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DID OPEN SOLAR MAGNETIC FIELD INCREASE DURING THE LAST 100 YEARS? A REANALYSIS OF GEOMAGNETIC ACTIVITY

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Abstract. Long-term geomagnetic activity presented by the *aa* index has been used to show that the heliospheric magnetic field has more than doubled during the last 100 years. However, serious concern has been raised on the long-term consistency of the *aa* index and on the centennial rise of the solar magnetic field. Here we reanalyze geomagnetic activity during the last 100 years by calculating the recently suggested IHV (Inter-Hour Variability) index as a measure of local geomagnetic activity for seven stations. We find that local geomagnetic activity at all stations follows the same qualitative long-term pattern: an increase from early 1900 to 1960, a dramatic dropout in 1960s and a (mostly weaker) increase thereafter. Moreover, at all stations, the activity at the end of the 20th century has a higher average level than at the beginning of the century. This agrees with the result based on the *aa* index that global geomagnetic activity, and thereby, the open solar magnetic field has indeed increased during the last 100 years. However, quantitatively, the estimated centennial increase varies greatly from one station to another. We find that the relative increase is higher at the high-latitude stations and lower at the low- and mid-latitude stations. These differences may indicate that the fraction of solar wind disturbances leading to only moderate geomagnetic activity has increased during the studied time interval. We also show that the IHV index needs to be corrected for the long-term change of the daily curve, and calculate the corrected IHV values. Most dramatically, we find the centennial increase in global geomagnetic activity was considerably smaller, only about one half of that depicted by the *aa* index.

1. Introduction

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 magnetic activity is indicated, e.g., by the well-known fact that the average amplitude of sunspot cycles during the latter part of the 20th century is higher than in the beginning. The increasing sunspot activity leads, according to a simple model presented by Solanki, Schüssler, and Fligge (2000), to a corresponding 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 (also called the interplanetary magnetic field).

The heliospheric magnetic field is known to be the main modulator of cosmic rays and a significant cause of geomagnetic activity. Lockwood, Stamper, and Wild

(1999) used the long-term geomagnetic *aa* index to show that the heliospheric magnetic field is now more than twice stronger than 100 years ago. Recently, using long-term measurements of cosmogenic isotopes and a sophisticated chain of physical models, it was shown (Usoskin *et al.*, 2003) that the solar cycle averaged sunspot activity since the 1940s is higher than at any other time during the last 1000 years.

Despite the versatility and uniformity of these important results, serious concern has recently been raised on the centennial rise of solar magnetic activity. E.g., the long-term consistency of the geomagnetic *aa* index on which perhaps the most reliable evidence of the centennial rise is based, has been seriously questioned (Clilverd *et al.*, 2002). Because of problems with the *aa* index, Svalgaard, Cliver, and Le Sager (2003) introduced the Inter-Hour-Variability (IHV) index as a more straightforward and homogeneous measure of local long-term geomagnetic activity. Using the data from the Cheltenham/Fredricksburg station pair, they found no evidence for an increase in the corresponding IHV index during the last 100 years.

In this paper we calculate the IHV index for several geomagnetic stations in order to obtain a more global and reliable view of the long-term development of the global geomagnetic activity and in order to conclude whether or not there is reliable evidence for a centennial increase of geomagnetic activity and, thereby, of the open solar magnetic field. Moreover, we study in detail the daily variation of the magnetic field, its long-term change and its effect on the IHV index.

2. Data and Daily Variation

We use here data from six stations and one station pair which have a long record of magnetic observations from the early 1900s. The codes, coordinates, local midnight UT hours, and start years of these stations are depicted in Table I. (The stations are listed in the order of decreasing latitude). CLH and FRD form a station pair that is included here in order to allow a comparison with the results by Svalgaard, Cliver, and Le Sager (2004).

Figure 1 depicts the yearly averaged daily variation curves of the H-component for CLH/FRD and SOD for some sunspot minimum and maximum years. (The daily average was subtracted in each case in order to remove the effect of the secular variation of the magnetic field). One can see that while the daily curves at the two stations are very different (even if shifted so as to coincide in LT time), they remain fairly similar in form over the nearly 100 year time interval. We recall that the daily curve is, especially at low and mid-latitudes like CLH/FRD, mostly due to the dayside ionospheric S_q (quiet day) current.

Figure 1 shows that although the form of the daily curve remains roughly the same each year, its range (difference between daily maximum and minimum) varies greatly, especially between the minimum and maximum sunspot years. Figure 2

TABLE I

Information on stations used. Magnetic coordinates are calculated using the IGRF 2000 model.

		Geographic		Geomagnetic		Midnight	
Station	IAGA code	latitude	longitude	latitude	longitude	UT hour	Data start
Sodankylä	SOD	67.47	26.60	63.96	120.25	22	1914
Sitka	SIT	57.05	224.67	60.33	279.79	9	1902
Eskdalemuir	ESK	55.32	356.80	57.86	83.85	0	1911
Niemegk	NGK	52.07	12.68	51.89	97.69	23	1901
Cheltenham	CLH	38.73	283.16	49.14	353.71	5	1901
Fredericksburg	FRD	38.20	282.63	48.59	353.11	5	1956
Tucson	TUC	32.25	249.17	40.06	315.63	7	1909
Honolulu	HON	21.31	201.91	21.57	269.37	10	1902

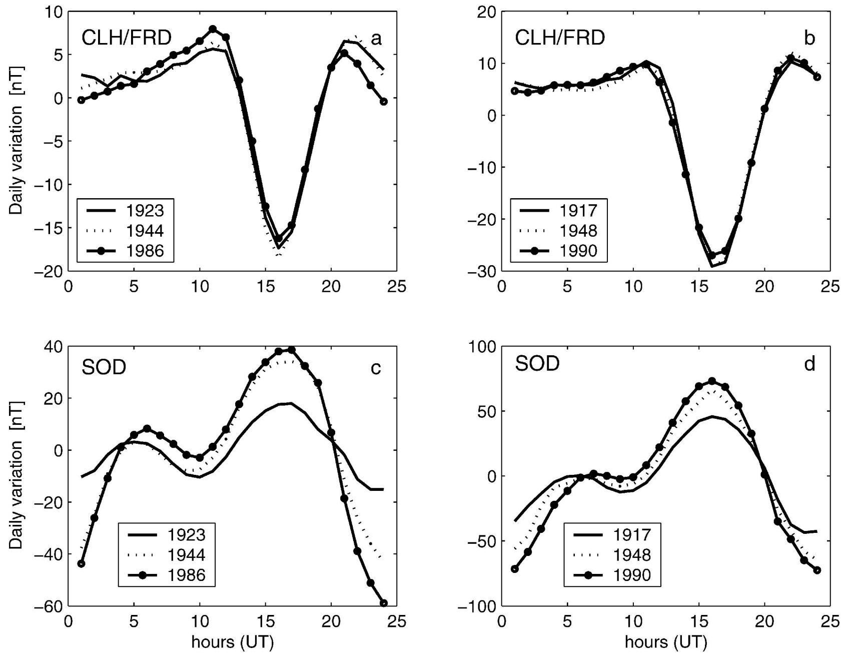

Figure 1. Daily curves for CLH/FRD and SOD stations for some sunspot minimum (a and c) and maximum (b and d) years. Time is given in UT hours.

depicts the yearly averaged range of the daily curve for a number of stations over the whole time interval. The variation of the daily range with the solar cycle is apparent. Moreover, one can see in Figure 2 that the similarity between the daily range and sunspot number curves (and the correlation between the corresponding values) is excellent for the low- and mid-latitude stations (Figure 2c and d). This is

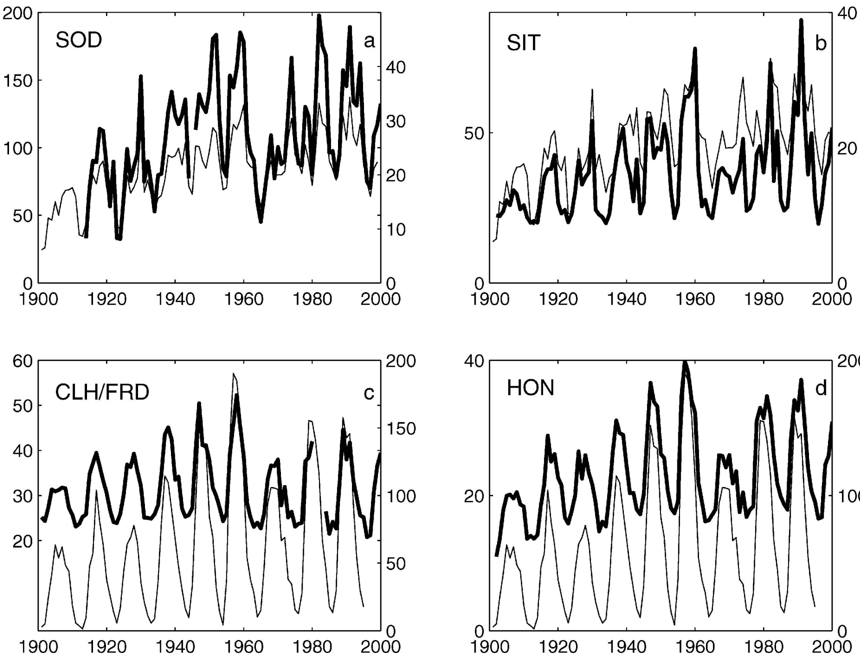

Figure 2. Yearly averages of the daily range at 4 stations (*left axis* in nT units, *thick lines*) together with the *aa* index (panels a and b; *right axis* in nT units, *thin lines*) and sunspot numbers (panels c and d; *right axis*, *thin lines*).

in accordance with the fact that the S_q variation is mainly due to solar UV radiation, and thereby, is closely correlated with sunspot numbers. However, at high latitudes (Figure 2a and b), where current systems other than the S_q current start dominating the daily curve, the daily range curves correlate better with geomagnetic activity than sunspot numbers.

3. Original IHV Index

Figure 1 shows that the CLH/FRD daily curve has a smooth section (almost a plateau) in the local pre-midnight hours from 00 to 06 UT prior to an increase at about 10 UT and a large depletion at local noon. Because of this smoothness (and because this time coincides with the geomagnetically active pre-midnight local sector) Svalgaard, Cliver, and Le Sager (2004) used the CLH/FRD data in their analysis and defined the IHV index as an average of the six absolute differences of the successive hourly values of the H component between 00 and 06 UT (19 – 01 local time).

We have calculated the IHV index (from the H component) for all the eight stations of Table I to form seven long-term series of local geomagnetic activity. (CLH and FRD IHV values were calculated separately and joined together in the same way as in Svalgaard, Cliver, and Le Sager, 2004). Figure 3 depicts the seven

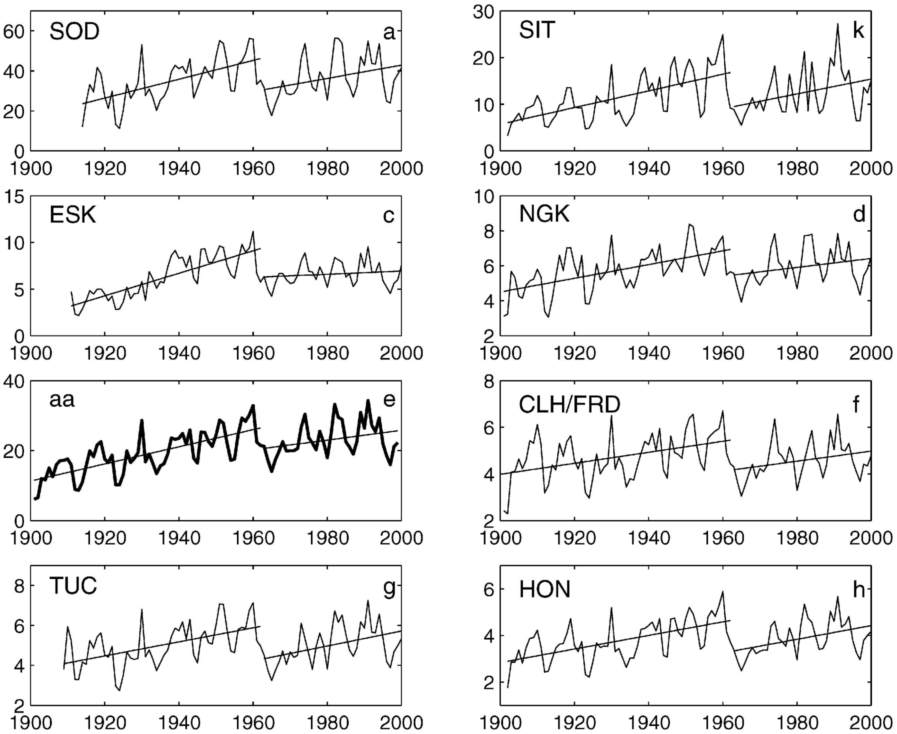

Figure 3. Yearly averages of the uncorrected IHV index (in nT) for the 7 stations together with the *aa* index (panel e).

series of yearly averaged IHV values and the *aa* index for comparison. The absolute values of the IHV indices vary, as expected, 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 IHV curves depict a clear solar cycle variation which more closely follows the cyclicity of the *aa* index than of sunspots. In fact, the IHV index seems to present a fairly good proxy of local geomagnetic activity, as suggested by Svalgaard, Cliver, and Le Sager (2004).

Moreover, all the seven IHV series, as well as the *aa* index, depict the same qualitative long-term pattern during the last 100 years: There is an increase of activity from the beginning of the 20th century until 1960, then a dramatic drop in the early 1960s, and (in most stations) weaker increasing activity 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. Because of the (often 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 time interval.

However, the centennial increase is evident and in all the seven series the IHV index attains a higher average level at the end of the century than in the beginning. We have quantified this increase by calculating the average values of the IHV index during the last (1979–2000) and first (1901–1922) 22 years of the century. (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 percentage change (increase) of local geomagnetic activity in Table II. This qualitatively uniform development in all the seven series proves that geomagnetic activity has indeed increased during the last 100 years, as has earlier been claimed on the basis of the *aa* index.

Note, however, that the relative increase (column 4 of Table II) depicted by the seven series varies greatly, being higher at the high-latitude stations (up to 70% at ESK) and lower at the low- to mid-latitude stations. While this difference can not yet be fully understood, it 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. Also, the CLH/FRD IHV series is exceptional in depicting by far the smallest increase of about 6% only, less than half of the second smallest increase at TUC and a tenth of the increase at ESK and SIT. This exceptionally weak increase of local geomagnetic activity at CLH/FRD made Svalgaard, Cliver, and Le Sager (2004) to erroneously doubt the increase of global geomagnetic activity during the last 100 years.

Although we find that there is no doubt that global geomagnetic activity has increased during the last 100 years, the exact amount of this increase is not completely unambiguous. The corresponding relative increase in the *aa* index is 65%, i.e., close to the percentage increase at SIT and ESK. However, a considerably lower increase is found at the mid-latitude stations (NGK, CLH/FRD; about 50°) that are closest in magnetic latitude to the *aa* index stations. We can now make a conservative estimate of the centennial increase in global geomagnetic activity based on the results of Table II. Selecting one high-latitude (SIT), one mid-latitude (NGK) and one low-latitude (HON) station from among those stations whose observations start either in 1901 or 1902, we obtain an average centennial increase of 35%. (We neglect here CLH/FRD since, as mentioned by Svalgaard, Cliver, and Le Sager, 2004, the values before 1915 may be overestimated). This is also very close to the overall averaged increase of all stations of about 34%. Accordingly, we find that the centennial increase is considerably lower, roughly by a factor of two, than depicted by the *aa* index.

4. Corrected IHV Index

As discussed above (see Figures 1 and 2), the range of the daily curve varies strongly with solar activity (and geomagnetic activity at high latitudes). Since the sunspot cycles depict a roughly similar long-term evolution (increase of cycle amplitudes until SC 19 in 1957; drop and increase) as geomagnetic activity, it is clear that the daily range is also affected by this long-term change, as can also be seen in Figure 2.

Because of its very definition, the IHV index depends on the range of the daily curve during the 7 pre-midnight hours (19 – 01 local time). Therefore, the long-term change of the daily range is expected to contribute to the long-term change of the IHV index. Moreover, 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. We have done this 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-q value from these smooth yearly curves in the same way as the IHV index is calculated for each day from the raw data.

The averaged values of the IHV-q index at the start (1901–1922) and end (1979–2000) of the 100-year time interval (and the relative change) are included in Table II. Note that the smallest IHV-q values are found for CLH/FRD, in agreement with the flatness of the daily curve during the IHV hours (see Figure 1). Considerably larger IHV-q values are found in many other stations, in particular in SOD where the daily curve is very steep in the local pre-midnight hours (see Figure 1). Note that in most stations the relative long-term change in IHV-q is positive and of the same order of magnitude as the relative change in IHV, except at ESK where it is negative.

We have formed the corrected IHV-cor index by subtracting the yearly IHV-q values from the original daily IHV index. Figure 4 depicts the yearly averaged IHV-cor indices for a few stations together with the original IHV index. We have also depicted the best fitting lines to the IHV-cor series in Figure 4. Note that the correction seems to be more important at high and low latitudes while at mid-latitudes the correction is smaller. The averaged values of the IHV-cor index at the

TABLE II

Values of the IHV, IHV-q and IHV-cor indices in the beginning (1901–1922) and at the end (1979–2000) of the last century.

Station	IHV start	IHV end	Relative change	IHV-q start	IHV-q end	Relative change	IHV-cor start	IHV-cor end	Relative change
SOD	28.65	40.00	40%	12.64	18.81	49%	16.01	21.20	32%
SIT	8.59	13.89	62%	2.12	5.37	153%	6.48	8.52	31%
ESK	3.96	6.77	71%	1.51	1.24	−18%	2.45	5.52	125%
NGK	5.11	6.19	21%	0.69	0.82	19%	4.42	5.37	21%
CLH/FRD	4.47	4.73	6%	0.46	0.47	2%	4.01	4.26	6%
TUC	4.63	5.40	17%	1.08	1.35	25%	3.55	4.06	14%
HON	3.37	4.15	23%	0.87	1.19	37%	2.50	2.96	18%

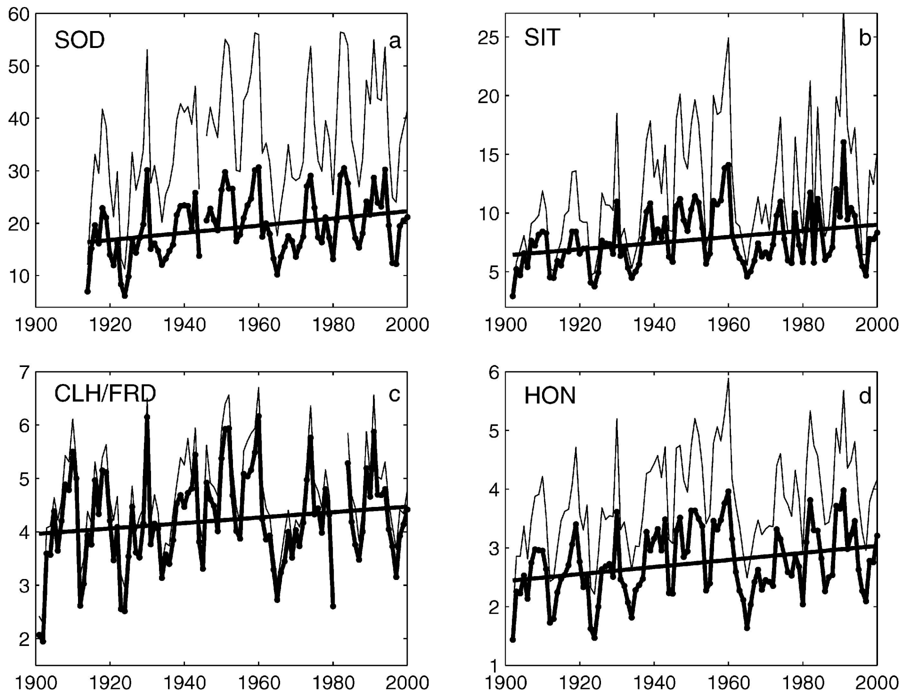

Figure 4. Yearly averages of the corrected (*thick lines*) and uncorrected (*thin lines*) IHV index for 4 stations. Best fitting lines to IHV-cor are also included.

start and end of the 100-year time interval (and the relative change) are included in Table II. A faster long-term increase in IHV-q than in IHV leads to a smaller increase in the corrected IHV-cor index. This is the situation in SOD, TUC, and HON where the centennial increase in IHV-cor is some 15–20% smaller than in IHV. Even a larger reduction is found for SIT where the increase in the corrected IHV-cor is nearly one half of the original IHV value. In the other (interestingly, all mid-latitude) stations the reverse is true and there is a larger centennial increase in IHV-cor than in the original IHV. The extreme is, because of the exceptional change of the daily curve, the ESK station where the IHV-cor depicts a 60% larger increase than IHV. Thus, the net result of the daily curve correction is that the average centennial increase in the IHV-cor remains nearly the same, at about 35%, as in the original IHV index. However, if the centennial increase is calculated from the same three longest stations as above (SIT, NGK, HON), a somewhat smaller value of about 24% is obtained for the IHV-cor.

Moreover, in order to further study the centennial increase in the various stations we have normalized both the original and the corrected IHV series at each station by their respective averages and depicted the slopes of the best fitting lines in Table III. This table verifies the above results of the higher centennial increase at high latitudes and the different effect of the daily curve correction at high and low

TABLE III

The slope (multiplied by 10^4) of the best fitting line for normalized IHV (original and corrected) values and the *aa* index.

Data	SOD	SIT	ESK	NGK	*aa*	CLH/FRD	TUC	HON	Mean	St. dev.
IHV/*aa*	40	55	47	24	61	11	20	26	32	16
IHV-cor	35	34	77	24		12	19	22	32	21

Mean and standard deviation are obtained from IHV values only.

latitudes vs. mid latitudes. Moreover, Table III also gives the average slope of the centennial increase (and its standard deviation) at the seven stations. Note that this average slope is roughly the same, about 0.0032, both for the original and corrected IHV index. This average slope corresponds to the average centennial increase of about 38%, in a very good agreement with the average increase estimated above using the 22-year time intervals, but remains clearly below the corresponding slope (about 0.0061) for the *aa* index. These results further underline our main result that the centennial increase is indeed real but considerably smaller than (roughly one half of) that depicted by the *aa* index.

5. Conclusions

We have reanalyzed geomagnetic activity during the last 100 years by calculating the recently suggested IHV index as a measure of local geomagnetic activity for 7 stations (or station pairs). We find that local geomagnetic activity in all stations follows the same qualitative long-term pattern as depicted by the geomagnetic *aa* index: an increase from early 1900s to 1960, a dramatic drop in the 1960s and a (mostly weaker) increase thereafter. At all stations the average local geomagnetic activity during the last two decennia of the 20th century is stronger than during the first two decennia. This verifies the result based on the *aa* index that global geomagnetic activity, and thereby, the open solar magnetic field has indeed increased during the last 100 years.

However, we find that the amount of centennial increase varies greatly from one station to another. In particular, a very small increase is found in the CLH/FRD series, which was erroneously interpreted in evidence of no centennial increase. We find that the relative increase is higher at the high-latitude stations and lower at the low- to mid-latitude stations. These differences may indicate that the fraction of solar wind disturbances leading to only moderate geomagnetic activity has increased during the studied time interval. We have also shown that the IHV index needs to be corrected for the long-term change of the daily curve, and we have calculated the corrected IHV values. In four out of seven stations this correction reduces the estimated centennial increase of local geomagnetic activity.

Summarizing, our results give strong evidence that the centennial increase indeed took place during the last century. However, the increase of about 65% depicted in the *aa* index is roughly twice larger than our more global estimate of about 24–35% based on seven series of long-term observations.

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