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Centennial increase in geomagnetic activity: Latitudinal differences and global estimates

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[1] We study here the centennial change in geomagnetic activity using the newly proposed Inter-Hour Variability (*IHV*) index. We correct the earlier estimates of the centennial increase by taking into account the effect of the change of the sampling of the magnetic field from one sample per hour to hourly means in the first years of the previous century. Since the *IHV* index is a variability index, the larger variability in the case of hourly sampling leads, without due correction, to excessively large values in the beginning of the century and an underestimated centennial increase. We discuss two ways to extract the necessary sampling calibration factors and show that they agree very well with each other. The effect of calibration is especially large at the midlatitude Cheltenham/Fredricksburg (CLH/FRD) station where the centennial increase changes from only 6% to 24% caused by calibration. Sampling calibration also leads to a larger centennial increase of global geomagnetic activity based on the *IHV* index. The results verify a significant centennial increase in global geomagnetic activity, in a qualitative agreement with the *aa* index, although a quantitative comparison is not warranted. We also find that the centennial increase has a rather strong and curious latitudinal dependence. It is largest at high latitudes. Quite unexpectedly, it is larger at low latitudes than at midlatitudes. These new findings indicate interesting long-term changes in near-Earth space. We also discuss possible internal and external causes for these observed differences. The centennial change of geomagnetic activity may be partly affected by changes in external conditions, partly by the secular decrease of the Earth's magnetic moment whose effect in near-Earth space may be larger than estimated so far.

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1. Introduction

[2] One of the most interesting and important questions in solar-terrestrial physics is whether the magnetic activity of the Sun has indeed greatly increased during the last 100 years. A significant increase in solar activity is indicated, for example, by the well-known fact that the average amplitude of sunspot cycles during the latter half of the 20th century is higher than in the beginning. The increasing sunspot activity leads, according to a simple model presented by *Solanki et al.* [2000, 2002], to a long-term increase in the total solar magnetic field, as well as in the open solar magnetic field, i.e., in the heliospheric magnetic field (HMF) (also called the interplanetary magnetic field).

[3] In recent years, geomagnetic activity (GA) has become a very important heliospheric parameter. The *aa* index [see, e.g., *Mayaud*, 1980] is, because of its exceptionally long time span, one of the most common proxies of GA in long-term studies and has been used, for example, to examine the long-term change in the solar wind and in the heliospheric magnetic field. On the basis of the *aa* index, *Lockwood et al.* [1999] suggested that the radial component of the heliospheric magnetic field is now more than twice as strong as 100 years ago. Cosmic rays and cosmogenic isotopes have also been used to study the long-term change in the heliosphere. *Usoskin et al.* [2003] and *Solanki et al.* [2004] have shown, using the ^{10}Be and ^{14}C isotopes and a chain of physical models, that the present solar activity level is unique at the timescale of a thousand or even several thousand years.

[4] Despite the seeming versatility and conformity of these important results, one may argue that they are mainly based on qualitative rather than quantitative agreement. In particular, the model by *Solanki et al.* [2002] includes adjustable parameters which can lead to very different quantitative estimates for the change of the heliospheric field. Also, the results based on cosmogenic isotopes do not yield an independent, quantitative estimate of past solar activity because of their dependence on other than solar factors, such as climatic and atmospheric effects in the case of ^{10}Be and global circulation in the case of ^{14}C. However, geomagnetic activity can give an independent estimate of the changing heliospheric conditions and solar activity

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Table 1. Information on Stations Used[a]

Station	IAGA Code	Geographic Coordinates		Geomagnetic Coordinates		MN Hour	Data Start	HMS Start
		Latitude, deg	Longitude, deg	Latitude, deg	Longitude, deg			
Sodankylä	SOD	67.47	26.60	63.96	120.25	2200	1914	1914
Sitka	SIT	57.05	224.67	60.33	279.79	0900	1902	1915
Niemegk	NGK	52.07	12.68	51.89	97.69	2300	1901	1905
Cheltenham	CLH	38.73	283.16	49.14	353.71	0500	1901	1915
Fredericksburg	FRD	38.20	282.63	48.59	353.11	0500	1956	1956
Tucson	TUC	32.25	249.17	40.06	315.63	0700	1909	1915
Honolulu	HON	21.31	201.91	21.57	269.37	1000	1902	1915

[a]Magnetic coordinates are calculated using the IGRF 2000 model. MN hour indicates the local midnight hour in UT, and HMS start stands for the year when hourly mean sampling started.

during the last 150 years. Thus, although there are still several open questions related to its heliospheric causes, the value of geomagnetic activity is raised as, perhaps, the most important heliospheric parameter for studying solar change during the last 100–150 years.

[5] However, serious concern has recently been raised regarding long-term indices of geomagnetic activity and the centennial rise of solar activity based on them. In particular, the long-term consistency of the geomagnetic *aa* index, which has been the only measure of global geomagnetic activity in centennial timescales, has been seriously questioned [*Svalgaard et al.*, 2003, 2004]. One should also note that the *aa* index (and many other similar proxies) cannot be properly reproduced or verified at the present time, for example, because the original measurements do not exist in digital format. Because of this situation, *Svalgaard et al.* [2004] introduced the so-called Inter-Hour Variability (*IHV*) index as a more straightforward, homogeneous, and easily verifiable measure of long-term geomagnetic activity. The *IHV* index is defined as an average of six absolute differences of the successive hourly values of the *H* component between 1900 and 0100 local time. Note that since the hourly values of the measured magnetic field are available in digital format in the World Data Centers for several stations, the *IHV* index can be easily calculated and verified.

[6] Using the data from the Cheltenham/Fredricksburg station pair only, *Svalgaard et al.* [2004] found no evidence for an increase in the corresponding *IHV* index during the last 100 years. However, *Mursula et al.* [2004] calculated the *IHV* index for several stations and found that geomagnetic activity follows the same qualitative long-term pattern at all stations: an increase from the early 1900s to 1960, a dramatic dropout in the 1960s, and a weaker increase thereafter. At all stations, the activity at the end of the 20th century was found to have a higher average level than at the beginning of the century. Although this qualitatively agrees with the result based on the *aa* index, the quantitative estimate of the centennial increase in global geomagnetic activity was found to be considerably smaller, only about one half of that depicted by the *aa* index. The difference was even larger if only midlatitude stations were used, close to the latitudes of the *aa* stations.

[7] In this paper we note that the very early registrations of hourly magnetic field values used hourly samples (often measured at a sharp hour or half hour) rather than hourly means which were consistently used at all stations only later. Since the hourly samples have a larger variability than the hourly means, this will affect the value of the *IHV* index, which is also a measure of magnetic variability. Accordingly, without correcting this change in sampling, the *IHV* values in the beginning of the last century will become artificially large, and the centennial increase will be underestimated. Here we calibrate the effect of changed sampling to the *IHV* indices at a number of stations in order to quantify more reliably the amount of the centennial increase in geomagnetic activity.

2. Stations, Data, and *IHV* Indices

[8] We will use here data mostly from the same stations as were used by *Mursula et al.* [2004]. However, we will omit the Eskdalemuir (ESK) station in the present study, since the data of this station depict problems that have not yet been fully quantified (see later discussion). The six stations (actually, five stations and one station pair) included in the present study have the longest and most uniform records of magnetic observations from the early 1900s onward. The codes, coordinates, local midnight UT hours, start years of observations, and start years of hourly mean registration (as opposed to hourly samples) of these stations are depicted in Table 1.

[9] As mentioned above, the *IHV* index [*Svalgaard et al.*, 2004] is defined as an average of the six absolute differences of the successive hourly values of the *H* component between 1900 and 0100 local time (LT). This definition was originally based on the fairly flat daily curve at the Cheltenham/Fredricksburg (CLH/FRD) station in this LT sector and on the fact that this LT sector is geomagnetically the most active. We have used this definition to calculate the *IHV* values for the six stations. These will be called the *IHV*-raw indices.

[10] As discussed by *Mursula et al.* [2004], the range of the daily curve varies with solar activity and more closely with geomagnetic activity at high latitudes. Therefore it is also affected by the long-term change. Since geomagnetic activity is defined as a deviation from the quiet time daily curve, the long-term variation in the daily range has to be removed from the *IHV* index. This was done by *Mursula et al.* [2004] as follows. We first calculated the yearly averaged daily curves for each station in order to obtain a proxy for the quiet time daily variation in each year. Then we calculated the yearly quiet time *IHV* value, the so-called *IHV-q*, from these smooth yearly curves. Finally, the corrected *IHV*-cor index was obtained by subtracting the yearly *IHV-q* values from the original daily *IHV*-raw index. Here we will study the effect of the changed sampling both on the

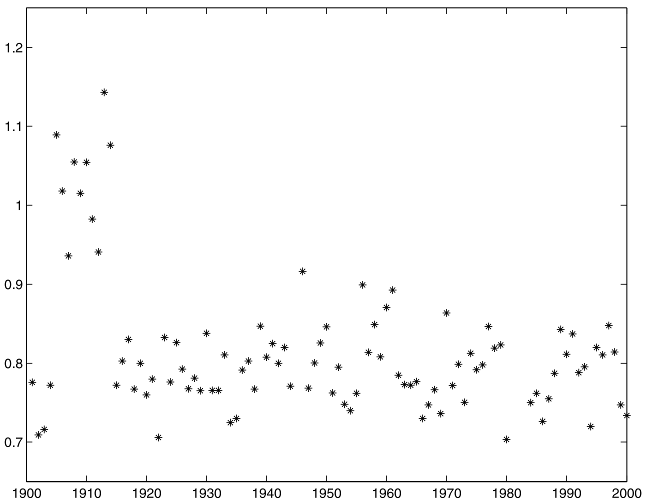

Figure 1. Ratio of annual *IHV*-raw values between CLH/FRD and NGK. The effect of changing sampling is seen as an increase of the ratio from 1904 to 1905 (when NGK sampling changed) and a decrease from 1914 to 1915 (when CLH sampling changed).

original *IHV*-raw and on the daily curve corrected *IHV*-cor indices.

3. Sampling and Other Data Problems

[11] As shown in Table 1, many stations changed their registration from hourly sampling to hourly means in 1915. However, at Niemegk (NGK) this was already done in 1905. (Sodankylä (SOD) used hourly means from the start of observations in 1914.) We have depicted in Figure 1 the ratio of the annual averages of *IHV*-raw values between CLH/FRD and NGK. The effect of the changed sampling is seen as an increase of the ratio from a roughly constant lower level to a higher level in 1905 when NGK sampling was changed and as a decrease of the ratio back to a lower (roughly but not quite similar) level in 1915 when CLH sampling was changed. We have calculated the average level of the CLH/FRD-NGK ratio in 1901–1904 (0.7433), in 1905–1914 (1.031), and since 1915 (0.7918). The ratio 1.031/0.7433 = 1.39 gives an estimate of the required sampling calibration factor for NGK *IHV*-raw, while the ratio 1.031/0.7918 = 1.30 gives a similar estimate for CLH/FRD *IHV*-raw. One way to calibrate the sampling change would be to divide the uncalibrated annual *IHV*-raw indices by these and similar calibration factors. However, as will be discussed later, we have used another method which leads to quite similar results.

[12] We have estimated similarly the sampling calibration factors for the six stations using NGK as a reference station because of its earlier sampling change. These calibration factors (called the RC-raw and RC-cor calibration factors) are depicted in Table 2. As Table 2 shows, the effect of the sampling change in *IHV*-raw is to increase it by about 20–40%. As noted above, this change is due to hourly samples having a larger variability than hourly means which, without due correction, leads to artificially large *IHV* values in the beginning of the last century. Table 2 shows that the sampling calibration factors are indeed quite large and therefore that the level of geomagnetic activity in the beginning of the last century and the centennial trend were greatly underestimated in earlier analyses using the *IHV* index [*Svalgaard et al.*, 2004; *Mursula et al.*, 2004].

[13] A similar step to that shown in Figure 1 is seen in the station versus NGK ratio in all other stations except for Sitka (SIT) for tens of years after 1915, allowing a robust estimate for the calibration factor. At SIT, large fluctuations in the NGK ratio made the estimate of the calibration factor more uncertain. The value obtained for SIT, 1.14, is also smaller than for any other station. However, we have also calculated the similar ratios for *IHV*-cor where the steps are seen even more clearly, even at SIT. It is interesting to note that in all cases the RC-cor calibration factors for *IHV*-cor are quite close (within 10%) to the RC-raw for *IHV*-raw (see Table 2). Also, the RC-cor calibration factor for SIT (1.27) is much closer to the RC-cor calibration factors of all other stations. (Note that we obtain only one estimate of RC factor for all other stations but three independent estimates for NGK from its ratios with CLH/FRD, SIT, and Honolulu (HON). HON and CLH/FRD ratios yield quite a similar result for NGK, but SIT gives a larger value of about 1.60. Because of the above-mentioned problems with SIT, we use the mean of the two other stations for NGK in Table 2.)

[14] When calculating the above IHV ratios for the various stations, we found a problem with the ESK station. Figure 2 shows the similar ratio of yearly *IHV*-raw values between ESK and NGK stations. A much larger step of about 60–70% is seen in 1932 which cannot be understood in terms of the sampling being changed from hourly samples to hourly means. (A similar step is also seen in the ratio of ESK and all other stations, even at the same time. Thus the problem is with the ESK data.) Because of this feature, the ESK data, without due correction, are inappropriate for a long-term analysis of geomagnetic activity using the *IHV* method and will be omitted in the present analysis. A detailed study analyzing and correcting the ESK data is under preparation. Note also that a recent paper by *Clilverd et al.* [2005] calculating the *IHV* index for

Table 2. Sampling Calibration Factors RC-raw and RC-cor for *IHV*-raw and *IHV*-cor From Station/NGK Ratios and MH-raw and MH-*q* for *IHV*-raw and *IHV*-*q* From the 1-Minute/1-Hour Ratios in 1996 and 2000

Station 2000	RC-raw	RC-cor	MH-raw 1996	MH-raw 2000	MH-*q* 1996	MH-*q* 2000
SIT	1.14	1.27	1.40	1.30	0.923	0.939
NGK	1.39	1.41	1.37	1.36	1.19	1.68
CLH/FRD	1.30	1.32	1.30	1.32	0.940	1.52
TUC	1.29	1.43	1.35	1.30	0.897	0.941
HON	1.21	1.31	1.17	1.18	0.904	1.04

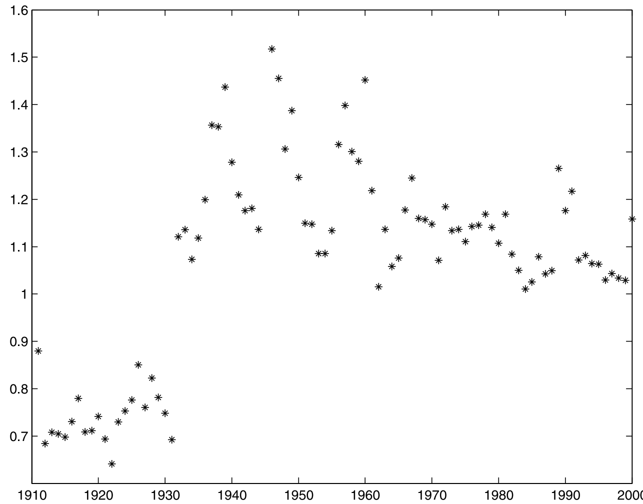

Figure 2. Ratio of annual *IHV* values between ESK and NGK. An abrupt increase of the ratio is seen to occur in 1932. This is due to an error in ESK data to be discussed in a separate paper.

the ESK station without any correction is erroneous in this part.

4. Solving the Sampling Problem

[15] In order to further examine the validity and size of the calibration factors extracted as above, we have made another, more detailed study as follows. Since, for the more recent years, we have more frequently sampled data available from all stations, we have constructed two series of daily *IHV*-raw values for each station: one (to be called 1-min *IHV*-raw) using 1-min resolution data, taking only one 1-min sample per hour, and the second (to be called 1-hour *IHV*-raw) using hourly means of the same station. These two daily *IHV*-raw series were calculated for one sunspot minimum year, 1996, and one sunspot maximum year, 2000. Figure 3 depicts the 1-min and 1-hour *IHV*-raw indices in 1996 and 2000 for the NGK station. The two series of daily *IHV*-raw values were then averaged to annual means whose ratio, which is called here the minute-hour raw (MH-raw) ratio, was calculated for the 2 years. These ratios form another set of calibration factors for the *IHV*-raw indices at the various stations and are included in Table 2. Note that these MH-raw calibration factors are mostly very close to the calibration factors found above, using station versus NGK ratios of annual *IHV* indices. This verifies the consistency of the two methods and the size of the calibration needed to correct the effect of the changed sampling upon the *IHV* index.

[16] Note also the interesting fact that for three stations, the MH-raw calibration factors are in a weak inverse relation with sunspot activity although, in principle, higher solar activity should lead to larger variability and therefore to a larger calibration factor. This can be understood by noting that higher solar activity also enhances the range of daily variation [see, e.g., *Mursula et al.*, 2004]. Thus, if the inclination of the *IHV* section of the daily curve increases with solar activity, the increased variability caused by

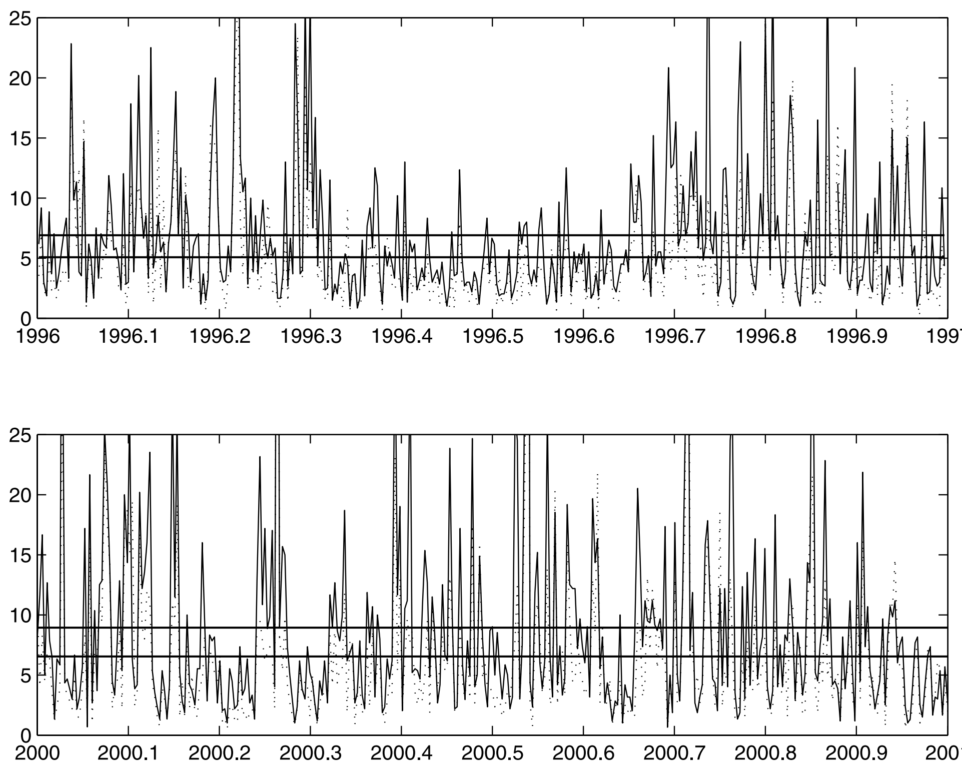

Figure 3. Daily *IHV* values calculated from the hourly samples (solid lines) and hourly means (dotted lines) for the NGK station for (top) 1996 and (bottom) 2000. Horizontal lines depict the corresponding yearly averages for *IHV* using hourly samples (top lines) and hourly means (bottom lines).

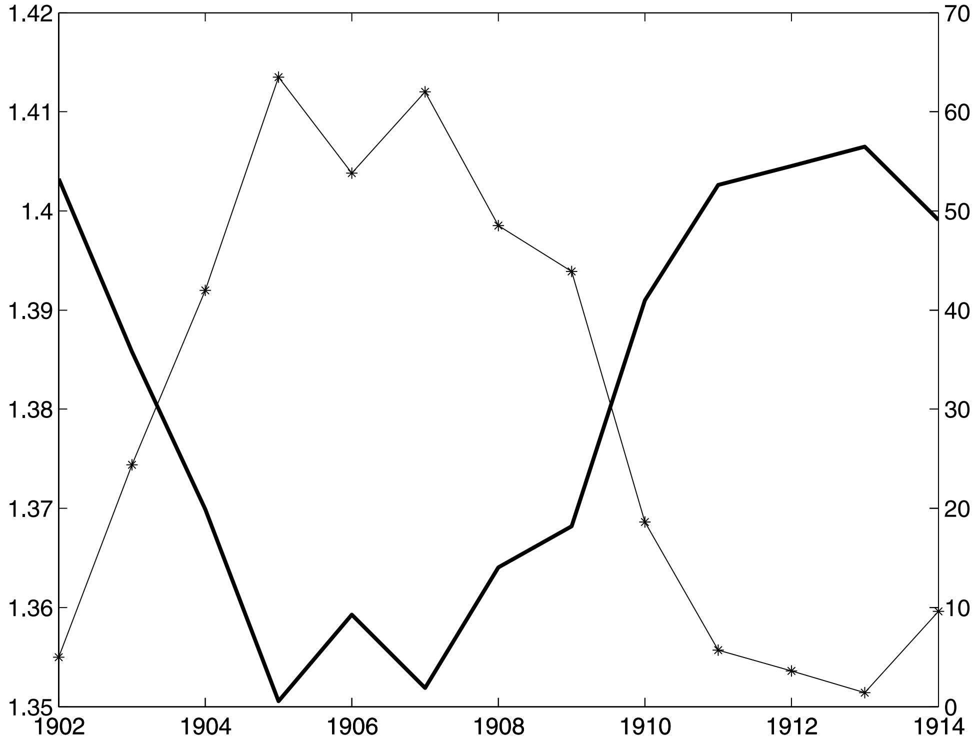

Figure 4. MH-raw calibration factors for SIT *IHV*-raw (thin line with asterisks, left axis) and the sunspot numbers (thick line, right axis) for 1902–1914.

hourly samples has a relatively smaller effect on *IHV*. Only if the daily curve during the *IHV* hours is rather flat, the effect of the larger daily range in active years is not enough to (over)compensate the increased variability.

[17] Because the MH-raw calibration factors are very similar, but more definite than the station versus NGK ratio-based calibration factors, we will use the former when calibrating the *IHV* indices for the effect of changed sampling. Moreover, using these factors, we can take the weak solar activity dependence into account. We assume that these (annual) calibration factors are linearly dependent on the (annual) sunspot number and use the values for 1996 and 2000 in order to extract this linear relation for each station. Figure 4 shows the dependence of these annual calibration factors on annual sunspot numbers for those early years when SIT was registering hourly samples. The same analysis was repeated for all other stations, using the appropriate MH-raw ratio for each station and calculating the corresponding relation with sunspot numbers. Figure 5 depicts the similar ratios of annual indices between CLH/FRD and NGK as depicted in Figure 1 but now using the calibrated *IHV*-raw indices. One can see that the steps depicted in Figure 1 have now disappeared.

[18] As described above (for details, see *Mursula et al.* [2004]), the correction of the *IHV*-raw indices for the changing daily curve, i.e., the calculation of the *IHV*-cor index, was done by subtracting the yearly *IHV-q* values from the daily *IHV*-raw indices. In analogy with the calibration of the *IHV*-raw indices described above, we have also calculated the annual MH-*q* calibration factors for the *IHV-q* values (see Table 2). Note that contrary to MH-raw, the MH-*q* calibration factors are all increasing with solar activity, with the largest increase found at the two midlatitude stations (CLH/FRD and NGK). Also, many of the MH-*q* calibration factors are slightly less than 1, again in marked difference to the MH-raw calibration factors. This is due to the fact that when the annual daily curve is calculated, there is practically no difference whether one uses hourly samples or hourly means since the additional variation vanishes in the average. However, when using the first minute of the hour, as we have done in this study, one introduces a time delay of half an hour between the two

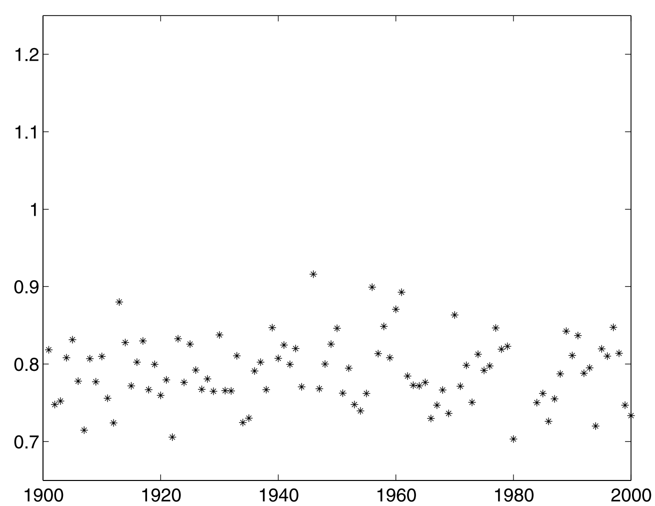

Figure 5. Ratio of calibrated *IHV*-raw values between CLH/FRD and NGK, depicting rather constant behavior even during the early years of varying sampling.

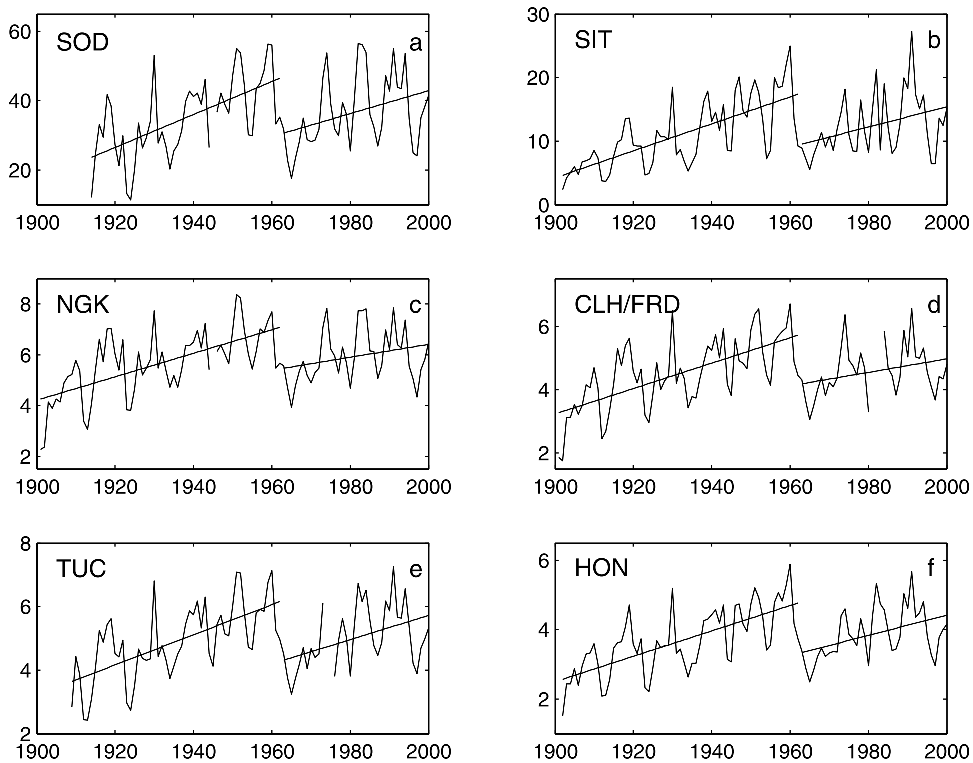

Figure 6. Yearly averages of the sampling calibrated *IHV*-raw index (in nT) for the six stations included in the study.

average daily curves. This temporal difference is mainly responsible for the observed calibration factors for *IHV-q*. Note that the temporal difference has little effect when one calculates the daily *IHV*-raw indices since the daily variation dominates the small temporal effect. Since we do not know how the hourly sampling was done in the early years, an inherent arbitrariness will remain in the *IHV-q* calibration. However, since the *IHV-q* values are rather small compared to *IHV*-raw indices, especially for low-latitude and midlatitude stations, the effect of this arbitrariness is very small even in the calibrated *IHV*-cor indices (obtained by subtracting the calibrated *IHV-q* from the calibrated *IHV*-raw) and has no practical significance for their centennial evolution.

5. Sampling Calibrated *IHV*-raw and *IHV*-cor Indices

[19] We have depicted the calibrated yearly *IHV*-raw indices for all six stations in Figure 6. As expected from the known latitudinal variation of geomagnetic activity, the absolute values of the *IHV* indices vary greatly with the magnetic latitude of the station so that the values at the highest SOD station are roughly an order of magnitude larger than at the lowest HON station. Despite this difference, all the six *IHV* series depict the same qualitative long-term pattern during the last 100 years. On top of the solar cycle variation, there is a fairly persistent trend of increasing activity from the beginning of the 20th century until 1960, then a dramatic dropout in early 1960s, and a weaker increasing trend thereafter. We have underlined this pattern in Figure 6 for each station by including the best fitting line for the period until 1962 and another line for 1963–2000. As noted earlier [*Mursula et al.*, 2004], because of the, for most stations, overall maximum in 1960, there is no uniform increase in geomagnetic activity during the last 100 years. Therefore a two-line fit presents this step-like behavior better than a one-line fit over the full interval. Note also that the same step-like pattern is also found in the *aa* index (see below and *Mursula et al.* [2004, Figure 3]) and all other indices of geomagnetic activity.

[20] The effect of sampling calibration is to lower the uncalibrated *IHV*-raw indices during the early years when hourly sampling was used. Naturally, the effect is largest at those stations which were operating long before they changed to use the hourly means, as were SIT, CLH/FRD, and HON. All these stations started operating soon after the beginning of the 20th century and changed to measuring hourly means in 1915 (see Table 1). NGK changed to hourly means earlier, in 1905, and Tucson (TUC) started operating only in 1909. Therefore the early *IHV* values at these two stations experienced a smaller overall reduction because of sampling calibration. In SOD, no calibration was needed. The effect of sampling calibration is clearly visible in the early *IHV*-raw values for most stations (compare Figure 6 and Figure 3 of *Mursula et al.* [2004]) and therefore makes an essential contribution to the question of the centennial change of geomagnetic activity (see next section) and its relation to other solar and heliospheric parameters.

[21] As discussed above, the MH-raw sampling calibration factors of many stations are inversely proportional to sunspot numbers. Since the sunspot cycles at the start of the previous century were rather low, the overall, cycle-averaged calibration factors are slightly larger for the early years

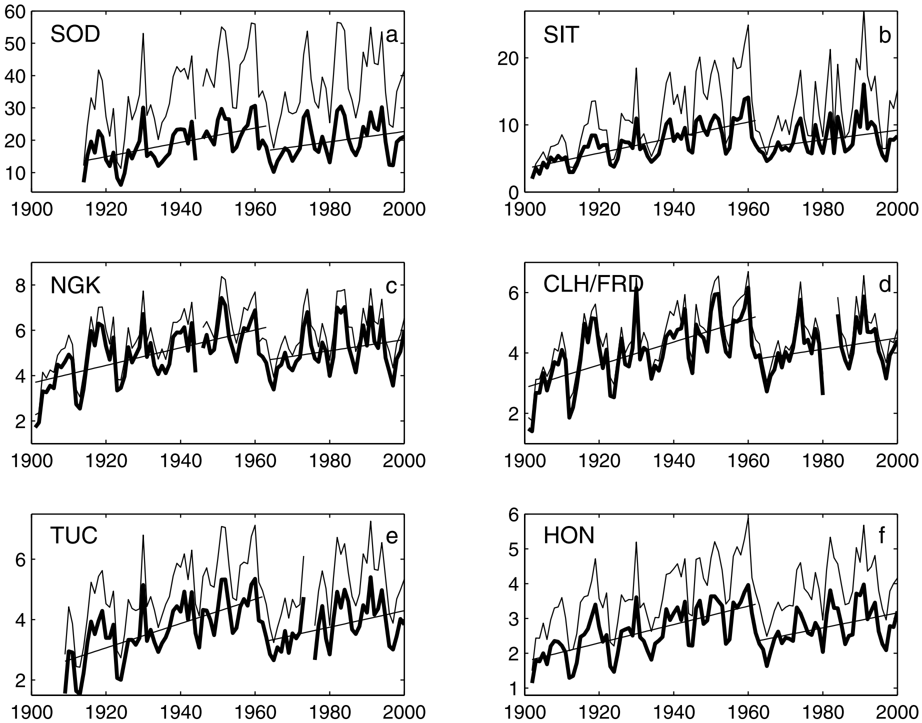

Figure 7. Yearly averages of the sampling calibrated *IHV*-raw (thin lines) and *IHV*-cor (thick lines) indices for the six stations. Best fitting lines to the *IHV*-cor are also included.

than they are for present times. For example, for SIT *IHV*-raw (see Figure 4), the overall MH-raw calibration factor is about 1.38, i.e., rather close to the value for a modern sunspot minimum year. However, note that since the sunspot cycle variation of the calibration factor is rather weak, using a constant calibration factor would only lead to a small error (roughly 10%) in the calibration factor and an error of only a few percent (less than 4%) in the *IHV*-raw indices.

[22] The yearly averages of the calibrated *IHV*-cor indices for the six stations (together with the *IHV*-raw indices) are depicted in Figure 7. As found earlier [*Mursula et al.*, 2004], the daily curve correction, i.e., the *IHV-q* values, are relatively the smallest at the two midlatitude stations CLH/FRD and NGK and relatively the largest at high latitudes.

6. Centennial Increase

[23] We have quantified the centennial increase by calculating, as was done by *Mursula et al.* [2004], the average values of the *IHV*-raw and *IHV*-cor indices at the six stations during the last (1979–2000) and the first (1901–1922) 22 years of the previous century. (Note that because of different start years, the stations cover slightly different fractions of the first 22 years.) We have depicted these average levels as well as the implied percentage changes of local geomagnetic activity in Table 3. Note that all six *IHV*-raw and *IHV*-cor series depict an increase during the last century.

6.1. Latitudinal Differences

[24] The relative increase varies considerably in the different stations. However, we note that the increases in the various stations cannot always be simply compared because of the different start years. Still, it is clear that the largest centennial increases are found at high latitudes (SOD, SIT), somewhat smaller increases at low latitudes (TUC, HON) and, surprisingly, the smallest increases at midlatitudes (NGK, CLH/FRD). Note that the increase at SOD remains considerably smaller than at SIT, most likely because of the

Table 3. Mean *IHV*-raw and *IHV*-cor Values for the Six Stations at the Beginning (From Start Until 1922) and at the End (1979–2000) of the Last Century and Their Relative Increases, Together With the Mean-Normalized Six-Station (1914–1922) and Three-Station (1902–1922) Global *IHV* Averages and Corresponding Values for *aa* Index and the Revised *aa* Index Raised by 2 nT

Station/Global	*IHV* Start	*IHV* End	Relative Increase, %
SOD IHV-raw	28.65	40.00	39.6
SIT IHV-raw	7.31	13.89	90.0
NGK IHV-raw	4.90	6.19	26.3
CLH/FRD IHV-raw	3.83	4.73	23.5
TUC IHV-raw	4.16	5.40	29.8
HON IHV-raw	3.08	4.15	34.7
SOD IHV-cor	16.01	21.20	32.4
SIT IHV-cor	5.13	8.52	66.1
NGK IHV-cor	4.24	5.37	26.7
CLH/FRD IHV-cor	3.40	4.26	25.3
TUC IHV-cor	3.03	4.06	34.0
HON IHV-cor	2.18	2.96	35.8
IHV-1914-raw	0.905	1.046	15.6
IHV-1914-cor	0.924	1.034	11.9
IHV-1902-raw	0.774	1.126	45.5
IHV-1902-cor	0.790	1.107	40.1
aa-1914	17.90	24.63	37.6
aa-1902	15.20	24.63	62.0
aa-1914-2nT	19.90	24.63	23.8
aa-1902-2nT	17.20	24.63	43.2

shorter data length. The increase at TUC probably remains smaller than HON because of the same reason.

[25] We note that the latitudinal differences in the centennial trends are a new, partly unexpected, and, so far, unexplained phenomenon which may be due to internal or external causes. The internal cause for the large centennial increase at high latitudes could be the change of the effective location of the stations with respect to the auroral oval due to the secular variation of the strength and orientation of the Earth's magnetic field. The decreasing field strength increases the radius of the auroral oval, increasing the general proximity of stations to the oval. The centennial change in the dipole moment has been estimated to move the oval roughly by 1° closer to the stations, leading to only a small effect for the *aa* index [*Clilverd et al.*, 1998]. However, the effect could be more important for high-latitude stations. The large centennial increase at high latitudes may also be due to external causes. If the increasing solar activity leads, as suggested, to an increase in HMF intensity, it would affect a larger overall disturbance level, particularly at high latitudes.

[26] In addition, the centennial increase of HMF strength would also cause an intensification of magnetic fields in HMF shocks and magnetic clouds, possibly intensifying magnetic storms. This could perhaps also explain why the centennial increase is larger at low latitudes than at midlatitudes. Note that the ring current is the only magnetospheric current system that affects the low latitudes most strongly. (Storms may also enhance other current systems like field-aligned currents that affect the midlatitudes. However, the temporal duration of these current systems during the storm is considerably shorter than that of the ring current.) We also note that a recent extension of the *Dst* index [*Karinen and Mursula*, 2005, 2006] shows that the average storm has become slightly more intense and shorter during the last 70 years. In addition to the above-mentioned external cause, the Earth's decreasing magnetic moment may also cause a relatively larger centennial increase at low latitudes than at midlatitudes. With the decreasing magnetic moment, the average ring current location will move closer to the Earth, enhancing the observed storm intensity on the ground. Moreover, it can also explain the observed shortening of the storm main phase since ring current loss via charge exchange with neutral particles will be enhanced at lower altitudes.

6.2. Effect of Sampling Correction

[27] As expected, calibrating the sampling change in the way described above leads to larger values for the centennial increase than estimated previously on the basis of the *IHV* index (compare Table 3 and Table II of *Mursula et al.* [2004]). By far the largest relative effect to the centennial change caused by calibration is found for CLH/FRD where the increase in *IHV*-raw was only 6% before calibration but 23.5% after calibration. In *IHV*-cor it was 6% before and 25.3% after calibration. So geomagnetic activity was made roughly four times larger when the sampling change was taken into account and calibrated. Note that before calibration, the CLH/FRD IHV series was exceptional in depicting by far the smallest centennial increase of all stations. On the basis of this exceptionally small increase at CLH/FRD, *Svalgaard et al.* [2004] were misled to conclude that there was no increase in geomagnetic activity during the last 100 years.

[28] The effect of calibration is quite large also in SIT (in *IHV*-raw, previously 62%, now 90.0%; in *IHV*-cor, previously 31%, now 66.1%), HON (in *IHV*-raw, previously 23%, now 34.7%; in *IHV*-cor, previously 18%, now 35.8%), as well as in TUC (in *IHV*-raw, previously 17%, now 29.8%; in *IHV*-cor, previously 14%, now 34.0%). Accordingly, the centennial increase at these stations was raised by 45–75% in *IHV*-raw and by 100–140% in *IHV*-cor after properly taking into account the changed sampling. (At NGK the corresponding change is much smaller, only from 21% to 26.3/26.7% because of the earlier implementation of hourly means.) These figures clearly demonstrate that it is important to correct the effect of the sampling change when studying the centennial development of geomagnetic activity using the *IHV* method. It is also obvious that ESK data must be similarly corrected before the corresponding *IHV* index can be reliably used in a long-term study.

[29] Table 3 shows that, as found earlier [*Mursula et al.*, 2004], the centennial increase in *IHV*-cor is considerably smaller than in *IHV*-raw at the two high-latitude stations (SOD, SIT). This shows that the long-term change of the daily curve is an essential effect at the centennial timescale mainly at high latitudes. Also in agreement with earlier results, a very similar centennial increase is found for *IHV*-raw and *IHV*-cor at midlatitude stations. However, contrary to earlier results, the centennial increase is slightly larger in *IHV*-cor than in *IHV*-raw at low-latitude stations. Nevertheless, the roughly equal centennial increases in *IHV*-raw and *IHV*-cor at low latitudes and midlatitudes suggest that the remaining arbitrariness in the calibration of *IHV-q* is of minor importance for long-term development.

6.3. Global Average and Comparison With *aa* Index

[30] It is clear from the above consideration of *IHV* indices at the various stations that calibrating the sampling change also increases the centennial increase in the global geomagnetic activity according to the *IHV* indices. Thus calibrating the sampling change further verifies that global geomagnetic activity has indeed increased considerably during the last 100 years. However, having found that the centennial increase is quite different at different latitudes, the amount of the centennial increase in global geomagnetic activity remains somewhat ambiguous and depends on the selection of stations to be included in the global average.

[31] If one selects only midlatitude stations, as is done, for example, in the case of the *aa* index, our analysis shows an average centennial increase of about 25–26% which, because of the large change in CLH/FRD, is almost twice the centennial increase before sampling calibration [*Mursula et al.*, 2004]. However, even this larger value is much smaller than the 62% centennial increase in the *aa* index (aa-1902 in Table 3). This difference may, in principle, result from various reasons. First, there may be some longitudinal differences due, for example, to the different effective location of the stations with respect to the auroral oval. However, since the two midlatitude stations used (NGK and CLH/FRD) are quite widely separate in longitude and still depict, after sampling calibration, very similar centennial increases, the large difference between the *aa* and

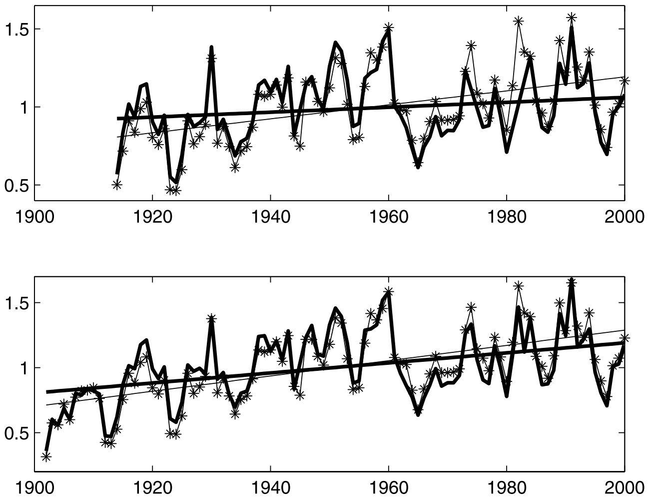

Figure 8. Yearly values of the global (top) six-station IHV-1914-cor and (bottom) three-station IHV-1902-cor indices (thick lines) and the *aa* index (thin line with asterisks) normalized to its mean. Best fitting lines both to the global *IHV* and to *aa* are included.

IHV indices can hardly be due to longitudinal differences. This interpretation is further supported by the fair proximity of NGK and the northern *aa* station in England.

[32] Second, such a difference could ensue if the *aa* index indeed would overestimate the centennial increase. In fact, according to a recent estimate [*Jarvis*, 2005], the *aa* values from 1900 until 1957 are too low by roughly 2 nT because of instrumentally caused shifts in 1938 and around 1980. If we then raise the early *aa* indices by this amount, the corresponding revised *aa* index (aa-1902-2nT in Table 3) depicts a centennial increase of about 43% which is still considerably larger than shown by *IHV* at midlatitudes.

[33] The third and, perhaps, most likely explanation is that since the *aa* index and the *IHV* index are determined quite differently, the observed differences may arise because the two indices measure partly different physical processes. Since the *aa* index measures variability at timescales shorter than 1 hour, its larger centennial increase suggests that such short-term variability has increased more than the variability on hourly timescales. Anyway, this suggests that a simple comparison of centennial increases in two different indices is not straightforward or even physically motivated unless their differences are studied in more detail. Another approach would be to study, for each index separately, the dependence of the index on external driving factors and to extract the centennial change of these factors for mutual comparison. (Such a study is underway.)

[34] Since both the high and low latitudes depict a larger centennial increase than the midlatitudes, using only midlatitude stations for global geomagnetic activity (as for the *aa* index) would underestimate the observed centennial increase. So far, no such truly global average has been calculated, since "global geomagnetic activity" has commonly been defined by using only midlatitude stations. With the present observation of latitudinally varying centennial increase, such an approach is not justified and will need revision. In pursuit of having a truly global estimate for the centennial increase, we can use the six stations which represent the high, middle, and low latitudes (two stations from each) roughly on an equal footing. We have calculated in Table 3 the average centennial increase as depicted by the *IHV* indices at the six stations over the time interval (1914–2000) covered by all stations. The *IHV* values at each station were first normalized by their means before averaging, in order to set all the stations to the same absolute level. The six station averages, IHV-1914-raw and IHV-1914-cor, are shown in Figure 8 and depict an average increase from 1914 to 2000 of 15.6% and 11.9% (see Table 3). These numbers can be compared with the 37.6% increase in the *aa* index over the same time (aa-1914 in Table 3) or with the 23.8% increase in the revised *aa* index (aa-1914-2nT in Table 3).

[35] Similarly, we have formed a longer global average, IHV-1902-raw and IHV-1902-cor (see Figure 8 and Table 3), from one high-latitude (SIT), one midlatitude (NGK), and one low-latitude (HON) station which all were operating at least since 1902. These stations depict an average global increase from 1902 to 2000 of 45.5% (IHV-1902-raw) and 40.1% (IHV-1902-cor) which can again be compared with a 62% increase in the *aa* index (aa-1902 in Table 3), or with the 43.2% increase in the revised *aa* index (aa-1902-2nT in Table 3). Note, however, that in view of the above discussion, the excellent agreement of the latter with the simultaneous IHV-1902-raw and IHV-1902-cor indices must be taken as partly coincidental. Moreover, comparing the centennial increases in *aa* and *IHV* after 1902 with those after 1914, one can see that the two indices increased by slightly different relative amounts at different time intervals, which also favors the view that the two indices (especially when calculated for different latitudes) reflect slightly different physics. All in all, these results strongly emphasize the need for reproducible and straightforward long-term indices of geomagnetic activity.

7. Conclusions

[36] We have studied here the centennial change in geomagnetic activity using the newly proposed Inter-Hour Variability (*IHV*) index. New, straightforward, reproducible, and homogeneous measures of geomagnetic activity are needed, especially since serious concern has been raised about the long-term consistency of the (nonreproducible) *aa* index. We have recalculated here the centennial increase in the *IHV* indices of several stations by taking into account the change of sampling at these stations from one sample per hour to hourly means in the early part of the last century. Since *IHV* is a variability index, the larger variability in case of hourly sampling leads, without due correction, to excessively large values of the *IHV* index in the beginning of the century and thereby to an underestimated centennial increase.

[37] We have discussed two different ways to extract the related sampling calibration factors and have shown that they agree very well with each other. We have calculated the calibration factors using the more recent, high-sampling magnetic field observations, taking even the small solar cycle dependence of the calibration factors into account. The effect of calibration was found to be especially large at the midlatitude CLH/FRD station where the centennial increase in *IHV*-raw/*IHV*-cor changes from only 6% to

23.5/25.3% because of calibration. As a result of calibration, CLH/FRD depicts a closely similar centennial increase as the other midlatitude station (NGK) used in this study. Still, even with this change, the centennial increase in *IHV* index at midlatitudes remains clearly below that depicted by the midlatitude *aa* index, even if the latter is corrected by 2 nT [*Jarvis*, 2005]. However, we note that any two indices that are differently determined (e.g., *aa* and *IHV*) include partly different physics, which denies a simple comparison of their long-term evolution.

[38] Since sampling calibration essentially enhances the centennial increase at all stations, it also enhances the earlier estimates on the centennial increase in global geomagnetic activity based on the *IHV* index. We note that because of the observed latitudinally varying centennial increase, a global estimate must include measurements from different latitudes. The six-station averaged *IHV* depicts an increase of 15.6% in *IHV*-raw and 11.9% in *IHV*-cor from 1914 to 2000, and a longer, three-station averaged *IHV* depicts an increase of 45.5% in *IHV*-raw and 40.1% in *IHV*-cor from 1902 to 2000. These results verify a significant centennial increase in global geomagnetic activity, in a qualitative agreement with the *aa* index. However, a detailed quantitative comparison between the two indices cannot be made because of the above-mentioned differences.

[39] The centennial increase was observed to have a rather strong and curious latitudinal dependence. The centennial increase is largest at high-latitude stations (SOD, SIT). Quite unexpectedly, it was found to be larger at low latitudes (TUC, HON) than at midlatitudes. These new findings indicate interesting long-term changes in the near-Earth space. We have discussed possible internal and external causes of these observed differences. External causes include possible long-term changes in the average properties of the heliospheric magnetic field and solar wind. The internal cause could be the decrease of the Earth's magnetic moment, which can explain the large increase at high latitudes by the equatorial expansion of the auroral oval. The decreasing magnetic moment can explain the larger centennial increase at low latitudes than at midlatitudes as an earthward shift of the average location of the ring current. Moreover, it can also explain the observed intensification and shortening of the average magnetic storm during the last century [*Karinen and Mursula*, 2005, 2006]. These results suggest that the centennial change of geomagnetic activity may be affected partly by changes in external conditions and partly by the secular decrease of the Earth's magnetic moment whose effect in near-Earth space may be larger than so far estimated.

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