tag{1}
\]

The distance \( x \) is, of course, \( 2 R_E \) greater when evaluated at noon than at midnight. We made a simple assumption of a \( 2 R_E \) thick layer to convert the numbers of De Michelis et al. [1997] into Amperes per unit radial distance, then integrated Figure 10 over \( x \) to infer how both a magnetometer at noon and one at midnight would be affected by the in situ average ring current shown in Figure 10. The ring current density measured near noon is small enough to only be a minor perturbation on the signature observable by a noon or midnight station.

[36] The result of this simple calculation is that the inferred perturbation at noon is \(-1.7 \) nT, and at midnight \(-2.1 \) nT. The calculation is quite sensitive to the profile of the current distribution. The existence of both eastward and westward currents means there is no real chance of reconstructing the global ring current purely from the single integrated measurement seen on the ground. However, conversely, it does appear that predicting the signatures seen at each local time is a good test for ring current models, and certainly tougher than predicting a single global \( Dst \) value.

5.2. Ring Current Change Around Substorms

[37] There has been something of a pendulum swing back and forth on notions of whether substorms contribute to \( Dst \) (that is, increase the magnitude of \( Dst \), making it more negative). (For that matter, the relation of \( Dst \) to the physical ring current is still sometimes questioned [Nosé et al., 2011].) The name “substorm” itself suggests a close connection to storms, and that was a common early assumption. Later reports have variously suggested the effects of substorms on ring currents as increasing \( Dst \), having no effect on \( Dst \), or even actually creating a positive swing in \( Dst \). The latter finding has particularly been found in a fairly large and thorough work by Ohtani et al. [2005]. How can this be reconciled with the results shown in Figure 9, which clearly show \( Dst \) is made more negative by substorms?

[38] Although the sample size in Ohtani et al. [2005] \textit{et al.} is much smaller – just 63 cases versus more than 23,000 in
that is not likely to be the only reason for such a stark difference. Results are often determined more by event selection criteria than the number of events. Figure 9 is chosen for the set of all isolated substorms, whereas the events chosen by Ohtani et al. [2005] are all during storms. Presumably this is the reason why the latter authors focused on dipolarizations rather than substorm onsets, which are much more difficult to identify under storm conditions. All the dipolarizations events considered are thus at a time when the ring current is already large. If one choses a random time when \( \text{Dst} \) is required to be large, the expected variation on both sides of the selected epoch is a reversion to mean. In fact, that is a reasonable interpretation of what Ohtani et al. [2005] found – a minimum in \( \text{Dst} \) at the chosen event epoch (which coincides with a dipolarization, but always is during a storm), with a rise in \( \text{Dst} \) on either side.

To check this explanation, we considered substorm onsets that occur when \( \text{Dst} \) is fairly large. To match the selection criteria of Ohtani et al. [2005] as closely as possible, we used their value of \( \text{Dst} < -50 \text{ nT} \) as the threshold criterion, rather than the \( -80 \text{ nT} \) level used for storms elsewhere in this paper. Figure 11 shows superposed epoch study for substorms which occur during a storm, so defined. This shows that \( \text{Dst} \) declines before the onset while remaining roughly flat thereafter. Recalling that picking a random time with \( \text{Dst} < -50 \text{ nT} \) produces a plot with a

**Figure 11.** Superposed epoch variations around substorm onset, but with the condition that \( \text{Dst} < -50 \text{ nT} \) at onset. (top) The four local time SMR indices and (bottom) global indices, SMR and SYM-H.
minimum at the imposed time and a rise on either side, the results shown in Figure 11 still appear to be consistent with the intrinsic effect of a substorm to be an enhancement of the strength of the ring current.

[40] Figure 11 does fall short of a complete reconciliation between the two studies, in that we find that the imposing the storm time condition (i.e., $D$s $< -50$ nT) only flattens out the enhancement of $D$s otherwise seen around storm onset, but we do not reach the $O$htani et al. [2005] result of an actual positive swing. Again, the latter is the same result that would be obtained by picking a random time with $D$s $< -50$ nT, namely a reversion toward mean on either side of the epoch of imposed condition. It is possible that some of the dipolarizations considered in the earlier paper are not, in fact, substorms. At any rate, substorms, as defined by the $S$ML index, do appear to produce a modest contribution to the ring current, shifting $S$MR (and $S$YM-$H$) a few nT more negative.

6. Summary and Conclusions

[41] The SuperMAG collaboration has about 98 magnetometers in the latitude range currently used for constructing $S$YM-$H$ (six stations) and $D$s (constructed using four). The exact number contributing to SuperMAG does vary somewhat from year to year. We used this larger number of stations to create the first regional, or partial ring current indices, $S$MR-$00$, $S$MR-$06$, $S$MR-$12$, and $S$MR-$18$, at one minute cadence for the years 1980–2010. Studying how these regional indices vary during storms and during substorms for the period 1997–2007 allows several conclusions to be drawn.

[42] Perhaps the most important is that the effects of substorms and their concomitant perturbations to the cross tail and auroral currents on the global ring current indices—including $D$s, $S$YM-$H$, and $S$MR—is much smaller than sometimes predicted or feared. This can be determined because the $S$MR-$00$ index shows substorms very clearly, with a rise on the order of 10–15 nT over 10–20 min in case studies, although the full superposed epoch cycle is about 100 min (presumably including recurrent substorms). The pattern of LT variations clearly indicates that it is auroral currents into the ionosphere and not the cross-tail current which constitute the biggest perturbation. This pattern includes a large positive signature near midnight, a smaller more gradual perturbation near dawn, and a negative signature at dusk.

[43] In contrast to these transient local-time dependent changes, the global indices including $S$MR and also the Kyoto $S$YM-$H$ value, are only slightly changed by a substorm onset, with perhaps a 2–3 nT net negative change from start to end. We interpret this net negative change as the modest and real (that is, geophysical) increase in ring current strength resulting from a substorm.

[44] The global ring current indices however do have a hidden weakness. Storms have strong, consistent, and highly reproducible local time differences as observed from ground magnetometers. These differences appear early in a storm, with dawn ($S$MR-$06$) dropping the least, and dusk ($S$MR-$18$) dropping the most, to the largest magnitude negative value. Symmetry does not occur until recovery is well under way, and thus $S$MR-$06$ never reach the values of the other indices. Since the time for $S$MR-$06$ to approach values seen in other sectors is about 12 h after the minimum in $S$MR (or $S$YM-$H$), it appears that only the processes of particle drift and ring current loss create axial symmetry.

[45] The regional indices show $S$MR-$00$ and $S$MR-$12$ are highly comparable in magnitude. By contrast, in situ observations suggest that the ring current is much stronger at midnight than at dawn. Simple calculations suggest that the reverse polarity inward ring current, which is eastward between 3 and about 4.5 RE [De Michelis et al., 1997] accounts for this putative discrepancy. Quite simply, the $2RE$ thickness of the Earth is a much larger fraction of the radial distance for this inner eastward current than for the westward current, located further out around 5–8 RE. Thus magnetometers in the $S$MR-$00$ zone are more strongly affected by the inner current. The contrast between the signatures seen on the ground in differing local time sectors is sensitive to the assumed profile of the geomagnetic currents. It does not seem possible that the detailed profile of the ring current could be constructed purely from the $S$MR regional indices. Nonetheless, since the differences between the local time sectors are profound, and follow repeatable patterns, $S$MR provides a far more discriminating test of ring current models than does the single global average value.

[46] We conclude that a regional version of the existing $S$YM-$H$ indices, namely the $S$MR indices introduced here, are valuable both to separate out the effects of substorms (which mainly affects $S$MR-$00$) and to provide a more stringent target for physical modeling of the ring current.

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