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Centennial geomagnetic activity studied by a new, reliable long-term index

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Abstract

We reanalyse geomagnetic activity during the last century using a recently proposed A_{h} index which modifies the K index method appropriate for using hourly data in long-term (centennial) studies. We calculate the local A_{h} index for six stations from different latitudes whose observations cover most of the previous century. We take into account and correct for the fact that the data sampling was changed from hourly spot values to hourly means in the early part of the last century. Since variability of spot values is larger, the early A_{h} indices, without due correction, would remain artificially large. Using recent high-sampling data, we estimate the required correction to be about 20%, i.e., large enough to make a significant effect for long-term estimates. The A_{h} index verifies that geomagnetic activity has increased during the last century at all stations. Also, the A_{h} indices prove our earlier finding that the amount of centennial increase varies greatly with latitude, being largest at high latitudes, smaller at low latitudes and, quite unexpectedly, smallest at mid-latitudes. The centennial increase depicted by the aa index is roughly twice larger than that depicted by the A_{h} index at mid-latitudes, and even larger than depicted by global A_{h} indices. Moreover, both the Ap index and the A_{h} indices verify that the scaling of the aa index was erroneously modified by a few nT in late 1950s, implying that the aa index must be revised. We also show that the A_{h} index correlates extremely well with the Ap index, better than the aa index and much better than the recently proposed, not-K based Inter-Hour Variability (IHV) index. Accordingly, the global A_{h} index offers the most reliable extension of the Ap index by roughly 30 years, and is recommended to be used in centennial studies of geomagnetic activity instead of the aa or IHV indices. Also, the local A_{h} indices can be used to extend the local K/ak indices to the centennial time scales.

Keywords: Geomagnetic activity; Long-term change; Geomagnetic indices

1. Introduction

The aa index (Mayaud, 1973) is one of the most important geomagnetic indices for long-term studies because of its uniquely long time span. Based on the aa index Lockwood et al. (1999) suggested that the strength of the heliospheric magnetic field was more than doubled during the last century. The increasing centennial trend found in solar and geomagnetic activity was further supported by results based on cosmogenic isotopes (Usoskin et al., 2003; Solanki et al., 2004) and quantified in theoretical models (Solanki et al., 2000, 2002).

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However, despite the seeming consistency of the above results, serious concern has recently been raised on the centennial increase (Svalgaard et al., 2003, 2004) and the long-term consistency of the geomagnetic aa index (Jarvis, 2005; Lockwood et al., 2008), which was long the only direct measure of global geomagnetic activity in centennial time scales. Jarvis (2005) and Lockwood et al. (2008) concluded that the scaling of the aa index was changed by a couple of nanoteslas in 1950s and that the index must be corrected accordingly. In fact, since the early magnetic observations from the aa index stations, or most other early observing magnetic stations, do not exist in digital format, at least not at a sufficiently high temporal resolution, it is difficult if not impossible to make a very detailed analysis of the correctness and long-term consistency of the aa indices. Therefore, other, more straightforward and more easily verifiable measures of geomagnetic activity are needed in order to be able to reliably study long-term changes in the near-Earth space and heliosphere.

Svalgaard et al. (2004) has recently introduced the so called Inter-Hour Variability (IHV) index as a simple, alternative measure of long-term geomagnetic activity using hourly data. The daily IHV index is defined as an average absolute difference between successive hourly values of the H component during seven night hours (19-01 LT). Since the hourly values are available in digital format in the World Data Centers (WDC) for several stations from the early years of the 20th century, the IHV index can be straightforwardly derived and reliably examined to the smallest detail, contrary to the aa index and, in fact, to all *K* indices of geomagnetic activity. Accordingly, the IHV index offers an interesting alternative to study the centennial development of geomagnetic activity.

We have calculated the daily IHV indices for several stations, correcting the indices for the effect of the changing daily curve (Mursula et al., 2004) and the change in data sampling from hourly spot values to hourly means, which occurred for most stations in 1915 (Mursula and Martini, 2006). (We have also recently corrected the IHV indices of the ESK station for the fact that the hourly values in WDC are two-hour running means Martini and Mursula, 2006.) We have shown that the IHV indices at all stations depict the same overall centennial pattern as other indices of geomagnetic activity: an increase from early 1900s to 1960, a dramatic dropout in 1960s and a weak increase thereafter. In particular, at all stations, the activity according to IHV indices at the end of the 20th century was clearly at a higher average level than at the beginning of the century. The correction due to the change in data sampling was found to be essential to reach this conclusion (Mursula and Martini, 2006), while earlier estimates with no correction attained opposite conclusions (Svalgaard et al., 2004). Moreover, based on the corrected IHV indices, we found that the centennial increases depict a curious latitudinal dependence, being largest at high latitudes, smaller at low latitudes and, unexpectedly, smallest at mid-latitudes. Also, we found that, despite the qualitative agreement with the aa index, the centennial increase in the aa index is significantly (roughly twice) larger than in the mid-latitude IHV indices and larger than in the global IHV index.

Despite its obvious benefits as a straightforward and easily verifiable measure of long-term geomagnetic activity, the IHV index has a few serious drawbacks. First of all, the IHV index is a measure of (hourly) variability while most other indices, including the aa index and all other *K* indices, measure the range of magnetic variation during some time interval (three hourly intervals in case of *K* indices). Second, while the daily averages of *K* indices include magnetic activity throughout the whole day, the IHV index takes into account night-side activity only. These differences are fundamental and imply that the IHV index and the *K* indices measure quite different processes in the near-Earth space. Thus, one can hardly expect excellent correlation between IHV and the *K* indices, which reduces the scientific applicability and usefulness of the IHV index. Also, such differences leave unclear whether the above mentioned long-term results based on IHV would remain the same if one could calculate them using *K* indices.

In order to combine the virtues (simplicity, accessibility, easy verifiability) of the IHV index and the traditional definition of geomagnetic activity according to the *K* indices, we (Mursula and Martini, 2007) have recently introduced a new index of geomagnetic activity, called the A_h index (*A* for amplitude, an analogue of the equivalent amplitude ak; h for hourly data). The A_h index is, in analogy with the IHV index, based on hourly data, but its definition follows the basic idea of the *K* index method, being a three-hourly range index which includes measurements from all local time sectors. When defining the A_h index, we have slightly modified and simplified the original K method in order to make the derivation of the A_h index not only more straightforward and transparent than the K indices but also more suitable and reliable for long-term studies. Here we calculate the A_h index for six long operating observatories, taking into account the effect of the changing data sampling, calculate the centennial evolution of geomagnetic activity according to the local and global A_h indices, and compare the A_h index and its centennial trend with those of the aa and Ap indices.

2. Stations and data

We will use here hourly data from the same six stations (actually, five stations and one station pair, CLH/FRD) as in our earlier papers (Mursula et al., 2004; Mursula and Martini, 2006). 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 listed in Table 1. These six stations have the longest and most uniform records of magnetic observations from early 1900s onwards. Note also that these stations include two high-latitude (SOD, SIT), two mid-latitude (NGK, CLH/FRD) and two low-latitude (TUC, HON) observatories, which allows to investigate, e.g., possible latitudinal differences in the long-term evolution and centennial trend of geomagnetic activity.

The data used here are hourly values stored and publicly available at the WDC. However, as we have discussed in detail earlier (Mursula and Martini, 2006; Martini and Mursula, 2006), the early hourly values were not hourly means. Rather, at most stations, the data for some of the first years in the beginning of the last century are hourly spot values (also called hourly samples), momentary values registered at some exact time (normally sharp or half hours). (see Table 1 for the year of changing data sampling at each station). While this difference does not much affect the long-term averages of geomagnetic components themselves, it does affect the level of variability in these data. Accordingly, as we have shown earlier (Mursula and Martini, 2006), the change in sampling from spot values to means reduces the IHV index typically by 30%. This had an important effect on the centennial increase in geomagnetic activity described by the IHV index. Without due correction, the IHV indices in the first years of the last century would be estimated too large, and the centennial increase would remain too low. An analogous situation is found for the new A_h index to be discussed in this paper, although the effect of sampling change and the related correction are smaller than for the IHV index.

3. Traditional and new indices of geomagnetic activity

The indices estimating local or global geomagnetic activity aim to yield a reliable measure of the observed irregular geomagnetic variations. In addition to irregular variations there are regular variations, like the solar quiet (S_q) daily variation, which need to be excluded from measures of geomagnetic activity. This is one of the key tasks when defining measures of geomagnetic activity. In the case of K indices the irregular variations are defined as the range (difference) between the upper and lower fitting quiet daily curves during each 3-h time interval, and associated with an integer number from 0 to 9, the local K index (Bartels et al., 1939; Mayaud, 1980; Menvielle and Berthelier, 1991).

Table 1
Information on stations used

Station	IAGA code	Geographic		Geomagnetic		MN hour	Data start	HMS start
		Lat.	Long.	Lat.	Long.			
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
Honolulu	HON	21.31	201.91	21.57	269.37	10	1902	1915

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

The K index scale is quasi-logarithmic and determined by the latitude dependent minimum range for the maximum K value of 9. The K indices are linearized to the corresponding equivalent amplitudes, so called local ak indices, by standard conversion tables.

The K values of 13 selected, long-running stations are first standardized and then averaged to form the global Kp index, as well as the corresponding linear Ap index. The Kp/Ap indices have been calculated since the Second Polar Year 1932, and have long been used as, perhaps, the most reliable measure of the global disturbance level in the geomagnetic field. Despite their reasonable temporal extent, the Kp/Ap indices do not even cover the last century and cannot be used for centennial studies. In order to extend the time span, Mayaud (1973) introduced the aa index as an average (scaled) ak value from two antipodal stations (actually, series of stations) which have been running since 1868. The aa index was long the standard, in fact, the only measure of geomagnetic activity used for centennial studies of global geomagnetic activity.

Despite their obvious merits, the K indices also have some inherent problems for long-term studies. The determination of the momentary K indices for each 3-h interval at each observatory was partly subjective, relying on the expertise and personal evaluation of the observer. This is particularly true because of the necessary usage of the quiet daily curve for which no quantitatively definite curves were most often used. The observers typically used analogue model curves based on the development of the respective magnetic component in the same season in previous years. The exact form of the quiet daily curve is especially important in case of rather quiet situations when trying to distinguish between the lowest K levels (0, 1 and 2). Since the early measurements were registered on analogue magnetograms, the high sampling data are not, at least at the present time, available in digital format for the early years. (In most cases, hourly values do exist in digital form.) Therefore, a detailed examination of the correctness of the daily curve removal and of the validity and long-term homogeneity of the K/ak values is not yet possible.

Also, the basic tenet of the K method to "digitize" the continuous range values to only 10 possible values of the K index is quite unfortunate, leading, e.g., to the problem of selecting, often rather arbitrarily, between two neighbouring K values. This selection is particularly difficult between 0 and 1 and, as mentioned above, further affected by the problem of the quiet daily curve. In fact, the selection problem may be the reason for the different distribution of, especially, the low K values at different stations (see, for example, Clilverd et al., 2005). The selection problem is particularly important for long-term studies since different observers (even at one station) may have a slightly different personal bias for this selection, leading to a systematic difference in the long-term trend. However, this problem could easily be circumvented by using continuous range values as the fundamental parameter of local geomagnetic activity, instead of the "digitized" K indices. (Note that the original restriction to a rather small number of K values was largely motivated by the implied facility of computing. Nowadays, there is no need for such a restriction.)

The K indices have yet another inherent problem for long-term studies. This is related to the existence of a fixed lower disturbance limit for the highest $K = 9$ level. In the case of a long-term increase of activity (i.e., growing range values) such a fixed lower limit may lead to an underweighting of the higher disturbance levels, leading to a erroneously small increasing trend. Also, with different long-term trends at different stations, it will distort the distributions differently. Even changing the lower limit for a higher value at some time would not improve the situation, since it would only further compromise long-term homogeneity of the station. The situation is basically similar to the above mentioned selection problem and is also due to the "digital" nature of the K index (or, the very small number of different K values). Again, using continuous range values (rather than "digital" K values) as the fundamental parameter with no artificial upper or lower limits would solve this problem.

Moreover, aside of these fundamental problems related to all K based indices, serious concern has recently been raised on the long-term consistency of the aa index (Svalgaard et al., 2003, 2004; Jarvis, 2005; Lockwood et al., 2008). Different authors (Jarvis, 2005; Lockwood et al., 2008) have come to the conclusion that the aa index was erroneously changed by roughly 2 nT in the 1950s due to changes in calibration, and that the index need to be revised accordingly. This error further demonstrates the need for alternative, more straightforward and easily reproducible long-term measures of geomagnetic activity.

The data availability problem has been corrected in the IHV index Svalgaard et al., 2003, 2004) which has recently been introduced as a new measure of local geomagnetic activity. Based on hourly values available in digital format, the IHV index can be straightforwardly derived and examined to the smallest detail, contrary to the K indices. Since the hourly data exist for several stations from the early years of the last century, the IHV index can yield an alternative method to study the centennial development of geomagnetic activity.

However, as mentioned above, the usefulness of the IHV index is limited since it is based on a very different principle than the more traditional K indices. The IHV index is a measure of hourly variability while the K index is a three-hourly range measure. Also, the IHV index includes only the night-time activity. The pre-midnight to midnight LT hours were originally selected (Svalgaard et al., 2004) for the IHV index because the daily curve at CLH/FRD station is rather flat at this time. Accordingly, the IHV index was expected to be free of the S_q variation, exempt from any further treatment as to the daily curve. However, it was shown (Mursula et al., 2004) that the range of the daily curve even in the IHV sector is not constant but varies over the solar cycle and even on longer time scales. Therefore, even the IHV requires some form of daily curve correction. Also, because the different LT sectors depict very different absolute activity levels and depend on different external drivers (dayside mainly on solar wind pressure, night sector on southward IMF), the IHV index and the K indices are bound to include different physics. We would also like to note that the three-hourly range of the K index was originally chosen in order to take into account the typical temporal character of the bay-like geomagnetic disturbance (mostly, the substorm). Obviously, the hourly variability of the IHV index is not dedicated for this aim.

4. The A_h index

The main aims of the A_h index are, on the one hand, to make use of the digital hourly values of the geomagnetic field, allowing a straightforward and easily verifiable treatment and, on the other hand, to follow the principle of the K index method as closely as possible and appropriate. Accordingly, the A_h index is produced in the following way. First, we calculate the quiet daily variation of the H-component for each month and each observatory separately. Since the IHV index is an appropriate daily monitor of local geomagnetic activity, we use the local IHV-cor indices (Mursula et al., 2004; Mursula and Martini, 2006) to find the five quietest days in each month for each observatory. (Uncorrected IHV-raw indices could also be used with little difference.) We use local rather than global quiet days in the derivation because the former give a better definition of the local conditions and because the official global quiet days have been selected only since 1932, thus missing the early part of the last century.

The quiet daily curve was then calculated each month and station as the average of the daily curves of the H component during the five locally quietest days. Note that monthly curves give a more accurate evaluation of the annual variation of the quiet daily curves than the seasonal model curves that were typically used by the observers. The most fundamental difference between the present and K index method is that finding the quiet daily variation is no longer subjective and can be easily reproduced and examined.

Thereafter, as in the derivation of the K index, the range was calculated as a difference between the upper and lower limiting quiet daily curves (of the respective month) during each 3-h interval. This three-hourly range will be called here the A_h index. No further classification ("digitization") of the range value is made, contrary to the K index method. Accordingly, in our method the range (or amplitude; analogue to ak) is the fundamental parameter measuring the disturbance level, and has a linear scale in units of nT. Also, the A_h index is continuous rather than the K index whose values are "digitized" to the 10 integer values. Therefore, the A_h index also solves the above mentioned problems of the K index method for centennial studies. Note also that the linear ak index is also restricted to 10 fixed values and therefore has the same problems as the K index.

5. Correcting the effect of changed sampling

As shown in Table 1, many stations changed their registration from hourly spot values (hourly samples) to hourly means in 1915. At NGK this was already done in 1905. Therefore NGK was used as a reference station in the following analysis (for more details, see Mursula and Martini, 2006). The effect of the changed sampling is clearly seen in the ratios of annual A_h averages. We have depicted in Fig. 1

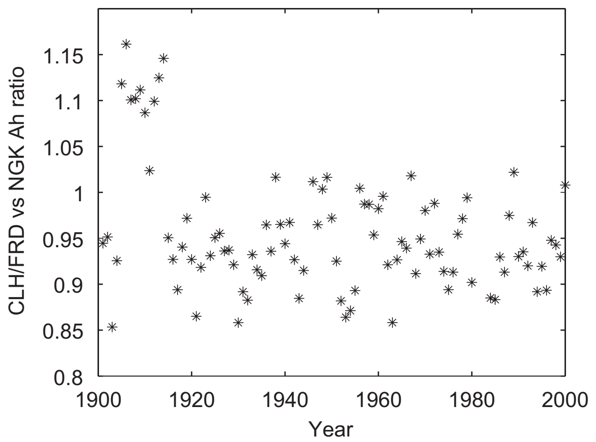

Fig. 1. Ratio of annual A_h values between CLH/FRD and NGK. The effect of changing sampling is seen as an increase of the ratio from 1904 to 1905 when NGK sampling changed and a decrease from 1914 to 1915 when CLH sampling changed.

Table 2
RF sampling calibration factors for A_h and their error estimates, CF-ratios in 1996 and 2000

Station	RF	Error of RF	CF-1996	CF-2000
SIT	–	–	1.24	1.27
NGK	1.20	0.035	1.16	1.26
CLH/FRD	1.18	0.017	1.17	1.17
TUC	1.15	0.061	1.13	1.16
HON	1.14	0.022	1.09	1.12

the ratio of the annually averaged A_h 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 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-NGK ratio in 1901–1904 (0.9187), in 1905–1914 (1.1074) and since 1915 (0.9389). The ratio $1.1074/0.9187 = 1.21$ gives an estimate of the required sampling correction factor for NGK A_h indices, while the ratio $1.1074/0.9389 = 1.18$ gives a similar estimate for CLH/FRD A_h indices.

We have estimated similarly the sampling correction factors for the six stations. These are called the RF factors and they are, together with their estimated errors, depicted in Table 2. As seen there, correcting the sampling change decreases the early A_h indices by about 14–20%. As mentioned above, this decrease is due to the fact that hourly spot values have a larger variability than hourly means, leading to larger ranges in the beginning of the last century. The same effect is valid for all measures of variability. For the IHV index the sampling correction was found to be larger, about 30% (Mursula and Martini, 2006). Without due correction, the level of geomagnetic activity is overestimated in the beginning of the last century and the centennial increase remains underestimated. For definiteness, we used the 1915–1926 period when calculating the RF factors in Table 2. (In all other stations except for SIT a very clear step is seen in the station vs. NGK ratio for the years after 1915, allowing a very robust estimate for the RF factor. At SIT, rather large solar cycle related fluctuations were seen in the NGK ratio, making the correction factor estimate more uncertain. The same situation was found earlier for the IHV ratios for SIT.)

In order to further verify the validity and size of the RF factors, we have made another, more detailed study following our earlier treatment for the IHV indices (Mursula and Martini, 2006). Since, for the recent years, we have more frequently sampled data available from all stations, we have constructed two series of A_h indices for each station, one (to be called A_{hmin}) using data sampled once a minute, taking one spot value per hour (each sharp hour), the other (the normal A_h) using hourly means of the same station. These two series were calculated for one sunspot minimum year, 1996, and one sunspot maximum year, 2000. The two A_h series were then averaged to annual means and the annual A_{hmin}/A_h ratio was calculated for the two years. These ratios (to be called CF-1996 and CF-2000 factors; see Table 2) form another, more definite set of correction factors for the A_h indices. Note that the CF factors are mostly very close to the RF factors, verifying the consistency of the two methods and the size of the correction needed to correct the effect of the sampling change upon the A_h index.

Note that for most stations the CF factors depict a weak, direct dependence on sunspot activity. This can be understood so that higher solar activity leads to higher variability, enhancing the difference in variability between spot and mean values compared to low activity times. The direct relation of CF factors on sunspot activity is contrary to the mostly inverse relation between sunspot activity and similar correction factors found for the IHV indices (Mursula and Martini, 2006). This difference is due to the fact that while the A_{hmin} and A_{h} values have been obtained with respect to the daily curve, the IHV indices include the (solar cycle dependent) daily curve. Thus, if the inclination of the IHV section of the daily curve increases with solar activity, the increased variability caused by hourly samples has a relatively smaller effect in IHV, leading to the observed inverse relation. This difference between the correction factors of A_{h} and IHV indices also demonstrates that the quiet daily curve is more correctly and systematically treated in the A_{h} indices (i.e., in the original K method) rather than in the raw IHV index where only a certain LT sector was selected.

Because the CF factors are very similar but more definite than the RF factors, we will use them when correcting the A_{h} indices for the effect of changed sampling. Moreover, as earlier when correcting the IHV indices (Mursula and Martini, 2006), we will assume that these (annual) correction 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. Fig. 2 shows the dependence of these annual factors on annual sunspot numbers for those years where SIT was registrating hourly samples.

The same analysis was repeated for all other stations (except SOD where hourly mean values were always registered), using the appropriate $A_{\mathrm{hmin}}/A_{\mathrm{h}}$ ratios for each station and calculating the corresponding relation with sunspot numbers. Fig. 3 depicts the ratios of the corrected annual A_{h} indices between CLH and NGK stations. One can

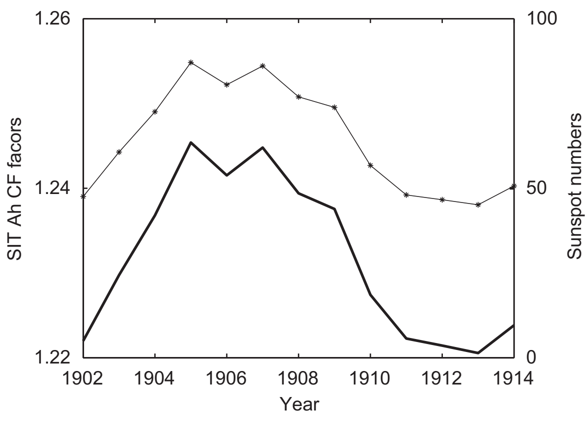

Fig. 2. The sampling correction factors (CF) for SIT A_{h} (thin line with stars; left axis) and the sunspot numbers (thick line; right axis) for 1902–1914 when SIT was measuring hourly spot values.

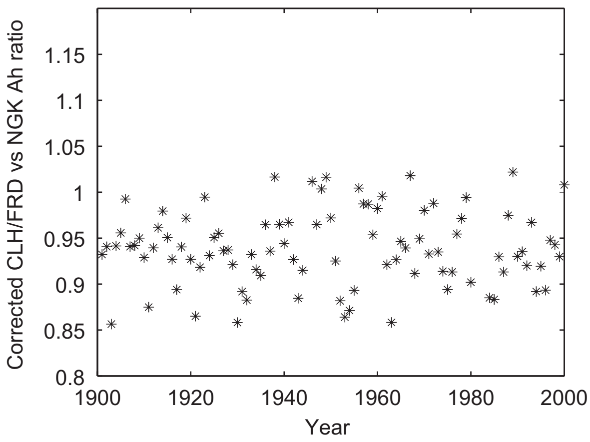

Fig. 3. Ratio of corrected annual A_{h} values between CLH/FRD and NGK depicting a rather constant behaviour even over the years when sampling was changed.

see that the steps depicted in Fig. 1 have disappeared. Since the sunspot cycles at the start of the previous century were rather low, the overall, cycle-averaged CF factors are slightly smaller for the early years than they would be for present times. However, since the sunspot cycle variation of the correction factors is rather weak, even using a constant correction factor would only lead to a small (less than 3%) error in the correction and only a minor error in the A_{h} indices.

The spread of points in Fig. 3 (and similar figures for other stations) can also be used to estimate typical errors in the annual RF factors (listed in Table 2). Note that these errors are of the same order of magnitude as the solar cycle variation of CF factors. However, these error estimates of RF factors are quite crude and should not be directly applied to CF factors. Obviously, no independent error estimate can be obtained for CF factors from the two values of CF-1996 and CF-2000. An error estimate based on annual averages, similar to the RF errors of Table 2, could be obtained for CF factors if the A_{hmin} and A_{h} values were calculated for more than two years. However, since geomagnetic activity also depicts a well-known seasonal variation, a more proper treatment would be to calculate the CF factors and their errors at a seasonal or monthly time resolution, thus improving the temporal accuracy of correction. Since such an improved treatment would be quite elaborate and is not expected to much change the above discussion, it will have to be postponed to subsequent studies of the A_{h} index.

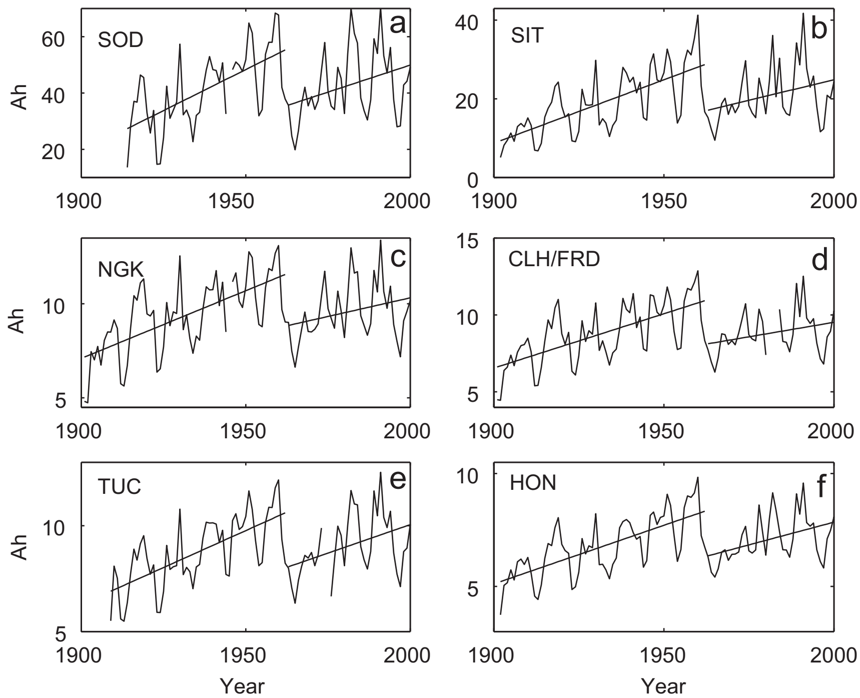

Fig. 4. Yearly averages of the sampling corrected A_h index (in nT) for the six stations included in the study. For each station two best fitting lines are included, one for the early period from data start until 1962 and another for 1963–2000.

6. Centennial increase and latitudinal ordering in A_h

We have depicted the corrected yearly A_h indices for the six stations in Fig. 4. The values of the A_h indices, as all geomagnetic disturbances, increase with the magnetic latitude of the station so that the annual A_h indices at the highest SOD station are roughly an order of magnitude larger than at the lowest HON station. Despite this difference in absolute level, all six A_h series depict the same qualitative long-term pattern during the last 100 years (Mursula et al., 2004; Mursula and Martini, 2006): 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 (when most stations had the overall maximum), then a dramatic dropout in early 1960s, and a weaker increasing trend thereafter. Accordingly, in order to emphasize this pattern, we have included in Fig. 4 for each station two best fitting lines, one for the early period until 1962 and another for 1963–2000. A qualitatively similar behavior is found also for other indices of geomagnetic activity, e.g., for the IHV indices (Mursula et al., 2004; Mursula and Martini, 2006), and all K indices, including the Ap and aa indices (see later). However, the various indices differ significantly in quantitative details.

We have quantified the centennial increase in the A_h indices in two different ways. First, we have calculated, following a similar treatment for the IHV indices (Mursula et al., 2004; Mursula and Martini, 2006), the average values of the A_h indices at the six stations during the last (1979–2000) and 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.) By this method one can quantify the centennial increase taking only into account the difference in activity level between the beginning and end of the last century. Thus, anything in between these time intervals, e.g., the local peak around 1960s, does not directly affect this estimate. This method is also independent of the possible normalization of the index (e.g., by its mean or to some other index like Ap). We have listed these two average levels as well as the implied percentual change (relative centennial increase) of geomagnetic activity in Table 3.

All six A_h series depict clearly larger values at the end of the last century. Moreover, the centennial

Table 3
Mean values of the A_h indices for the six stations at the beginning (from start until 1922) and at the end (1979–2000) of the last century, their relative increase and the slope of the best fitting line for the mean normalized values in 1914–2000

Station or index	A_h start	A_h end	Relative increase (%)	1000 * Slope 1914–2000
SOD	33.35	46.85	40.5	3.87
SIT	13.46	23.14	71.9	3.22
NGK	8.17	10.01	22.5	0.65
CLH/FRD	7.61	9.13	20.0	0.65
TUC	7.61	9.66	26.9	1.89
HON	5.94	7.49	26.1	1.58
A_{h6}	0.9186	1.0436	13.6	1.64
aa-1914	17.90	24.63	37.6	4.48
A_{h3}	0.8055	1.1023	36.8	3.57
aa-1902	15.20	24.63	62.0	5.88

Similar values are also shown for the mean normalized 6-station (1914–2000) and 3-station (1902–2000) global A_h averages and for the mean normalized aa-1914 and aa-1902 indices.

increases at the different stations depict the same latitudinal ordering found earlier based on the IHV indices (Mursula and Martini, 2006). Although the relative increases in Table 3 cannot be straightforwardly compared because of the different starting years, it is clear that the largest centennial increases are found at high latitudes (SOD, SIT), smaller increases at low latitudes (TUC, HON) and the smallest increases at mid-latitudes (NGK, CLH/FRD). (The increase at SOD remains smaller than at SIT because of the later start year.) This latitudinal ordering of the centennial trends is systematic and even more clear than in the IHV indices (Mursula and Martini, 2006).

Table 3 also shows the slopes of the best fitting lines to A_h at each observatory in 1914–2000. Before calculating the slopes we have first normalized the A_h series by their average values in 1914–2000. Using this normalization and the same time interval, the slopes of the A_h values at different stations can be reliably compared. One can see that the above mentioned latitudinal ordering is valid now even more clearly than when comparing the relative increases. (Note that, although the slopes are dependent on the absolute scale, the ordering remains the same.) The mid-latitude stations depict exactly the same, rather small slope while the slopes at the low-latitude stations are more than twice larger. Again, the slopes at the high-latitude stations are roughly twice larger than at low latitudes.

7. Global A_h indices and comparison with aa

Traditionally, global geomagnetic activity, in particular the global K indices like Kp/Ap and aa, is defined in terms of the mid-latitude disturbance level. Some form of latitudinal normalization is needed since the absolute activity levels vary greatly, as discussed above. However, the situation is basically different when one discusses the centennial trends of geomagnetic activity. As seen above, the centennial increase varies with latitude by a reasonable factor. Therefore, when defining a really global estimate for the centennial increase of geomagnetic activity, it is important to include stations from different latitudes, not only from mid-latitudes. Using only mid-latitude stations for global geomagnetic activity would seriously underestimate the centennial increase of global geomagnetic activity.

In pursuit of having a more global estimate for global geomagnetic activity and its centennial increase, we have used all the six stations since they represent high, mid- and low latitudes (two stations from each) roughly on an equal footing. The A_h values at each station were first normalized by their means in 1914–2000 in order to set all the stations to the same absolute level and the same time interval, and then averaged. This gives the six-station index to be called here A_{h6}. Since all of the six stations do not cover the whole century, we have defined another, slightly longer global index, the A_{h3} index based on three stations, one high-latitude (SIT), one mid-latitude (NGK), and one low-latitude (HON) station which all cover the time interval since 1902.

Table 3 also shows the relative increases and slopes of the best fitting lines for A_{h6} and A_{h3}. The A_{h6} index depicts a relative increase of 13.6% and slope of 1.64×10^{-3} in 1914–2000. These numbers should be compared with the 37.6% increase and slope of 4.48×10^{-3} in the aa index over the same time (aa-1914 in Table 3). Correspondingly, the A_{h3} index depicts an increase of 36.8% and a slope of 3.57×10^{-3} in 1902–2000 to be compared with the 62.0% increase and a slope of 5.88×10^{-3} in the corresponding aa index (aa-1902 in Table 3). Thus, we find that the centennial increase in the global A_h index is clearly lower than depicted by the aa index. This conclusion is in a good quantitative agreement with our earlier results based on the IHV indices (Mursula and Martini, 2006).

Also, when comparing the centennial increases in the local A_h indices with the increase depicted by aa index one finds that, although aa stations are located at mid-latitudes, the aa index effectively behaves in the long term like a high-latitude index. The centennial increase in the A_h indices at mid-latitudes (NGK, CLH/FRD) is about 21%. This is much smaller than the 62% increase in the aa index over the same time interval. Clearly, the aa index seems to exaggerate the increase over this time. This is also in accordance with the results based on the IHV index (Mursula and Martini, 2006).

Fig. 5 depicts the scatterplot of the yearly values of the aa index vs. the yearly values of the A_{h3} index. The slope of the best fitting line is 22.056 and the intercept −1.336. Because the form of centennial change is similar, the A_{h3} and aa indices are still fairly well correlated (correlation coefficient is 0.946). We have depicted the yearly values of the so obtained, aa normalized A_{h3} and the A_{h6} indices, together with the aa index in Fig. 6. Fig. 6 also includes the best fitting lines over the appropriate time intervals. The slopes of the shorter indices are 0.0365 for A_{h6} and 0.0975 for aa, and for the longer indices 0.0789 for A_{h3} and 0.122 for aa. The slopes of the aa index are considerably larger than those of the correlated global A_h indices, verifying again the larger centennial increase in the aa index.

We have depicted in Fig. 6 also the differences between the aa index and the global A_h indices. It is clearly seen that there is a systematic difference between aa and A_h. Despite considerable fluctuations, the aa index is, on an average, roughly 1–2 nT below the A_h indices from the start of the depicted time interval until the end of 1950s, and above the A_h indices by roughly the same amount since early 1960s. Accordingly, this comparison is in a very good qualitative agreement with recent studies of the aa index (Lockwood et al., 2008; Jarvis, 2005; Clilverd et al., 1998), concluding that the calibration of the aa index fails in late 1950s, most likely because of the change of the northern aa station from Abinger to Hartland. In order to quantify the step we have calculated the average value of the aa-A_{h6} and aa-A_{h3} differences from the start of the index until 1955 (−1.24 nT for A_{h6} and −1.18 nT for A_{h3}) and from 1965 onwards (1.49 nT for A_{h6} and 1.72 nT for A_{h3}). Thus, the total value of the step in the aa index about 2.5–3.0 nT. This is only slightly larger than the earlier estimates.

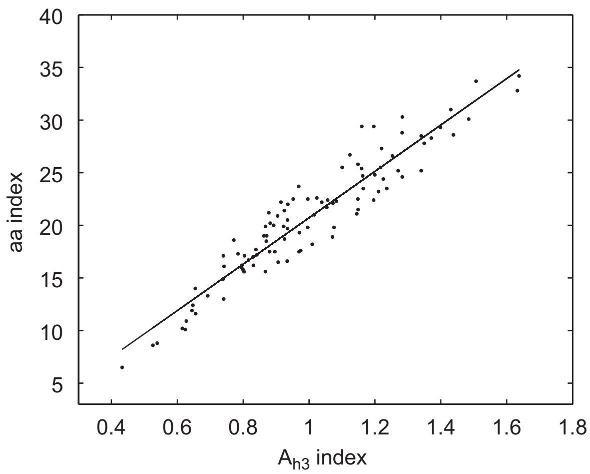

Fig. 5. Scatterplot of yearly averages of aa (in nT) vs. the A_{h3} index. The best fitting line is also shown.

8. Comparison with Ap

8.1. Correlation of Ap, aa and global A_h

In moderately long-term studies the Kp/Ap index is perhaps the most widely used geomagnetic index. The wide network of 13 stations makes the Kp/Ap index a more reliable estimate of the global geomagnetic activity than given by the aa index which is based only on two stations. (Note that two of the present stations (SIT, FRD) are included among the 13 Kp/Ap stations.) As seen above, while the A_h and IHV indices agree quite well about the amount of centennial increase, the aa index gives a considerably larger estimate. In order to further verify our estimates we have compared the

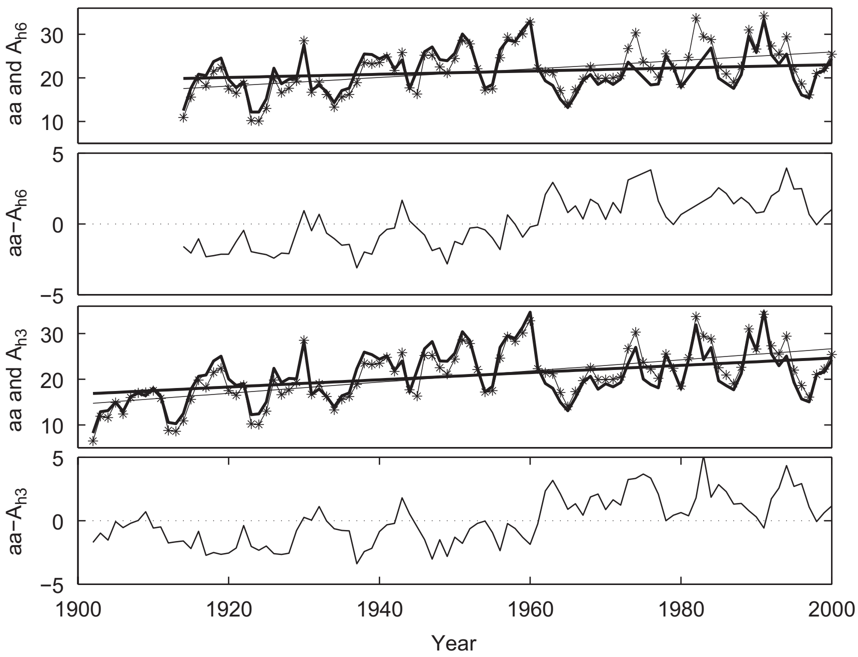

Fig. 6. Top and third panel: yearly averages of the aa index (thin line with stars) and the A_h indices (solid line; A_{h6} in top panel, A_{h3} in third panel) together with the respective best fitting lines (aa thin line; A_h thick line). Second and bottom panels depict the corresponding aa-A_h differences.

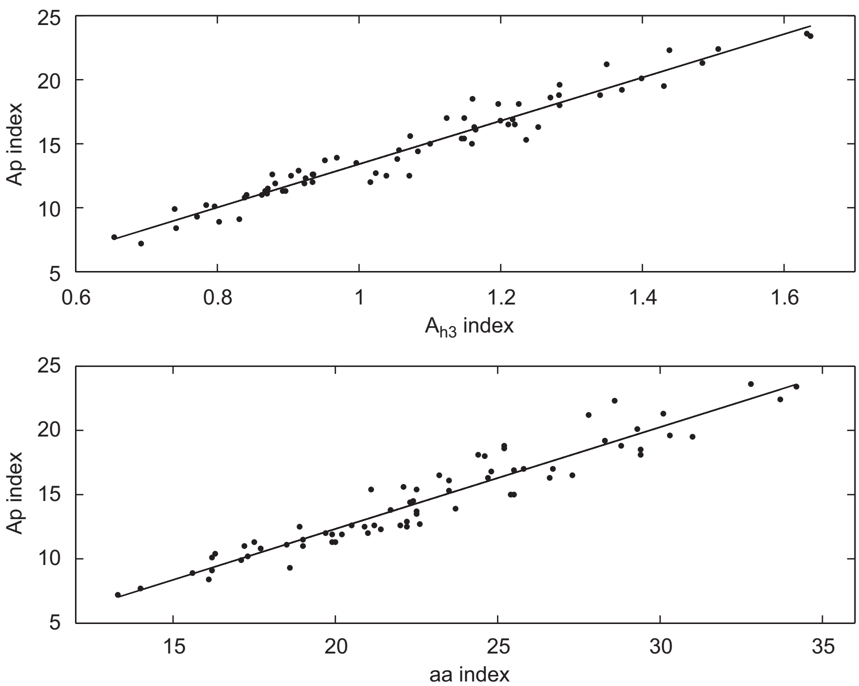

Fig. 7. Scatterplot of yearly averages of Ap vs. the A_{h3} index (upper panel) and Ap vs. the aa index (lower panel), together with the best fitting lines.

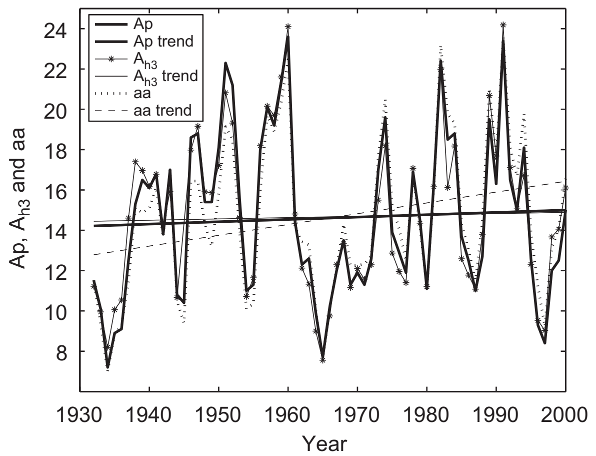

Fig. 8. Yearly averages of the Ap index (thick line), the Ap normalized A_{h3} index (thin line with stars) and the Ap normalized aa index (dotted line), together with the respective best fitting lines (Ap thick; A_{h3} thin; aa dashed). While the Ap and A_{h3} lines can hardly be distinguished from each other, the aa line depicts a clearly higher increase.

global A_{h3} index, as well as the aa index with the authoritative Ap index since 1932.

Fig. 7 depicts the two scatterplots of the yearly values of the Ap index in 1932–2000 vs. the A_{h3} index, as well as vs. the aa index. The correlation coefficients between Ap and aa is 0.95, and 0.97 between Ap and A_{h3}. (It is even higher, 0.98, between Ap and A_{h6}, not depicted in Fig. 7.) The good correlation between Ap and aa is expected. However, the fact that Ap correlates even better with the two global A_h indices is very convincing for the new method. We have depicted in Fig. 8 the yearly values of the Ap index and the correlated A_{h3} and aa indices, together with the best fitting lines, depicting the long-term development of the indices in 1932–2000. The slope and intercept of the best fitting line of Ap are 0.0116 and −8.14. For A_{h3} they are 0.0065 and 1.89, i.e., fairly close to those of Ap. On the other hand the slope of the aa index is considerably larger, 0.0536 (intercept is −90.76). Actually, the best fitting lines for Ap and A_{h3} in Fig. 8 are so close that they can hardly be distinguished. On the other hand, the best fitting line of the aa index shows a clearly larger increase, further emphasizing that aa index overestimates the centennial trend.

In order to demonstrate this in more detail we have depicted in Fig. 9 the differences between Ap and the other two indices (aa and A_{h3}). The Ap-aa difference depicts the same problem already mentioned above in that the difference is systematically above zero from the start until late 1950s and below zero from early 1960s onwards. This further verifies that the aa index experienced a step like level change at this time. On the other hand, the Ap-A_{h3} difference does not show any systematic, long-term deviation from zero over the studied interval, in agreement with the result that Ap and A_{h3} are more consistent and better correlated with each other than Ap and aa.

8.2. Correlation between Ap and local A_h and IHV

In order to further quantify the agreement between Ap and the A_h indices we have calculated the correlation between Ap and the local A_h index for each station separately. The respective correlation coefficients are listed in Table 4. One can see that the correlation is very good for each station, varying slightly with latitude so that the highest correlation is found for the two mid-latitude stations. This is understandable taking into account the fact that the Kp/Ap stations are mostly from mid-latitudes. Note also that most correlations between Ap and the local A_h indices are better than between Ap and aa. (For the low-latitude stations the correlations are smallest: for HON it is slightly smaller and for TUC equal to that with aa.)

We have also included in Table 4 the correlation of Ap with the local IHV indices at the same stations. One can see that the level of these correlations is also fairly good but remains clearly below the correlation between Ap and the local A_h indices. (For HON the two correlations are equal.) It is interesting to mention that, contrary to the correlation between Ap and the local A_h indices, the correlation between Ap and the local IHV indices is, in all cases, below the correlation between Ap and the aa index. This clearly results from A_h following the main principles of the K method more closely than IHV. This also suggests A_h indices, rather than IHV, to be used as the best available extension of the temporally limited Ap index since the beginning of the last century. The close agreement between Ap and the A_h indices is due, on one hand, to the similar basic definition of the range and the related treatment of the quiet daily curve and, on the other hand, to the fact that both indices include geomagnetic activity for the full day, i.e., from all local time sectors. Note also that since Ap correlates with the mid-latitude A_h indices better than with the aa index, these basic similarities are obviously more

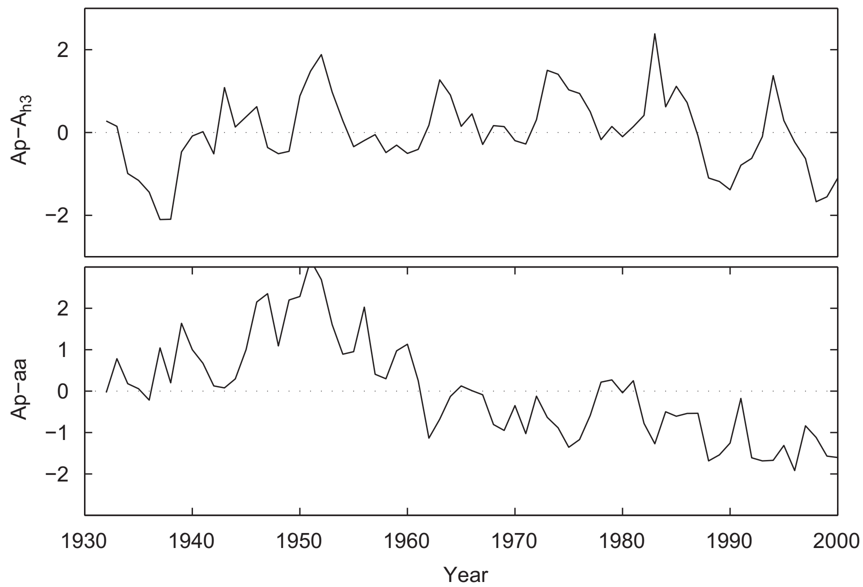

Fig. 9. Differences of yearly averages of Ap and the Ap normalized A_{h3} index (top panel) and Ap and the Ap normalized aa index (bottom panel).

Table 4
Correlation coefficients between Ap and the local A_h indices (upper part) and Ap and the local IHV (lower part) indices at the six stations

Station index	Correlation coefficient
Ap-A_h (SOD)	0.97
Ap-A_h (SIT)	0.96
Ap-A_h (NGK)	0.98
Ap-A_h (CLH/FRD)	0.98
Ap-A_h (TUC)	0.95
Ap-A_h (HON)	0.94
Ap-IHV (SOD)	0.91
Ap-IHV (SIT)	0.92
Ap-IHV (NGK)	0.92
Ap-IHV (CLH/FRD)	0.93
Ap-IHV (TUC)	0.90
Ap-IHV (HON)	0.94

important than mutual differences (different sampling frequency and different local/global nature).

9. Conclusions

We have reanalysed geomagnetic activity during the last century using a recently proposed A_h index which modifies the K index method appropriate for using hourly data in centennial studies. We have calculated the local A_h index for six stations whose observations cover most of the previous century. We have taken into account and corrected for the fact that the data sampling was changed from hourly spot values to hourly means in the early part of the last century. Since variability of spot values is larger, the early A_h indices, without due correction, would remain artificially large and the centennial increase too small. Using recent high-sampling data, we have estimated the required correction to be about 20%, i.e., large enough to make a substantial effect on long-term estimates.

The A_h index verifies that geomagnetic activity has increased during the last century at all stations. However, the exact amount of centennial increase varies from one station to another. The A_h indices prove our earlier finding based on IHV indices (Mursula and Martini, 2006) that the centennial increase varies with latitude, being largest at high latitudes, smaller at low latitudes and, surprisingly, smallest at mid-latitudes. The centennial increase in the aa index is roughly twice larger than depicted by the A_h index at mid-latitudes, and even larger than depicted by global A_h indices, in accordance with a similar result of an excessively large centennial increase in the aa index based on the IHV indices. The A_h index depicts an almost similar trend since 1932 as the Ap index but the aa index shows a clearly larger trend. Moreover, both the Ap index and the A_h indices verify that the scaling of the aa index was erroneously modified by a few nT in late 1950s, implying that the aa index must be revised.

We have shown that the A_h index correlates extremely well with the Ap index, clearly better than the aa index and much better than the IHV index. Accordingly, the global A_h index offers the most reliable extension of the Ap index by roughly 30 years, and is therefore recommended to be used in centennial studies of geomagnetic activity instead of the aa or IHV indices. Also, the local A_h indices can be used to extend the local K/ak indices to the centennial time scales. The good correlation between Ap and A_h and the problems in the aa index suggest that the earlier long-term studies based on the aa index should be recalculated using the A_h index.

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