CENTENNIAL CHANGE IN GEOMAGNETIC ACTIVITY: EVALUATING THE EFFECT OF CHANGED SAMPLING TO THE IHV INDEX

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ABSTRACT

The IHV (Inter-Hour Variability) index has recently been suggested as a homogeneous measure of local geomagnetic activity. We calculate the IHV index for six long-observing stations, correcting them with a sunspot-dependent calibration factor which takes into account the change of the registration method from hourly samples to hourly mean values. Without such a calibration, the IHV index, being a measure of variability, tends to overestimate the level of geomagnetic activity in the early years of the last century and, thus, to underestimate the centennial increase. The effect of calibration is especially large at CLH/FRD where the increase in IHV-raw (IHV-cor) changes from only 6% before calibration to 27% (30%) thereafter. After calibration, CLH/FRD depicts a closely similar centennial increase as the other mid-latitude station. The centennial increase in IHV is largest at high latitudes, somewhat smaller at low latitudes and smallest at mid-latitudes. The six-station average IHV depicts an increase of about 16% (IHV-raw) and 12% (IHV-cor) from 1914 to 2000, compared to the 38% increase in the aa index over the same time interval. Similarly, a longer, three-station average IHV depicts an increase of about 50% (IHV-raw) and 39% (IHV-cor) from 1902 to 2000, compared to the 62% increase in the aa index. Accordingly, the centennial increase in the global IHV index remains, despite the additional increase due to calibration, clearly lower than in the aa index.

Key words: Centennial change; geomagnetic activity; IHV index.

1. INTRODUCTION

In recent years, geomagnetic activity (GA) has become a very important heliospheric parameter. The aa index (Mayaud, 1980) is, because of its exceptionally long time span, the most used proxy of GA in long-term studies. It has been used, e.g., to examine the long-term change in the solar wind and in the heliospheric magnetic field. Based on the aa index Lockwood et al. (1999) suggested that the heliospheric magnetic field is now more than twice stronger than 100 years ago. While many other parameters like the sunspot numbers (Solanki et al., 2000), cosmic rays and cosmogenic isotopes (Usoskin et al., 2003) have also been used to study the long-term change in the heliosphere, the most direct evidence on centennial time scales is based on geomagnetic activity.

The aa index is formed from the K-indices derived from magnetic observations made at two, roughly antipodal locations. As for most K indices, the exact reproduction and *a posteriori* verification of the aa index is impossible. Moreover, since three different magnetic stations have been used at both two sites, the long-term consistency of the aa index has been questioned (Clilverd, 1998). In order to solve these problems, Svalgaard (2004) introduced the so called IHV index as a more straightforward and homogeneous measure of long-term geomagnetic activity. Using the data from the Cheltenham/Fredricksburg station pair, Svalgaard (2004) found no evidence for an increase in the IHV index during the last 100 years.

We have recently calculated the IHV index for several geomagnetic stations in order to obtain a more global view on the long-term development of global GA (Mursula et al., 2004). We found that long-term geomagnetic activity at all stations follows the same qualitative pattern: an increase from early 1900s to 1960, a dramatic dropout in 1960s and a weaker increase thereafter. At all stations, geomagnetic activity at the end of the 20th century was found to be at a higher average level than in the beginning of the century. This agrees with the result based on the aa index that global geomagnetic activity has indeed increased during the last 100 years. However, taking a global average of the IHV values, we found that the centennial increase in GA according to IHV was considerably smaller, only about one half of that depicted by the aa index. We also noted that the IHV

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Table 1. Information on stations used. Magnetic coordinates are calculated using the IGRF 2000 model. MN hour indicates the mid-night hour in UT, HMS start stands for the year when hourly mean registration started. CLH and FRD form a station pair.

Station	IAGA	Geographic		Geomagnetic		MN	Data	HMS
	code	lat	long	lat	long	hour	start	start
Sodankylä	SOD	67.47	26.60	63.96	120.25	22	1914	1914
Sitka	SIT	57.05	224.67	60.33	279.79	9	1902	1915
Niemegk	NGK	52.07	12.68	51.89	97.69	23	1901	1905
Cheltenham	CLH	38.73	283.16	49.14	353.71	5	1901	1915
Fredericksburg	FRD	38.20	282.63	48.59	353.11	5	1956	1956
Tucson	TUC	32.25	249.17	40.06	315.63	7	1909	1915

index needs to be corrected for the long-term change of the range of the daily curve in order to be comparable with other (in particular, the K-based) GA indices. We suggested a simple way to correct the IHV values for the change of the daily range, and calculated the corrected IHV values for all stations.

The IHV index is calculated from the hourly measurements of the H-component of the magnetic field at any station. However, after the previous study (Mursula et al., 2004) we have learnt that the sampling of these measurements was using hourly samples (e.g., at sharp hour or half-hour) rather than hourly means in the early part of the previous century. Since the hourly samples have a larger variability than the hourly means, this will affect the value of the IHV index which have to be calibrated for this change in the early part of the last century. This will be done this in the present paper.

2. STATIONS AND THE IHV INDICES

We will use data from the same stations (see Table 1) as in our earlier paper (Mursula et al., 2004), except for the Eskdalemuir station. (We neglect the Eskdalemuir station in the present study since the data of this station depicts other, yet unknown problems. These problems will be treated later in more detail). The five stations and one station pair included in the present study have the longest and most uniform records of magnetic observations from early 1900s. 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.

The IHV index (Svalgaard, 2004) is defined as an average of the six absolute differences of the successive hourly values of the H component between 19-01 local time (LT). This definition was originally based on the smooth daily curve at the CLH/FRD station in this LT sector, and on the fact that this LT sector is geomagnetically most active. We have used

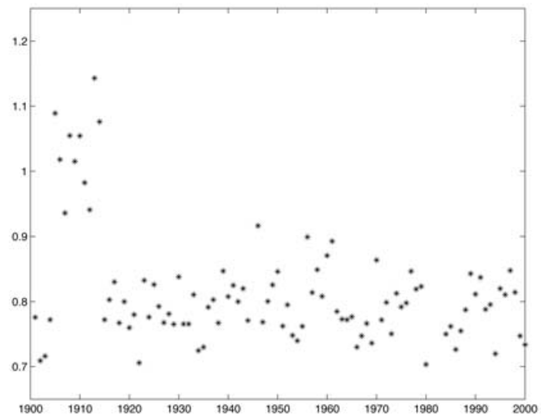

Figure 1. Ratio of annual IHV values between CLH/FRD and NGK.

this definition to calculate the IHV values for the six stations. These will be called the IHV-raw indices.

As discussed in Mursula et al. (2004), the range of the daily curve varies strongly with solar activity (actually, more closely with geomagnetic activity at high latitudes) and is also affected by the long-term change. Therefore, we corrected the IHV-raw indices for this effect, calling the corrected IHV indices by IHV-cor (Mursula et al., 2004).

3. SOLVING THE SAMPLING PROBLEM

As shown in Table 1, most stations changed their registration from hourly sampling to hourly means in 1915. However, at NGK this was already done in 1905. (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 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 a decrease of the ratio back to a lower (roughly but not quite similar) level in 1915 when CLH sampling was changed. This indicates that the change of sampling tends to reduce the annual IHV-raw values by roughly 40%. As noted above, this is due to the fact that hourly samples have a larger variability than hourly means which, without due correction, leads to artificially large IHV values in the beginning of the last century. Figure 1 shows that the changed sampling has indeed quite a large effect on IHV values and, therefore, greatly affects the centennial trend of geomagnetic activity derived from the IHV index.

We have calibrated the effect of changed sampling to IHV as follows. Since, for the recent years, we have more frequently sampled data available, we have constructed two series of daily IHV values, one using 1-minute resolution data, taking only one 1-minute sample per hour, the other using hourly means of the same station. These values were calculated for one sunspot minimum year, 1996, and one sunspot maximum year, 2000. The two series of daily IHV values were then averaged to annual means and the ratio of the two differently sampled IHV values was calculated for the two years. E.g., for the SIT station this 1-min/1-h IHV ratio was found to be 1.4 in 1996 and 1.3 in 2000. Note the interesting fact that the ratio is in inverse relation with sunspot activity. This is because high solar activity enhances the range of the daily variation whence the increased variability caused by hourly samples is relatively reduced. This fact was verified by similar calculations at other stations.

We will use the 1-min/1-h IHV ratio as the sampling calibration factor to correct the effect of changed smapling. Moreover, we assume a linear dependence of this factor on sunspot number and thereby introduce a solar cycle variable calibration factor. Figure 2 shows the dependence of this factor on sunspot activity for those years where SIT was registrating hourly samples. The same analysis was repeated for all other stations (except SOD), using the appropriate 1-min/1-h ratio for each station and calculating the related sunspot number dependence. Note also that the same calibration factors can be used both for IHV-raw as well as for the IHV-cor values.

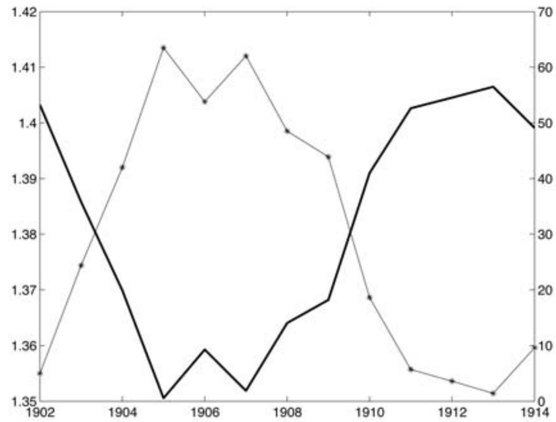

Figure 2. Annual sampling calibration factors for the IHV values of SIT (thin line with stars; left axis) and the sunspot numbers (thick line; right axis) for 1902-1914.

4. SAMPLING CALIBRATED IHV

We have depicted the calibrated yearly IHV-raw indices for all the six stations of Table 1 in Figure 3. As found earlier (Mursula et al., 2004), 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 therafter. We have underlined this pattern in Figure 3 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 and a two-line fit presents this step-like behaviour 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 later or, e.g., Figure 3 in Mursula et al., 2004) and all other indices of geomagnetic activity, thus further verifying that the local IHV indices yield a fairly good proxy of geomagnetic activity (Svalgaard, 2004).

The effect of the sampling calibration is to lower the uncalibrated IHV 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, like SIT, CLH/FRD and HON. All these stations started operating soon after the start of the 20th century, and changed to measuring hourly means in 1915 (see Table 1). Instead, NGK changed to hourly means already in 1905, and TUC started operating only in 1909. Therefore, the IHV values at these two stations experienced a smaller overall reduction due to sampling calibration. (In SOD, no calibration was needed). The effect of sampling calibration is clearly visible in the early IHV values for most stations (compare Figure 3 and Figure 3 in Mursula et al., 2004) and, therefore, makes an essential contribution to the question of the centennial change of

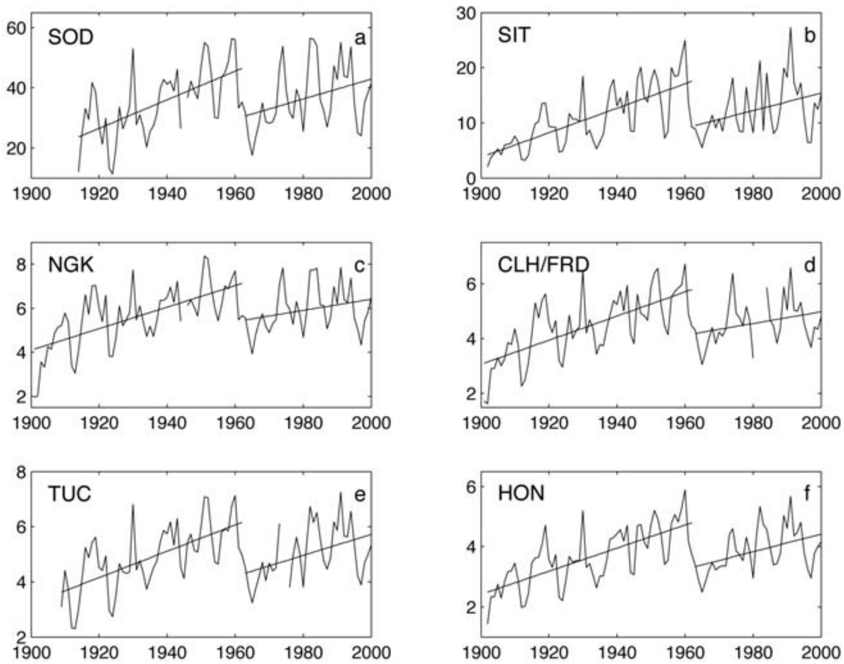

Figure 3. Yearly averages of the sampling calibrated IHV-raw indices (in nT) for the 6 stations included in the study. Best fitting lines are calculated from the start of data to 1962 and from 1963-2000.

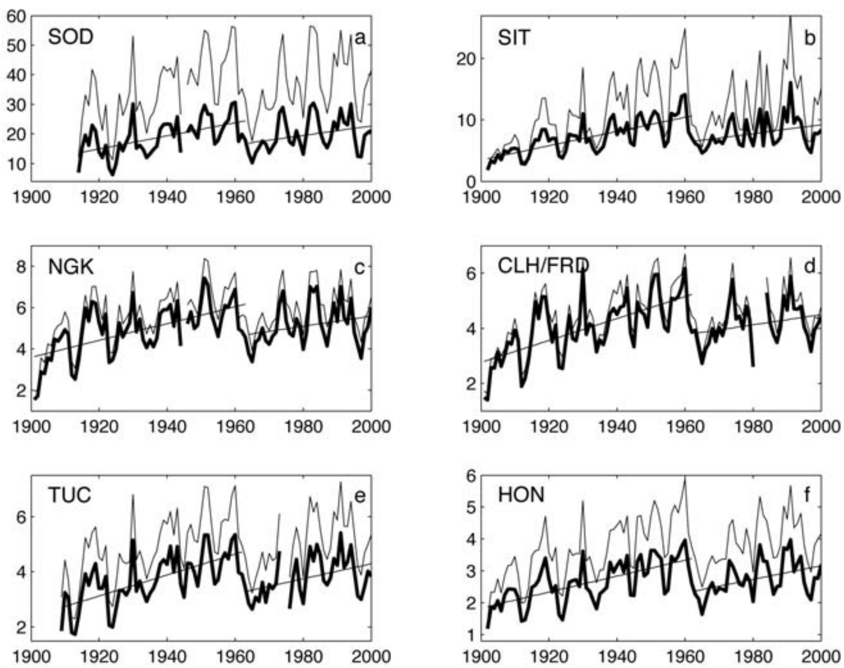

Figure 4. Yearly averages of the sampling calibrated IHV-cor (thick lines) and IHV-raw (thin lines) indices for the 6 stations.

Table 2. Mean values of the IHV-raw and IHV-cor indices for the six stations at the beginning (from start until 1922) and at the end (1979-2000) of the last century. Also, the mean-normalized 6-station (1914-1922) and 3-station (1902-1922) global IHV averages are included.

Station/Global	IHV start	IHV end	Relative increase
SOD IHV-raw	28.7	40.0	39%
SIT IHV-raw	6.9	13.9	101%
NGK IHV-raw	4.8	6.2	29%
CLH/FRD IHV-raw	3.7	4.7	27%
TUC IHV-raw	4.1	5.4	32%
HON IHV-raw	3.0	4.2	40%
SOD IHV-cor	16.0	21.2	33%
SIT IHV-cor	5.1	8.5	67%
NGK IHV-cor	4.2	5.4	29%
CLH/FRD IHV-cor	3.3	4.3	30%
TUC IHV-cor	3.2	4.1	28%
HON IHV-cor	2.2	3.0	36%
meanIHV6-raw	0.903	1.046	16%
meanIHV6-cor	0.924	1.034	12%
meanIHV3-raw	0.756	1.131	50%
meanIHV3-cor	0.793	1.106	39%
aa-1914	17.9	24.63	38%
aa-1902	15.2	24.63	62%

geomagnetic activity and its relation to other solar and heliospheric parameters.

As discussed above, the sampling calibration factor is inversely proportional to sunspot numbers. Since the sunspot cycles at the start of the previous century were rather low, the overall, cycle-averaged sampling calibration is slightly larger for the early years than it would be for present times. E.g., for SIT (see Figure 2, the overall 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 (roughly 10%) error.

As described in Mursula et al. (2004), the IHV-cor index aims to correct the IHV-raw index for the changing range of the daily curve. The daily IHV-cor index is obtained by subtracting the IHV value calculated using the yearly averaged daily curve from the daily IHV-raw value. Thus, the same sampling calibration factors can be used for the IHV-cor index as for the respective IHV-raw index. The yearly averages of the calibrated IHV-cor indices for the six stations are depicted in Figure 4. As found earlier (Mursula et al., 2004), the daily curve correction is relatively smallest at the two mid-latitude stations CLH/FRD and NGK, and relatively larger both at high and low latitudes. Thus, the IHV-cor indices are closest to IHV-raw values at CLH/FRD and NGK (see Figure 4). We also note that the daily correction at ESK was found to be opposite to all other stations (Mursula et al., 2004), reflecting the above mentioned (yet unknown) problems at this station.

5. CENTENNIAL INCREASE

We have quantified the centennial increase by calculating, as earlier in Mursula et al. (2004), the average values of the IHV indices during the last (1979-2000) and first (1901-1922) 22 years of the century. (Note that, because of different start years, the stations cover a slightly different fraction of the first 22 years). We have depicted these average levels as well as the implied percentual change (increase) of local geomagnetic activity in Table 2. All the six IHV-raw as well as IHV-cor series depict an increase during the last 100 years.

However, the relative increase varies considerably in the different stations. Note first that the relative increases in Table 2 can not be easily compared because of the different starting 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 the smallest increases at mid-latitudes (NGK, CLH/FRD). The increase at SOD remains much smaller than at SIT because of the shorter data length. The increase at TUC remains smaller than HON because of the same reason. We note that the latitudinal differences in the centennial trends are systematic and indicate a new, so far unexplained phenomenon. As noted in Mursula et al. (2004), the larger centennial increase at high latitudes may indicate that the fraction of those disturbances in the solar wind that cause only moderate geomagnetic activity (like substorms) observed mainly at high latitudes has increased during this time interval. However, this does not explain why the centennial increase is larger at low latitudes than at mid-latitudes.

The effect of calibrating the sampling change in the way described above leads to larger values for the centennial increase. By far the largest relative effect to the centennial change in IHV-raw due to calibrating the sampling change was found for CLH/FRD where the increase was only 6% (Mursula et al., 2004, see Table II in) before calibration but 27% after calibration. This change is even larger in IHV-cor indices which was 6% before and 30% after calibration. It is interesting to note that, before calibration, the CLH/FRD IHV series was exceptional in depicting by far the smallest increase of all stations and that, based on this exceptionally weak increase at CLH/FRD, (Svalgaard, 2004) erroneously claimed that there was no increase in geomagnetic activity during the last 100 years. The effect of calibration is quite large also in SIT, TUC and HON where the centennial increase in IHV-raw nearly doubled due to calibration. Table 2 also shows that the centennial increase in IHV-cor is considerably smaller than in IHV-raw at high-latitude stations, slightly smaller at low-latitude stations and roughly the same at mid-latitude stations.

Accordingly, there is no doubt that global GA has increased during the last 100 years. It is also clear that calibrating the sampling change is an important procedure when evaluating the centennial change in global GA. However, the exact amount of this increase is somewhat ambiguous. We have calculated in Table 2 also the average centennial increase as depicted by the IHV values at the six stations. (The IHV values were first normalized by their means before averaging in order to set the series on the same absolute level). The six station average (meanIHV6-raw and meanIHV6-cor) depict an average increase from 1914 to 2000 of about 16% and 12%. This should be compared with the 38% increase in the aa index over the same time (aa-1914). Clearly, the aa index seems to exaggerate the increase over this time.

Similarly, we have formed a longer global average from one high-latitude (SIT), one mid-latitude (NGK) and one low-latitude (HON) station, meanIHV3-raw and meanIHV3-cor, which depict an average increase from 1902 to 2000 of about 50% and 39%. These numbers are relatively closer to the 62% increase in the aa index (aa-1902), indicating that the centennial increase occurs at slightly different times in the aa index and in the three IHV stations. Still, we find that the centennial increase in the global IHV index is clearly lower than depicted by the aa index.

It should also be noted that the aa index consists of data from two mid-latitude stations. Therefore, it should rather depict a centennial increase which is close to the 30% increase at the two mid-latitude stations (NGK, CLH/FRD), i.e., roughly half of the actual increase. Instead, the centennial increase in the aa index is very close to that of the calibrated IHV-cor at SIT. Accordingly, the aa index seems to behave, effectively, as a high-latitude or sub-auroral station rather than a mid-latitude station. One solution to this problem could be that the daily variation in the aa index is not properly removed and contributes considerably to its long-term change.

6. CONCLUSIONS

We have calculated the IHV indices for six long-observing stations, correcting them with a sunspot-dependent calibration factor in order to take into account the change of the registration method from hourly samples to hourly mean values. Without such a calibration, the IHV index, as a measure of variability, tends to overestimate the level of geomagnetic activity in the early years of the last century and, thus, to underestimate the centennial increase. The effect of calibration is large at SIT, HON and especially at CLH/FRD where the increase in IHV-raw (IHV-cor) changed from only 6% before calibration to 27% (30%) thereafter. After calibration, IHV at CLH/FRD depicts a closely similar centennial increase as the other mid-latitude station.

The centennial increase in IHV is largest at high latitudes, somewhat smaller at low latitudes and smallest at mid-latitudes. We note that this ordering is not presently understood. The six-station average IHV depicts an increase of about 16% (IHV-raw) and 12% (IHV-cor) from 1914 to 2000, compared to the 38% increase in the aa index over the same time interval. Similarly, a longer, three-station average IHV formed from one high-latitude, one mid-latitude and one low-latitude station depicts an increase of about 50% (IHV-raw) and 39% (IHV-cor) from 1902 to 2000, compared to the 62% increase in the aa index. Accordingly, we find that the centennial increase in the global IHV index remains, despite the increase due to calibration, clearly lower than in the aa index.

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