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New indices of geomagnetic activity at test: Comparing the correlation of the analogue *ak* index with the digital A_h and IHV indices at the Sodankylä station ☆

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Abstract

We test here two recently proposed indices of geomagnetic activity, the A_h index and the IHV index, which are based on digitally available hourly geomagnetic measurements. We study their correlation at different temporal scales with the Sodankylä *ak* index that is based on analogue registrations and exists since 1914. Even at the highest temporal resolution, the three-hourly A_h indices correlate extremely well with *ak* (correlation coefficient = 0.873 for 243,374 points). Correlation is excellent at all local times, with correlation coefficients varying from dayside minimum of 0.81 to nightside maximum of 0.89, indicating that A_h describes the local time variability of the *ak* index very reliably. Using daily averages the correlation between *ak* and A_h is even higher (cc = 0.94) and considerably better than between *ak* and IHV (cc = 0.80). The standard deviation between daily averages of *ak* and the correlated A_h is only 6.9 nT but as large as 11.9 nT for IHV. At the monthly resolution and longer, the IHV indices correlate with *ak* almost equally well as A_h with *ak*. However, while the slopes of the best fit relations between *ak* and A_h are nearly the same at all temporal resolutions (yearly, monthly, daily, three-hourly), reflecting a highly linear relation between these two indices, the slopes between *ak* and IHV get consistently and significantly smaller with increasing resolution, indicating a fundamentally nonlinear relation between *ak* and IHV. These facts verify that IHV index is very different from all *K* based indices, including *ak* and A_h, and strongly suggest that A_h rather than IHV should be used as a long-term proxy or extension of local and global *ak*/*K* indices.

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

1. Introduction

Geomagnetic activity is among the most important parameters to study the long-term change in the Sun, heliosphere and near-Earth space. The longest geomagnetic activity index, the *aa* index (Mayaud, 1973) has been used in a number of studies of the long-term change in the Sun and the near-Earth space. For example, it has been used to suggest that the heliospheric magnetic field was more than doubled during the last century (Lockwood et al., 1999). However, serious concern has recently been raised on the consistency of the *aa* index (Mursula et al., 2004; Svalgaard and Cliver, submitted for publication; Jarvis, 2005; Lockwood et al., submitted for publication; Mursula and Martini, 2006).

The aim of geomagnetic indices is to estimate the level of irregular magnetic variations, excluding regular variations like the solar quiet (S_q) daily variation. In the most commonly used method, the *K* index method, irregular variations are defined as the range (difference) between the upper and lower fitting quiet daily curves during each three-hour interval, which is associated with an integer (0–9), the local *K* index (Bartels et al., 1939; Mayaud,

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1980; Menvielle and Berthelier, 1991). The K scale is quasi-logarithmic and determined by the minimum range for the K value of 9. K indices are linearized to equivalent amplitudes, the local *ak* indices.

A serious practical problem of all K indices is that the early measurements are not in digital format at sufficiently high sampling rate. Thus, examining the correctness and homogeneity of K/ak values is difficult. This is particularly important as recent analyses suggest that the calibration of the *aa* index was changed by roughly 2 nT in the 1950s (Jarvis, 2005; Lockwood et al., submitted for publication; Mursula and Martini, submitted for publication). Accordingly, the long-term consistency of *aa* is questionable and the index must be revised. Clearly other, more straightforward and verifiable measures of geomagnetic activity are needed for centennial studies.

Data availability problem is corrected by the IHV (Inter-Hour Variability) index (Svalgaard et al., 2003, 2004), a recent alternative measure of geomagnetic activity. IHV is calculated from absolute differences between successive hourly values of the H component during seven night hours with the aim to minimize the effect of the daily curve. Using hourly digital values available at the World Data Centers (WDC), IHV can be examined in detail (Mursula et al., 2004; Mursula and Martini, 2006,). IHV is a measure of hourly variability, while the K index is a three-hourly range measure. Also, IHV is a daily index including only night-time activity, while the eight three-hourly K indices cover both day and night. This makes a difference since geomagnetic activity has a strong diurnal variation. Thus, IHV and K indices measure considerably different processes of the near-Earth space.

As noted recently (Mursula and Martini, submitted for publication), the K indices have also some other problems for long-term studies. K index is based on the observer's personal evaluation and, with changing observers, the long-term consistency of K values is hard to guarantee. The K method to "digitize" ranges to 10 quasi-logarithmic values is problematic, forcing the observer to select, often arbitrarily, between two neighboring K values. This is particularly difficult for the low K levels where the exact form of the S_q curve is important. Because of the great number of low K values, the selection has a large effect in the long term.

In order to avoid these problems, the K method was recently modified by Mursula and Martini (submitted for publication) by introducing a new index, called A_h (A for amplitude, cf. the equivalent amplitude *ak*; h for hourly data) which is based on continuous range values ("amplitudes") instead of digitized K values. The fixed $K = 9$ limit is also problematic for long-term studies since, during increasing activity, such a limit may underweight the highest disturbance levels, leading to an erroneously small trend. This problem can also be avoided by the A_h index which uses continuous range values with no artificial limits.

Here we compare the correlation of the local "digital" A_h and IHV indices with the local "analogue" *ak* index of the Sodankylä station in 1914–2000. Sodankylä is one of the stations for which the ak/K indices have been calculated since the start of continuous observations in 1914. Note also that the hourly registrations at Sodankylä are hourly means already since the start of observations in 1914, not hourly samples (spot values) like in many other stations at that time. Accordingly, we can neglect the problem due to changing sampling which affects both A_h indices (Mursula and Martini, submitted for publication) and IHV (Mursula and Martini, 2006).

2. The three sets of indices

The three-hourly K indices are the fundamental parameters that have been determined from the analogue registrations at the Sodankylä station since 1914. The K indices can be transformed to the local three-hourly *ak* indices using the agreed quasi-logarithmic table between the two sets of indices. Since the K scale is quasi-logarithmic it is more correct to use the quasi-linear *ak* indices in comparisons with the linear A_h index and the quasi-linear IHV index.

The derivation of the IHV index has been discussed in number of papers (Svalgaard et al., 2003, 2004; Mursula et al., 2004; Mursula and Martini, 2006). Here we use, for definiteness, the "raw" IHV values without any correction to the long-term change of the nightside daily curve (see Mursula et al., 2004; Mursula and Martini, 2006). We use here the original definition of the 19–01 local time (LT) sector when calculating the daily IHV indices. However, any other selection for the local nightside time sector would lead to only minor changes.

Since the definition of the A_h index is quite recent (Mursula and Martini, submitted for publication), we repeat it briefly here. First, in order to derive the A_h index we must calculate the quiet daily, or S_q variation. We use local IHV indices to find the five quietest days in each month at each observatory. Using local rather than global quiet days gives a better account of local conditions. Also, the official global quiet days exist only since 1932. The S_q curve is defined as the average daily curve of the H component in the five quietest days of each month. This takes into account the seasonal variation of the quiet daily curve even more accurately than the seasonal model curves typically used by observers. Also, the quiet daily variation is no longer subjective and can be easily reproduced and examined. As in the K method, the quiet daily curve is then fit to the data in each three-hour interval as an upper and lower limiting envelope curve. The difference (range) between the two envelope curves is the A_h index of the respective three-hourly interval. No digitization of the range value is made, contrary to the K method. Accordingly, the continuous range (or amplitude) is the fundamental, linear parameter, and the A_h index solves the above mentioned problems of the K method in long-term studies.

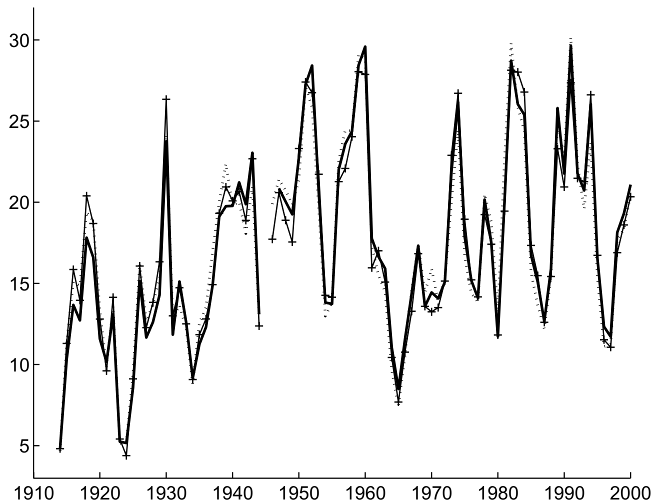

Fig. 1. The annual averages of the *ak* indices (black thick line), the A_h indices (dotted line) and the IHV indices (solid line with pluses) at the Sodankylä station in 1914–2000.

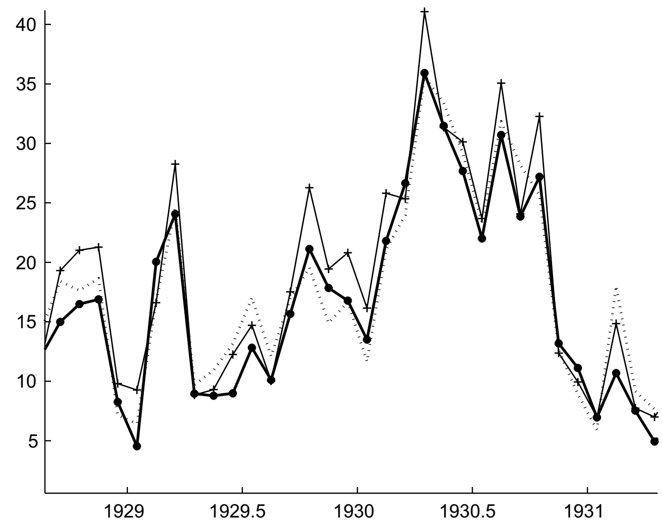

Fig. 2. The monthly averages of the *ak* indices (black thick line with small dots), the A_h indices (dotted line) and the IHV indices (solid line with pluses) at the Sodankylä station in 1929–1930.

3. Yearly averages

Fig. 1 depicts the yearly averages of the "analogue" *ak* indices, and the "digital" A_h and IHV indices calculated from the hourly values of the H component at Sodankylä station in 1914–2000. For Fig. 1 the yearly A_h and IHV indices were first fitted linearly to the *ak* indices. The best fits are $ak = 0.445{*}A_h - 1.35$; and $ak = 0.526{*}\mathrm{IHV} - 1.56$. Note that at this time resolution the A_h and IHV indices correlate with the *ak* index roughly equally well, with a correlation coefficient of $\mathrm{cc} = 0.98$.

The three indices depicted in Fig. 1 follow each other fairly closely over the whole time interval, depicting an excellent correlation between these three indices at the yearly resolution. The average standard deviations between (the fitted values of) the two novel indices and *ak* are roughly the same, only about 1.1 nT, i.e., some 6% of the average *ak* level of 17 nT. Note also that all the three indices reproduce qualitatively the same centennial behavior demonstrated by all indices of geomagnetic activity: beyond the solar cycle variation, there is a changing background with a fairly systematic increase from the beginning of the century until about 1960, then a dramatic dropout and a slower increase thereafter. The three indices follow each other in Fig. 1 so well that their differences can hardly be seen in the figure. Only occasional yearly values of the IHV index rise above (as, e.g., in 1916, 1918–1920), or below (e.g., in 1924, 1944) the two other indices. Even the A_h index rises in some years (e.g., in 1939, 1970) slightly above the other two indices.

4. Monthly averages

Fig. 2 depicts the monthly averages of the three indices for a section of data in 1929–1930. Again, the monthly averages of A_h and IHV indices have first been fitted to the monthly *ak* indices. The best fits between the monthly values are $ak = 0.422{*}A_h - 0.418$, and $ak = 0.480{*}\mathrm{IHV} + 0.080$. The overall fit is almost equally good, only slightly better for A_h ($\mathrm{cc} = 0.95$) than IHV ($\mathrm{cc} = 0.94$).

However, the standard deviation between (the fitted values of) the new indices and *ak* has increased considerably to about 2.5 nT for A_h and 2.7 nT for IHV, i.e., about 14–16% of the average *ak* level. The larger scatter is seen also in Fig. 2 where differences of about 5 nT are seen in several months between, especially, IHV and the *ak* index. This figure shows that the IHV indices tend to deviate more from the *ak* indices than the A_h indices already at the monthly resolution.

5. Daily averages

Fig. 3 depicts the daily averages of *ak*, A_h and IHV at the turn of 1929–1930 (a part of the time interval depicted in Fig. 2). The best fits between the daily values are $ak = 0.4257{*}A_h - 0.5417$, and $ak = 0.3476{*}\mathrm{IHV} + 4.792$. Fig. 3 shows much larger variability in all indices at this time resolution, reflecting the various disturbances in the Earth's magnetosphere (e.g., storms, substorms, etc.) whose duration is typically in the time scale from several hours to several days. While the monthly averages at the time of Fig. 3 (see Fig. 2) varied only between about 15 and 20 nT, the daily values range from 0 to 75 nT.

Similarly, the differences between the three indices are much larger than between the monthly (or yearly) averages. Fig. 3 depicts daily differences up to several tens of nT, especially between *ak* and IHV. However, although the variability and differences have increased considerably, the three indices follow each other overall rather well. This suggests that all these three different indices do seize the

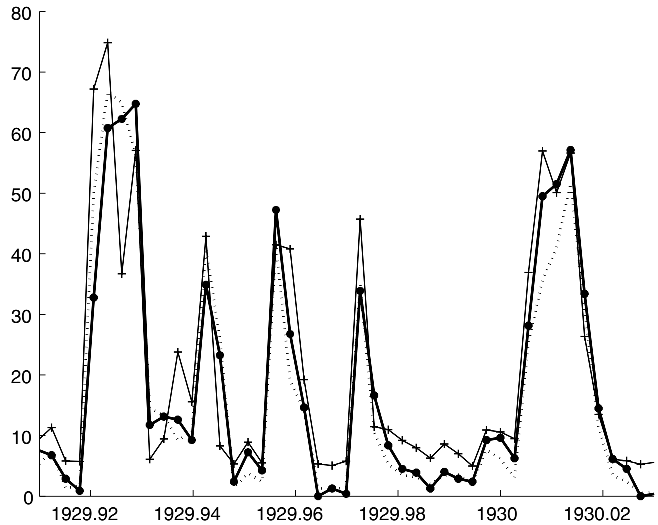

Fig. 3. The daily averages of the *ak* indices (black thick line with small dots), the A_h indices (dotted line) and the IHV indices (solid line with pluses) at the Sodankylä station around the turn of 1929–1930.

most essential features of near-Earth variability and, therefore, can be used as proxies of this variability, i.e., as indices of geomagnetic activity.

Still, in a detailed analysis one can find considerable differences between the studied indices at the daily resolution. First note that the correlation between the daily values of *ak* and A_h (cc = 0.94) is considerably better than between *ak* and IHV (cc = 0.80). Thus, the correlation between *ak* and A_h is almost equally good at the daily resolution as at the monthly resolution, while it is significantly lower at daily resolution between *ak* and IHV. Also, the average standard deviation (over the whole time interval 1914–2000) between *ak* and (the fitted) A_h is only 6.9 nT but as large as 11.9 nT for IHV. This quantifies the larger differences between *ak* and IHV also depicted in Fig. 3.

We have depicted in Figs. 4 and 5 the correlation between *ak* and A_h on one hand (upper panels) and *ak* and IHV on the other (lower panels). One can see that *ak* and A_h correlate extremely well both over the whole dynamic scale (0–370 nT; Fig. 4) as well as in the lower end of the index values (0–25 nT; Fig. 5). Note also that the intercept of the best fit correlation between *ak* and A_h is roughly zero (−0.5417).

On the other hand, correlation between *ak* and IHV, while depicting a fairly good correlation over the whole dynamic scale (0–400 nT; Fig. 4), includes much more scatter in Fig. 5. Note also that the intercept of the best fit correlation between *ak* and IHV is clearly non-zero (4.792). Moreover, there is clear indication in Fig. 5 that the relation between *ak* an IHV is nonlinear at the low end of index values.

6. Three-hourly averages

The *ak* and A_h indices are three-hourly indices. Thus, the full set makes eight times the number of days (and the number of IHV indices), altogether 243,374 data points (missing data excluded). Still, the correlation between all three-hourly *ak* and A_h indices is amazingly good (cc = 0.873). The best fit between the three-hourly values is $ak = 0.3617{*}A_h + 2.178$. Thus, even though the three-hourly *ak* values are restricted to only 10 different integer numbers (corresponding to the 10 different *K* values), the correlation between this considerably larger number of

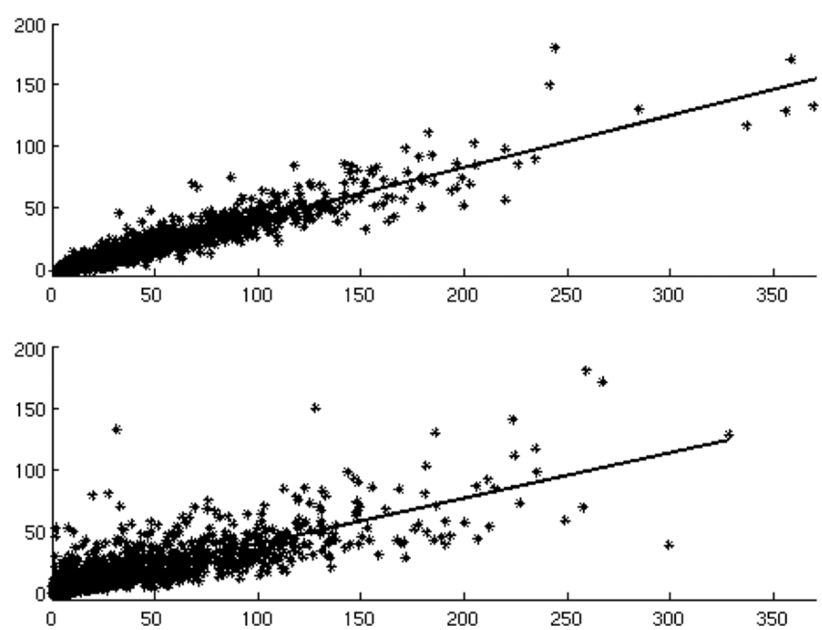

Fig. 4. Scatterplot of daily averages of *ak* and A_h (upper panel) and *ak* and IHV (lower panel). Only every 20th point is included in the plot. Best fitting lines (using all data points) are included.

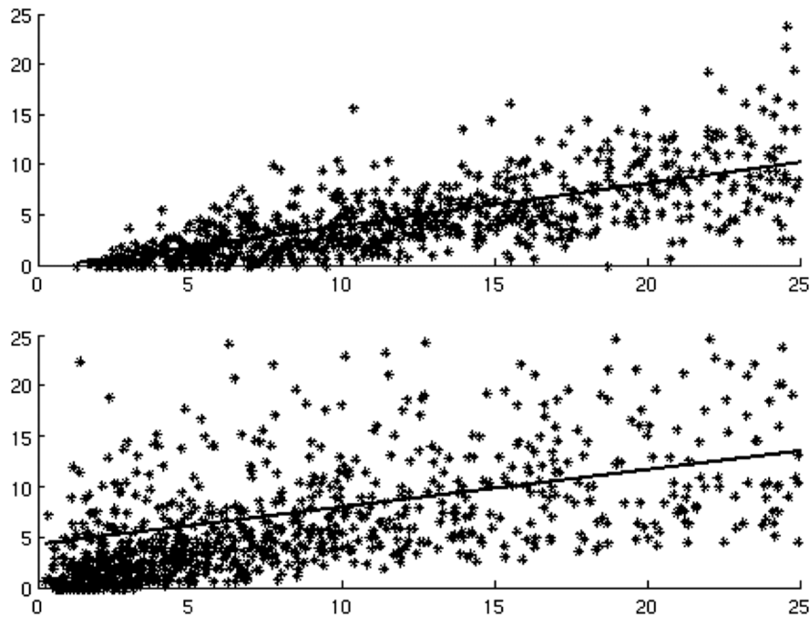

Fig. 5. The low value end of the scatterplot of daily averages of *ak* and A_h (upper panel) and *ak* and IHV (lower panel). Only every 20th point is included in the plot. Best fitting lines (using all data points) are included.

data points is better than the correlation between the daily values of *ak* and IHV.

We have also calculated the correlation between the eight pairs of simultaneous three-hourly *ak* and A_h values separately. The correlation is very good in each UT (or LT; SOD LT = UT + 2.5 h) sector separately, with correlation coefficients varying from 0.81 to 0.89. The smallest correlation was found in the third sector (UT = 6–9), i.e., in the pre-noon LT sector, the largest half a day later in the seventh UT sector (18–21 UT), i.e., in the pre-midnight sector. While the correlation was expected to be good (and highest) at the nightside, the high level of correlation at each LT sector is indeed amazing. Note that in each LT sector the correlation between *ak* and A_h is better than between the daily averages of *ak* and IHV (for the same number of data points).

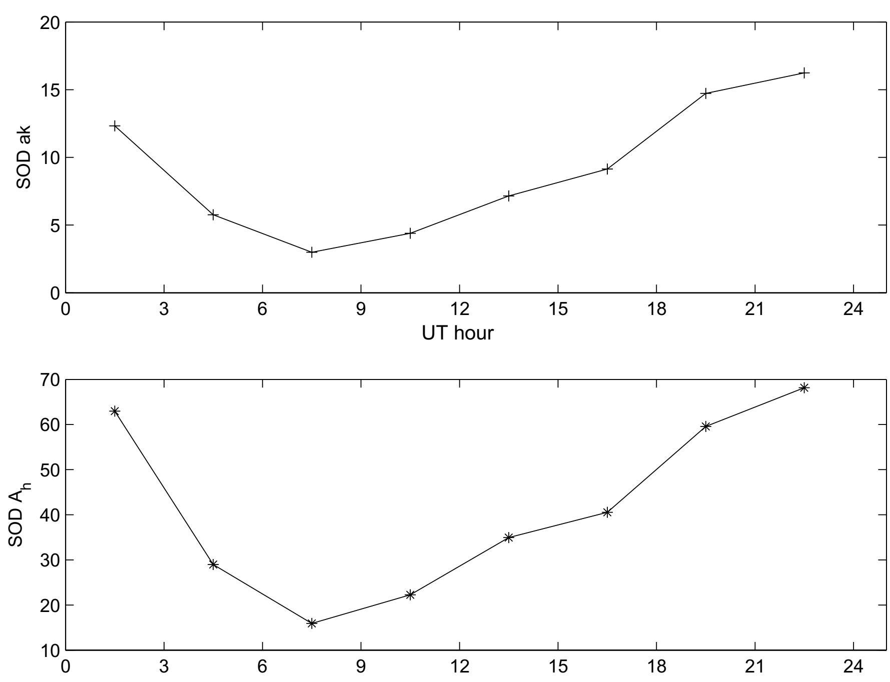

Fig. 6. The average values in 1914–2000 of (upper panel) SOD *ak* indices, and (lower panel) SOD A_h indices in the eight three-hourly UT sectors separately.

We have also calculated in Fig. 6 the average values of *ak* and A_h indices in 1914–2000 in the eight three-hourly UT sectors separately. Fig. 6 shows that geomagnetic activity has a strong diurnal variation with maximum in the night sector and minimum in the third (pre-noon) sector. The diurnal variation is very similar in the two indices, with the ratio between daily maximum and minimum being roughly 4 in each index. (Absolute scales are different because of different normalization.) The correlation coefficient between the curves is 0.981, implying a confidence level better than 99.99%. This extremely good correlation yields strong additional evidence for the detailed success of the A_h index to follow the properties of the *ak* index.

7. Discussion and conclusions

We have studied here two recently proposed indices of geomagnetic activity, the A_h index and the IHV index, that are based on digitally available hourly geomagnetic measurements. Using as a comparison the *ak* index of the Sodankylä station that is based on analogue registrations and exists since 1914, we studied the correlation between *ak* and A_h and between *ak* and IHV at different temporal scales.

Even at the highest temporal resolution, the three-hourly A_h indices were found to correlate extremely well with the *ak* indices, yielding a correlation coefficient of 0.873 between 243,374 data points. The correlation was excellent at all local times, with correlation coefficients varying from dayside minimum of 0.81 to nightside maximum of 0.89. Taking into account the large local time variation of geomagnetic activity with roughly four times larger activity in the nightside, this agreement is outstanding, and shows that the A_h indices can indeed describe the local daily variability of geomagnetic activity included in the *ak* index extremely reliably. Note that in each LT sector the correlation between *ak* and A_h is better than between *ak* and IHV on daily averages (with the same number of data points).

Using daily averages improves the correlation between *ak* and A_h even higher with $cc = 0.94$. This is a considerably higher correlation than between *ak* and IHV ($cc = 0.80$) at the same temporal resolution. Also, the average standard deviation (over the whole time interval 1914–2000) between daily averages of *ak* and (correlated) A_h is only 6.9 nT but as large as 11.9 nT for IHV. The lower correlation between *ak* and IHV is reflects the fact that the basic definition of IHV is greatly different from that of the *K* method, while A_h follows the basics of the *K* method, modifying them slightly. Thus, all *K* indices (including A_h) are three-hourly range indices, but the IHV is a measure of hourly variability. Also, the IHV index takes into account the variability at a fixed night sector only. Taking into account the greatly different dynamics in the different LT sectors and the changes in the LT distribution of activity from one day to another (which IHV does not include), the lower correlation between *ak* and IHV is understandable.

The strong diurnal variation of activity denies a detailed comparison between all *K* based indices (which include local activity from all LT sectors) and IHV (which includes night sector only). Since the local time distribution of geomagnetic activity varies from storm to storm (also from day to day), it is necessary for a geomagnetic activity index to cover activity at all local time sectors, and not to restrict to a fixed, limited LT sector only, even if that sector would include the dominant part of the daily activity on an average. It is quite possible that there are systematic changes in the solar wind and interplanetary magnetic field (e.g., a long-term change in the IMF winding angle) that lead to a systematic change in the LT distribution of activity. An index that is restricted to a limited and fixed local time sector, like the IHV index, is then on loose ground. This imposes a severe restriction for the use of IHV indices for long-term studies. On the other hand, indices based on the *K* method include the activity from all local time sectors and can better guarantee long-term homogeneity.

We have shown that at the monthly resolution and longer the IHV indices correlate with *ak* indices almost equally well as A_h with *ak*. This is no wonder since, as noted above (see also Fig. 6), the night sector includes most of daily activity, on an average. However, taken into account the variability in the LT distribution of activity, the success of correlation between *ak* and IHV at longer time scales can not be considered very reliable. Accordingly, it is advisable to use, even at the yearly resolution, the A_h index instead of the IHV index when extending the local (and related combined global) ak/K indices indices to earlier times.

We also note that the slopes of the best fit relations between *ak* and A_h are nearly the same at all studied temporal resolutions (yearly, monthly, daily, three-hourly), reflecting a highly linear relation between these two variables. However, interestingly, the slopes between *ak* and IHV get consistently and significantly smaller (from 0.526 for yearly averages to 0.3476 for daily averages) with shorter sampling times (higher temporal resolution). This shows that the relation between *ak* and IHV is fundamentally nonlinear, further demonstrating the greatly different character of the IHV index. The nonlinear relation between the lower end of *ak* an IHV values is also seen in Fig. 5. These facts give further evidence for the above suggestion that A_h rather than IHV should be used as a long-term proxy or extension of local and global ak/K indices.

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