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Long-term changes in indices of geomagnetic activity at the auroral station Sodankylä

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Abstract

Here we compare the traditional analog measure of geomagnetic activity, Ak, with the more recent digital indices of IHV and Ah based on hourly mean data, and their derivatives at the auroral station Sodankylä. By this selection of indices we study the effects of (i) analog vs. digital technique, and (ii) full local-time vs. local night-time coverage on quantifying local geomagnetic activity. We find that all other indices are stronger than Ak during the low-activity cycles 15–16 suggesting an excess of very low scalings in Ak at this time. The full-day indices consistently depict stronger correlation with the interplanetary magnetic field strength, while the night-time indices have higher correlation with solar wind speed. The Ak index correlates better with the digital indices of full-day coverage than with any night-time index. However, Ak depicts somewhat higher activity levels than the digital full-day indices in the declining phase of the solar cycle, indicating that, due to their different sampling rates, the latter indices are less sensitive to high-frequency variations driven by the Alfvén waves in high-speed streams. On the other hand, the night-time indices have an even stronger response to solar wind speed than Ak. The results strongly indicate that at auroral latitudes, geomagnetic indices with different local time coverage reflect different current systems, which, by an appropriate choice of indices, allows studying the century-scale dynamics of these currents separately.

Keywords: Geomagnetic activity; Geomagnetic indices; Long-term change; Solar wind parameters; Solar activity

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1. Introduction

Geomagnetic activity is one of the most important parameters to study the variation of solar activity and its effect on the near-Earth space at different time scales. The ground-based observations of geomagnetic disturbances of external (solar-related) origin carry important information about the solar UV/EUV radiation, the solar wind and the interplanetary magnetic field (IMF), as well as about the dynamics of ionospheric and magnetospheric current systems. By definition only those disturbances of the geomagnetic field that are driven by the solar wind and the IMF are classified as geomagnetic activity, as opposed to the smoothly varying regular field associated with quiet magnetic conditions.

Geomagnetic activity is usually quantified by index numbers that characterize the local and/or global magnetic field variations. The key process in quantifying geomagnetic activity is to separate the irregular variations that are superposed on the regular daily S_R variations. The average daily curve, solar quiet (Sq), is deduced from S_R and represents the most likely S_R variation (for more details see, e.g., Menvielle and Berthelier, 1991; Nevanlinna, 2004). One must note, however, that the Sq curve (even more S_R) is fundamentally unknown and even temporally (e.g., seasonally) variable, thus its exact quantification is problematic. Over the years a number of geomagnetic indices have been implemented, differing from each other in their way of separating the imprints of regular and irregular effects in the magnetic records.

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1.1. Geomagnetic indices used

Probably the most common measure of geomagnetic activity in long-term studies is the *K* index (or more generally speaking the *K*-based indices). The *K* index was introduced by Bartels et al. (1939); see also Bartels (1957), Mayaud (1980) in order to measure the range of irregular field variations during each three-hour interval. The S_R variation is represented by an analog model curve reflecting the undisturbed daily variation for the given station. The observed daily variation is then matched manually to this ideal S_R curve during each three-hour period of the day. The difference between the ideal and true daily curve is classified as *K* variation and associated with an integer number between 0 and 9, according to a pre-determined, quasi-logarithmic scale. The quasi-logarithmic *K* index can be converted to a linear scale, which is called *ak*. The average of the eight three-hourly *ak* values is the daily *Ak* index (Bartels, 1951; Mayaud, 1980).

The *Ak* index is calculated locally (i.e., based on the magnetic data of a particular station), but after certain averaging procedures the local *Ak* indices may form global measures of the geomagnetic disturbance level. The longest such global measure is the *aa* index (Mayaud, 1973) that is derived from observations of two antipodal stations since the late 1800s. Lockwood et al. (1999) used the annual *aa* index to show that the strength of the solar open magnetic field has more than doubled during the last century, which is one of the most important results of space climate science.

However, the verification of the *aa* method (especially quantifying the possible effect of observatory and observer changes on the long-term drift of the index) is highly problematic, because most of the last century data is not available in digital format in sufficiently high sampling frequency. For several decades only hourly mean magnetic data is available; even more, most stations registered magnetic variations only once per each hour in the earliest years of the last century. To have an independent estimate of the field variation in these early years, a number of recent attempts have been made to implement new, so-called digital indices for long-term studies. These indices are based on digitized hourly values of the magnetic H component that is readily available for most stations for a good part of the last century in the World Data Center. Here we discuss two of these indices in more detail, the Inter-Hourly Variability (*IHV*) index (Svalgaard et al., 2004; Svalgaard and Cliver, 2007), and the *Ah* index (Mursula and Martini, 2007a).

The two measures use fundamentally different approaches in quantifying the irregular field variations. The *Ah* index follows as closely as possible the derivation principles of the analog *Ak* index. First the Sq curve is estimated in each month, based on the five quietest days, and this curve is used thereafter in each three hour period of a day to quantify the range deviation of the actual measurement from the estimated quiet variation (note that for annual activity indices based on hourly raw data, which is used in our study, it introduces negligible differences if the index is derived from S_R or Sq). The *IHV* method, on the other hand, uses a unique approach; it assumes that the regular effect is absent (or at least negligible) during the local night hours. Therefore it simply defines the daily activity level as the averaged hour to hour variability of seven hours around local midnight.

It is often tacitly assumed that these different geomagnetic activity indices, despite their basic and methodological differences, respond uniformly to the near-Earth space currents and solar wind drivers, and, therefore, were used interchangeably. For example, digital measures derived from auroral data were extensively used in comparisons with analog global measures: significant and strong correlations were found (Clilverd et al., 2005) between the traditional *aa* index and the more recent *IHV* index at high-latitude on annual scales. Based on these correlations, attempts have been made to correct a calibration error of about 2 nT found in the global *aa* index, which affected its long-term trend (Lockwood et al., submitted for publication). Furthermore the correlations were used to extend the *Ap* index back in time using *IHV* or *Ah* (Mursula and Martini, 2006, 2007a).

1.2. Science objectives and methodology

More recently, however, it was found that the annual averages of traditional range indices based on analog (i.e., high sampling) observations (*K*/*Ak*) and the more recent indices based on hourly means seem to respond differently to solar wind conditions. Using dominantly subauroral station data, Lockwood et al. (submitted for publication) finds that while the long-term changes in solar wind speed are reflected in the drift of the range indices, this is true only to an almost negligible extent in those digital indices studied. Therefore, the interchangeable use of these indices in long-term studies is not at all straightforward, and the verification of *K*-type indices with the recent digital measures still remains problematic. Furthermore, when analyzing higher than annual sampling (up to daily averages) auroral data, Mursula and Martini, 2007b found a very strong correlation between the digital *Ah* and the analog *Ak* indices, while a significantly weaker and non-linear dependence was found between *IHV* and *Ak*. This discrepancy between the two digital measures indicates that even other characteristics in addition to the digital/analog sampling nature of the index alone have a crucial effect on long-term estimates.

Therefore, in this paper we use the analog *Ak* index and apply the digital *IHV* and *Ah* algorithms to data from the auroral Sodankylä Geophysical Observatory, Finland (SOD, 67°22′ GGlat, 26°38′ GGlong, 63.9° CGMlat) to study up to what level these indices reflect the same magnetic phenomena at this auroral region, especially as concerns their century-scale evolution. We aim to clarify to what extend the observed deviations between the analog and hourly mean indices are the result of the different sampling or the different local time (LT) coverage. Also, we quantify the methodological effects on the solar wind coupling of the annual activity indices to see whether they are similarly significant at the auroral zone as it was reported (Lockwood et al., submitted for publication) from low and mid-latitude stations. Such systematic approach should unveil the effects of the different derivation methods described on the long-term estimates that is very little known about, let alone quantified.

We emphasize that our primary interest is what global and/or local effects induced upon the various local magnetic indices result in systematic relative differences on the long-term; therefore our study is strictly speaking a local study in its nature, even though some of its implications are valid more widely. We have three reasons to conduct our study using SOD data; First of all, SOD data was extensively used in the past (see examples above) for long-term comparisons among the different indices. Secondly, the station has good quality, relatively long and homogeneous *Ak* series. The *Ak* indices as well as the original observations are available at SOD station from 1914 except for a short data gap after World War II. *Ak* is used here as a reference measure of geomagnetic activity to which all other indices are compared. Thirdly, to our knowledge, SOD station is the only station, which, uninterruptedly since 1965, still calculates another traditional index: the *Q*/*Aq*. This index will prove to be an interesting addition in understanding the role of LT selection.

In order to study the effect of the LT restriction on long-term estimates, we have derived two other sets of indices based on hourly means of the SOD H-component, to be called *IHV*24 and *Ah*-night. *IHV*24 uses a similar inter-hour variability recipe as *IHV* but includes all 24 h of the day (as opposed to seven night hours used by *IHV*). The 23 inter-hour deviations are averaged to form the daily index value, hence the chosen notation of *IHV24*. Note that approximating the irregular activity by a simple daily variability is possible only because: (i) in this auroral region the amplitude of irregular activity is significantly more dominant than that of the solar regular change, and (ii) for most of our purposes annual averages provide sufficient resolution. Yet, the index should not serve as substitute for such well-founded measures as the *IHV* or *Ah* indices without careful consideration. In another approach, we have calculated an LT sector-limited *Ah* index, *Ah*-night, which includes only the two 3-h *Ah* values from 18-20 UT and 21-23 UT (20-22 LT and 23-01 LT at SOD), in order to determine if any difference between *IHV* and the other indices is the result of its different LT coverage or the fact that, unlike *Ak* and *Ah*, *IHV* quantifies activity on slightly different timescale (hourly instead of 3-h). The one hour difference in LT coverage between the *IHV* (20-02 LT), and *Ah*-night (20-01 LT) indices does not introduce observable difference in the statistical properties of the indices. With this selection of indices we aim to separate and study the effects of: (i) analog vs. digital technique, and (ii) full-LT (*Ah*, *IHV*24) vs. night-LT coverage (*Ah*-night, *IHV*) on quantifying geomagnetic activity.

Let us emphasize here again that *Ah*-night and *IHV*24 are formed for the sole purpose of the following relative drift study; they are not to be automatically used as separate indices on their own right.

2. Comparison with the local *Ak* index

2.1. Residuals of the best linear fit

Lockwood et al. (submitted for publication) suggests that the difference between the inter-hour and range indices (with full-LT coverage) may arise from the different timescales of the various physical changes. Many hours of sustained high-frequency variability resulting from the interaction with fast solar wind streams would be averaged out by indices based on hourly mean values. This assumption can be verified easily by studying the long-term pattern of the relative discrepancies of the digital indices. To study such relative changes, we first look at the fit residuals. We call *Ak*(*Ah*) the *Ak* index obtained from *Ah*, using the best fit linear regression between annual *Ak* and *Ah* from 1914 to 2000 (similarly for the other indices; *Ak*(*IHV*), *Ak*(*IHV*24), and *Ak*(*Ah*-night)). Fig. 1 depicts the evolution of the residuals to the fits, i.e., the differences of *Ak*–*Ak*(*Ah*), *Ak*–*Ak*(*IHV*24), *Ak*–*Ak*(*IHV*), *Ak*–*Ak*(*Ah*-night). The zero base level is obtained when the best fitting value of the compared index is equal to *Ak*; negative (positive) value is found if the index value is larger (smaller, respectively) than *Ak*. For comparison, the annual sunspot numbers are also depicted in Fig. 1 for the same period.

These residuals are on the order of about 10% of the typical index value. Note that, while a few nT discrepancy

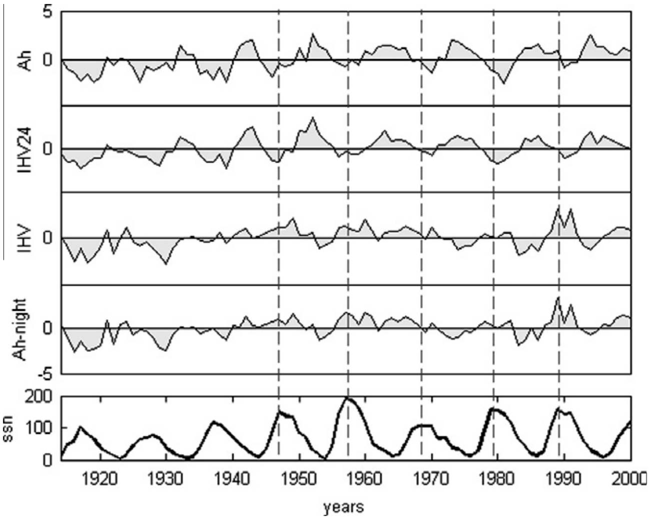

Fig. 1. Residuals in nT of the best linear regression fits to *Ak* of the four indices, *Ah*, *IHV*24, *IHV*, and *Ah*-night, in 1914–2000. The same scales are used for all four indices. For comparison, the annual sunspot numbers are also included for the same period in the bottom panel. The approximate solar maxima are marked by vertical dashed lines after 1940.

might seem rather small, it is actually of the same order of magnitude as the registered total long-term increase in the average level of global geomagnetic activity over the last century. Also, the earlier reported upward shift of the *aa* index due to instrumental changes, which seriously questioned the long-term robustness and thereby the reliability of the index, was found to be about 2 nT (Jarvis, 2005). This amplitude is just on par with changes being discussed here.

The most distinctive pattern is a moderate but systematic variation of fit residuals over the course of a solar cycle. Since the 1930s *Ak* depicts consistently relatively larger values during the declining phases of solar cycle than the other full-LT indices (*Ah* and *IHV*24), and relatively lower values around solar cycle maxima. This indicates that the indices based on hourly mean data (*Ah* and *IHV*24) are indeed somewhat less sensitive than the analog *Ak* index to high-frequency fluctuations, which typically occur during the declining phase of the solar cycle as a result of frequent magnetic reconnections driven by the Alfvén waves in high-speed solar wind streams (HSS).

The fit residuals of the night-LT indices (*IHV*, *Ah*-night) show, in a large part of the data set, an opposite behavior over the solar cycle compared to the full-LT indices. Accordingly, HSS-driven fluctuations during the declining phase have an even more dominant effect on these indices than on *Ak*. This is despite the fact that, since the indices are based on hourly mean values, one would expect less sensitivity to high-frequency variations. It is therefore clear that the night-LT restriction overcompensates for the smoothing effect of hourly means.

Fig. 1 also shows that, while the residuals seem to oscillate around the zero level in the later decades, in the beginning of the time series until about 1940 all indices are relatively larger than *Ak*. Therefore all digital indices depict a noticeable drift with respect to *Ak*. We suggest this to be related to the large number of quiet days in those early years, where the original, manually scaled *K* values are set to zero, while the digital indices are likely to yield a value larger than zero. However, this alone does not explain why the residuals of the full-day and night-time indices, which show anti-correlation in later decades, are in phase during the earlier period. This may either be due to an unknown data error in *Ak*, or a physical difference in the solar wind between these epochs. We note that the very possibility of this kind of comparisons demonstrates the viability of hourly digital indices in studying and understanding early analog indices.

2.2. Partial correlations

To quantify the qualitative patterns of the fit residuals, we calculate the linear correlation factors between them at zero lag, shown in Table 1. Due to the different behavior in the early decades of last century we have used the results only after 1940. These coefficients give the level of correlation between the different indices after the effect of the *Ak*-type variation is removed. All but one of the correlations is significant above the 2σ level. The correlation coefficients between indices of the same LT coverage are strongly positive. On the other hand, somewhat weaker but significant (except between the residuals of *Ah* and *Ah*-night, where the significance falls just below the 2σ level) anti-correlations are found consistently between the indices with different LT coverage. This means that, when the most dominant *Ak*-type variation is eliminated from the indices, the remaining activity registered is strongly local-time dependent.

Table 1
Correlation coefficients between the residuals of best linear fits depicted in Fig. 1 (partial correlation coefficients with respect to *Ak*) at SOD for 1940–2000 inclusive. Coefficients of same type of indices (i.e., full-LT vs. full-LT or night-LT vs. night-LT) are marked with bold scripts. Since the matrix is symmetric, values are depicted only once. Unmarked coefficients are significant with above 2σ; coefficient marked with star is just below the 2σ level ($p = 0.096$).

	*IHV*24	*IHV*	*Ah*-night
Ah	**0.86**	−0.32	−0.22*
*IHV*24		−0.36	−0.30
IHV			**0.93**

Finally, we note that the above conclusions hold even if one uses, instead of annual averages, some higher sampling data up to daily averages (these results are not shown here).

2.3. Correlating the digital indices with Ak

Table 2 shows the correlation coefficients (r) at zero lag between the annual and daily averages of *Ak* and the four other activity indices; *Ah*, *IHV*24, *IHV*, and *Ah*-night. Regarding annual averages, all four indices correlate roughly equally well with *Ak*, with a high coefficient of about $r = 0.98$. However, while the correlation between *Ak* and the two other indices with full-LT coverage (*Ah* and *IHV*24) decreases only moderately for daily averages, the correlation becomes significantly weaker for the night-LT indices (*IHV* and *Ah*-night).

To further study how the association between the indices is affected by the timescale used, Fig. 2 depicts the correlation coefficients at zero lag between *Ak* and the indices as the function of the averaging timescale. The averaging length runs from one day to 365 days with one-day steps, and at each step the correlation is defined between *Ak* and the given index. There is a clear difference between the full-LT indices and the night-LT indices; while the

Table 2
Correlation coefficients between annual/daily averages of the SOD *Ak* index and the *Ah*, *IHV*24, *IHV*, and *Ah*-night indices for 1914–2000 inclusive, and *Aq* in 1957–2000. All coefficients are statistically significant with confidence level better than 99.9%.

	Ah	*IHV24*	*IHV*	*Ah*-night	*Aq*
Annual means	0.98	0.98	0.98	0.98	0.97
Daily means	0.936	0.956	0.774	0.768	0.619

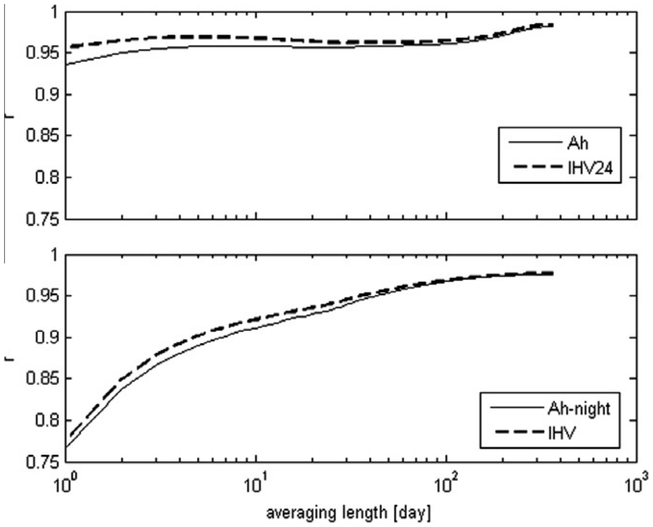

Fig. 2. Correlation coefficients between *Ak* and full-LT indices (upper panel), and night-LT indices (bottom panel), as a function of averaging length. The significances remain within 2σ for all indices over all timescales. Because of the rapid change at averaging intervals shorter than about a week, the time scale is plotted logarithmically.

full-LT indices show only minor change in their association with *Ak* over the timescales studied, the night-LT indices undergo significant change.

Fig. 2 shows that, based only on correlation studies, both digital full-LT indices (*Ah* and *IHV*24) could reliably be used as surrogates of *Ak* practically at all timescales longer than one day. On the other hand, night-LT indices (*IHV* and *Ah*-night) exhibit similar correlations with *Ak* as the full-LT indices for averaging scales longer than about 50 days (roughly two solar rotations). The degrading correlation of night-LT indices towards shorter time scales implies that the short-term evolution of the night-LT sector is much different from that of the full-LT averaged activity. That is, the night-LT indices, unlike the full-LT indices, do not simply measure the same magnetic phenomena with only a somewhat damped response due to their different sampling, but they are dominantly linked to different processes (current systems) of the magnetosphere. This is despite the fact that the amplitude of the annual fit residuals for both types of digital measures are roughly of the same order. For long averaging scales the indices lose the details of their short-term evolution and therefore the improvement of correlation is expected. We also note that, since both night-LT indices, *Ah*-night and *IHV*, exhibit nearly identical correlation patterns with *Ak*, the non-linear dependence and relatively weak correlation of daily *IHV* with *Ak* and *Ah* (Mursula and Martini, 2007b is solely due to the different LT coverage and not the different interval (i.e., hourly vs. 3-h), which *IHV* uses to define irregular activity.

2.4. Secular change of magnetic latitude at Sodankylä

In this study, there is concern that the relative differences discussed previously might be caused by a secular change of the magnetic field at Sodankylä. Table 3 shows the change of the corrected geomagnetic latitude (CGML) for the period of 1915–2000. The CGM coordinates were calculated using the IGRF/DGRF models using the http://www.omniweb.gsfc.nasa.gov/vitmo/cgm_vitmo.html web site. The total change in CGML over the interval studied in our paper is only about 1° in geomagnetic latitude. Furthermore, the change is not uniform: there is a steady increase until late 1950s, then decrease until the late 1970s (when the relative geomagnetic location becomes roughly the same as in the early 1940s), which is then followed by a continuous increase. Clearly, such a pattern cannot be observed in the relative strengths of the indices which systematically depict solar cycle dependence of roughly the same amplitude (see Figs. 1 and 7). Therefore we conclude that there is no evidence supporting the assumption that the relative change of Sodankylä's geomagnetic latitude could be responsible for the systematic discrepancies of the indices over the last century.

Table 3
Sodankylä's corrected geomagnetic (CGM) latitudes in degrees during the studied period of 1915–2000 in five years steps.

Year	CGM latitude
1915	62.50
1920	62.65
1925	62.79
1930	62.92
1935	63.02
1940	63.10
1945	63.17
1950	63.21
1955	63.23
1960	63.22
1965	63.20
1970	63.16
1975	63.13
1980	63.18
1985	63.28
1990	63.36
1995	63.43
2000	63.54

3. Coupling to interplanetary parameters

3.1. Correlating annual averages

Various coupling functions to solar wind parameters (solar wind speed, *V*, and IMF strength, $|B|$ or $|B_S|$) have been derived to estimate the energy transfer from the solar wind into the Earth's magnetosphere and ionosphere (Akasofu, 1981; Holzer and Slavin, 1982; Bargatze et al., 1985). One of the most efficient coupling functions on annual scale is the $|B|V^p$ (Finch and Lockwood, 2007), where p is often taken to be constant with $p = 2$. Also, this particular coupling function was used by Finch et al. (2008) and Lockwood et al. (submitted for publication) and we will take it into account here. Therefore, we concentrate also on the couplings of the various geomagnetic indices derived at SOD to $|B|V^p$. Let us note, however that one would get very similar results using $|B_S|$ (rectified magnetic field) instead.

Fig. 3 shows the linear correlation coefficients at zero lag between the five indices and the coupling function $|B|V^p$ for the different values of exponent $p(-1 < p < 3)$. The maximum value of correlation of $r = 0.94$ is about the same for all indices. However, the two digital full-LT indices (*Ah* and *IHV*24) correlate best at a lower value of p of about $p = 1.4$ than all other indices, indicating that they are relatively more dependent on IMF strength. The analog *Ak* index has its maximum correlation at $p = 1.9$.

Results of Fig. 3(a) are directly comparable with Fig. 6(a) of Lockwood et al. (submitted for publication) where they find that the studied mid-latitude hourly indices with full-LT coverage have a much weaker dependence on solar wind speed V with $p = 0.3$ than the analog *aa* index for which they find $p = 2$. While the results for the analog indices, *aa* and *Ak*, agree very well with each other, the value $p = 0.3$ is clearly much lower than the one found here at auroral latitude for the *IHV* and *Ah* indices of hourly data.

3.2. Dependence on the coupling function exponent

In order to understand this difference better Fig. 4 depicts the annual *Ah* time series together with V, $|B|$, and the coupling function $|B|V^p$, with $p = 1.4$ (maximum correlation with *Ah*) and $p = 2$ (maximum correlation of *aa*) in 1965–2000. The effect of the high-speed solar wind streams is most prominent in the years around 1974 and 1994. In these two years strong recurrent activity is observed as solid peaks in V, while such enhancement is absent (or much smaller) in $|B|$. $p = 0.3$ means that, as studied by Lockwood et al. (submitted for publication), sub-auroral full-LT indices based on hourly means practically fail to observe the enhanced recurrent activity and during the two periods of descending solar activity discussed here, they follow very closely $|B|$ instead of V (see Fig. 7 in Lockwood et al., submitted for publication). At auroral latitudes the situation is clearly different and even the full-LT indices of hourly mean data are very much able to detect recurrent activity. Although the best correlation occurs with $p = 1.4$, one can see in Fig. 4 that the difference is actually marginal: while $p = 1.4$ seems to be a better approximation around 1974, during the enhanced period of 1994 $p = 2$ gives the better estimate. Therefore we argue that at this latitude the difference resulting in the different sampling is negligible for annual averages, and the hourly mean and analog indices with full-LT coverage have a roughly uniform response to solar wind drivers.

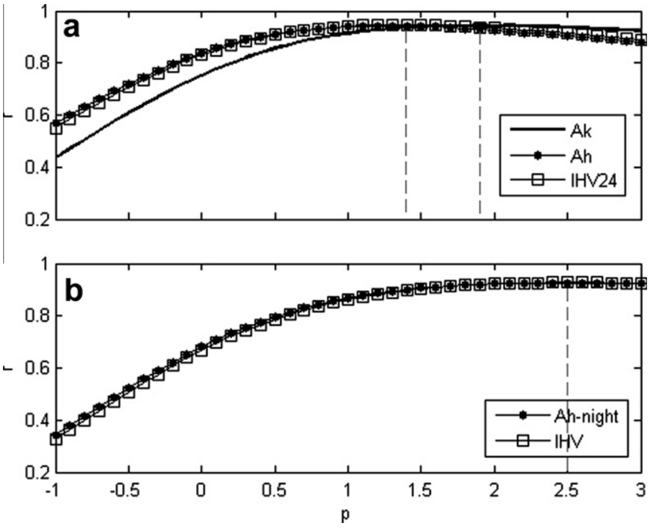

Fig. 3. Correlation coefficients between the coupling function $|B|V^p$ and full-LT indices (upper panel) and night-LT indices (bottom panel) in 1965–2000 as a function of the exponent $p(-1 < p < 3)$. The significance over the whole parameter space remains better than 2σ.

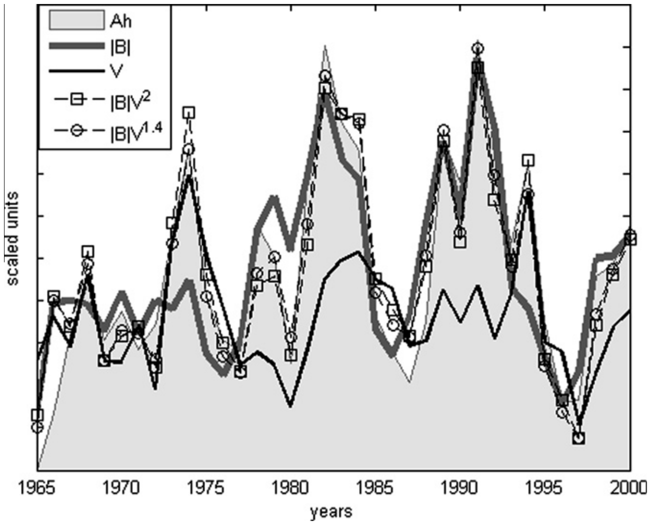

Fig. 4. Annual means of *Ah* values (shaded area) and the best linear fit series to *Ah* of solar wind parameters $|B|$ (marked with thick solid gray line), V (solid black line), and $|B|V^p$ (dashed lines) with exponent $p = 2$ and $p = 1.4$ in 1965–2000. The effect of recurrent activity is seen as strong enhancement at 1974 and 1994 in V, $|B|V^p$, and *Ah* series, while no dominant change can be observed in $|B|$.

On the other hand, Fig. 3(b) shows that digital indices constructed from night-LT observations only (*IHV* and *Ah*-night), uniformly respond to a much higher p of about $p = 2.5$ giving evidence for a considerably stronger dependence on V. Moreover, the correlation does not seem to decrease significantly if the exponent is increased further. We suggest that the above result of the different coupling of full-LT and night-LT indices can be understood as follows. While the dayside sector is sensitive to IMF strength $|B|$ and solar wind pressure, it was shown (Tanskanen et al., 2005; Finch et al., 2008) that the LT-night hours included in the *IHV* and *Ah*-night indices are those where the westward electrojet is most likely to be observed and the magnetic disturbances are most closely linked to the magnetospheric storage-release system, depending more dominantly on solar wind speed V.

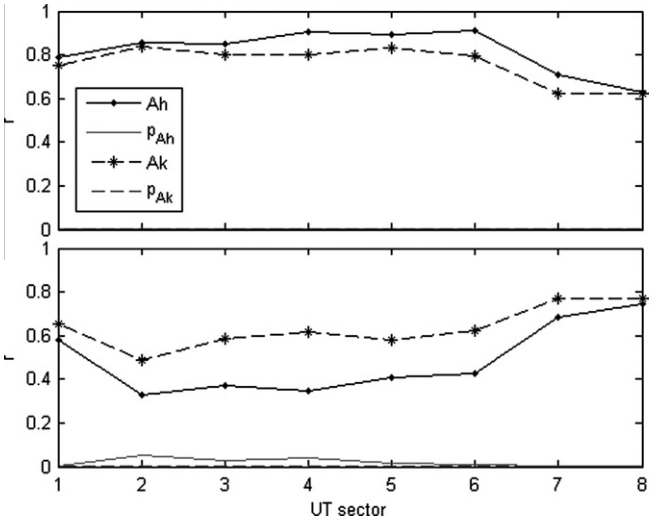

Fig. 5. Linear correlation coefficients at zero lag between the annually averaged *Ah* and *Ak* indices, calculated in the eight 3-h UT bins separately, and the IMF strength, |*B*| (upper window), and the solar wind speed, *V* (bottom window) in 1965–2000. The probability for random correlation is also depicted (p_{Ah} and p_{Ak} for the *Ah* and *Ak* indices, respectively). The significance of the correlations between *Ah* and *V* drops to about 2σ, typically in the local daytime hours. Note that the probabilities are depicted also in the upper window, they are just too small to observe.

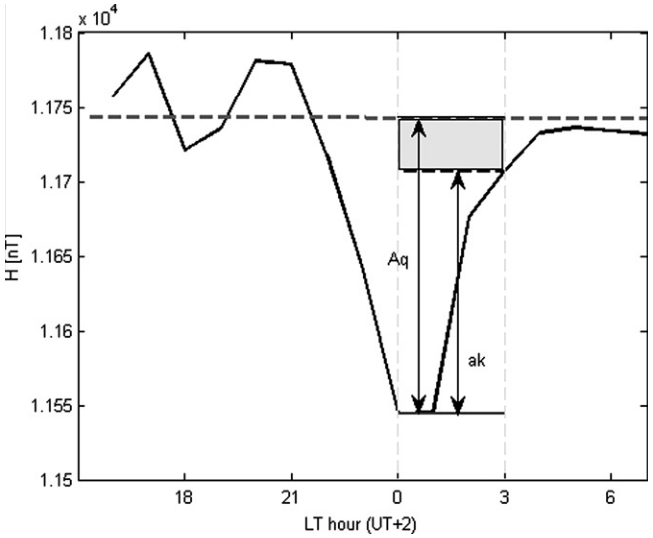

Fig. 6. Substorm activity registered in the magnetic H-component on 10–10 January, 1914 at SOD station. The approximate daily curve is indicated by a thick dashed line. The effect of the different derivation methods of *Aq* and *ak* on quantifying this particular activity peak is represented by the shaded rectangle.

This general conclusion is also well observed at SOD station (Fig. 5). Here we calculate the linear correlation coefficients between the annually averaged solar wind bulk flow speed, *V* (bottom window), and IMF strength, |*B*| (upper window), and *Ah* and *Ak* series in eight UT bins separately, in the overlapping period of 1965–2000. It is clear that the coupling to these solar wind drivers exhibits opposite diurnal variation. One typically finds the strongest coupling of both indices with |*B*| (*V*) during the daytime (nighttime, respectively) hours. We note that this LT dependence is well observed by both types of indices. While the significance of the correlation with |*B*| remains above 3σ throughout the day for both measures, the coupling of the full-day hourly mean index, *Ah*, to *V* depicts similar significance as *Ak* only in the local night hours (coinciding with the period used by the night-LT indices), where the deviation between the analog and hourly mean indices minimizes.

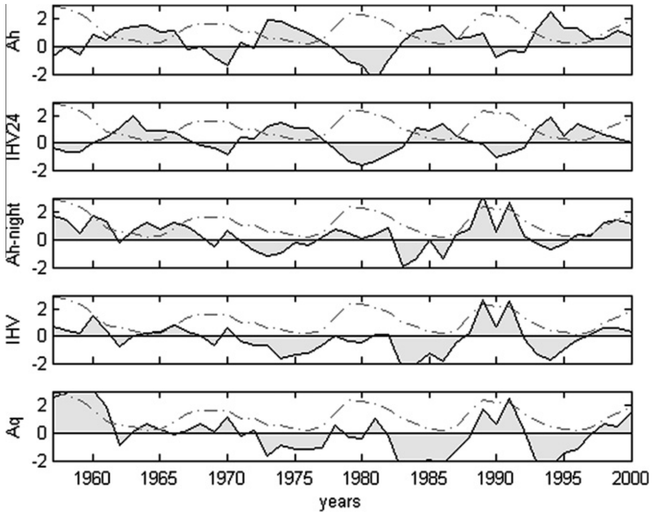

Fig. 7. Residuals in nT of the linear regression fits to *Ak* of the five indices, *Ah*, *IHV*24, *Ah*-night, *IHV*, and *Aq* in 1957–2000, marked with shaded area. For comparison, the annual sunspot numbers are also indicated qualitatively for the same period with dashed-dotted lines.

The above results demonstrate that the LT restriction has a more dominant effect on the annual indices than the different sampling. It not only compensates for the expected sampling effect, but even further enhances the index sensitivity to solar wind speed driven fluctuations. We also note that, since this coupling has clear night-LT preference observed also at sub-auroral regions (not shown), one would obtain very similar long-term patterns for the night restricted geomagnetic indices at other latitudes as well. Note that this also eliminates the possibility that the discussed systematic deviations would be due to the close proximity of the auroral oval.

Table 4 shows the correlation coefficients at zero lag between the annually averaged indices, and *V* and |*B*| in 1965–2000. As it is expected from Fig. 5, the digital full-LT indices (*Ah*, *IHV*24) on one hand and the night-LT indices (*IHV*, *Ah*-night) on the other show slightly but consistently different relation with the solar wind drivers. The digital full-LT indices depict stronger correlation with |*B*|, while the night-LT indices are more dominantly driven by solar wind speed.

Since substorm occurrence is strongly modulated by high-speed streams (Tanskanen et al., 2005; Hwang et al., 2008), this also results in stronger coupling to V at the

Table 4
Correlation coefficients between annual averages of solar wind speed, V, and IMF strength, $|B|$, and the different indices for 1965–2000 inclusive. All coefficients are statistically significant with confidence level better than 99.9%.

	Ak	*Ah*	*IHV*24	*IHV*	*Ah*-night	*Aq*
V	0.68	0.56	0.59	0.74	0.73	0.75
$\|B\|$	0.75	0.84	0.83	0.67	0.68	0.65

nightside. Therefore, indices with only night-LT coverage are considerably better indicators of substorm driven activity than indices with full-LT coverage, including the analog range index, *Ak*. Note that, while the correlation of *Ak* with V and $|B|$ is intermediate between the digital full-LT measures and the night-LT indices *Ak* is more correlated with IMF than V, similarly to the other full-LT indices of digital sampling. Since we found that the 3-h values of *Ah* follow very closely the diurnal variation of *Ak*, the time restriction of night-LT measures emphasizes the activity of the magnetotail with respect to the indices of full-LT coverage, and it is irrespective of the sampling technique (digital or analog). Additionally, the larger overall correlation at high latitudes with solar wind speed indicates a larger relative importance of the storage-release system of the magnetotail compared to the directly driven activity.

4. The role of the night-LT selection at auroral latitudes

We have shown that the annual *IHV* and *Ah*-night indices, being restricted to the local night hours, demonstrate systematic deviations from full-LT indices not because of their inter-hour sampling but, rather, because they are more sensitive to the storage-release system of the magnetotail. In addition, we suggest that this effect of the LT selection at auroral latitudes may prove to be an important asset for long-term studies of magnetospheric dynamics. To understand this role we first have to discuss another traditional analog index, the Q index.

4.1. The *Q*/*Aq* index

The Q index was implemented for the 2nd International Geophysical Year in 1957 for stations poleward of about 58° GMlat (Bartels, 1957). After the campaign years, probably due to its inconveniently high sampling rate for those times, its calculation was abruptly stopped at all stations but SOD, which still calculates and publishes the index. As opposed to the K index, Q is based on the 15-min *absolute* deviation from the daily S_R curve (as opposed to the K index, which is derived as the *relative* deviation from Sq in a particular 3-h section of the day). Similarly to the K index, Q values are in quasi-logarithmic scale; the linearized version is called *Aq*, which is used here.

The effect of this procedure is demonstrated in Fig. 6, using an actual substorm occurrence registered in the H-component on 10–11 January 1914. The approximate S_R level is indicated with the thick dashed line, and the shaded area represents the difference if we measure the absolute (*Aq*) or the relative (*ak*) deviation from this baseline. As it is clear from Fig. 6, *Aq* tends to yield larger values for disturbances, especially for fluctuations occurring on shorter timescales than the 3-h characteristic time of the *Ak* index. With the relatively small difference in derivation the index was meant to quantify better the auroral oval boundaries and longer-term (e.g., seasonal) dynamics of the oval dimensions (Starkov, 1994).

4.2. *Aq* and the night-LT indices

Fig. 7 demonstrates how the annual *Aq* index compares with the other indices used in our study. The similar residuals of the best linear fit to *Ak* were calculated as previously, here for the overlapping period of 1957–2000. The positive deviation of the shaded area represents periods when *Ak* registers larger activity levels than the particular index in question, while negative deviation stands for the opposite. Most surprisingly the *Aq* residuals are almost identical to that of the night-LT indices, *IHV* and *Ah*-night. One of the most apparent patterns occurs around the year 1990 (with highly enhanced $|B|$ and low average V values in the solar wind), where it is the easiest to observe the systematic responses of these indices. That is, the annual *Aq* index effectively behaves as a night-LT index, by yielding enhanced activity during declining solar activity phases and a somewhat damped response around activity maxima, with respect to *Ak*. This is due to stronger (weaker) coupling to V ($|B|$, respectively), very much similarly to night-LT indices (see Tables 2 and 4). Lastly, the maximum correlation of $r = 0.93$ with $|B|V^p$ is found at $p = 2.6$ that is once more very close to what was earlier found for *IHV* and *Ah*-night ($r = 0.94$, $p = 2.5$).

We find that the LT restriction of the hourly mean indices of *IHV* and *Ah*-night on one hand, and the *Q*/*Aq* index method on the other have very similar effects on the long-term. If one studies the distribution of these annual indices in Fig. 8, one finds that these methodological changes uniformly result the distribution of the ‘parent’ indices to move towards higher values, to depict a more Gaussian main distribution pattern, and a significant second activity peak at the highest values.

Therefore, we suggest that the *IHV* index may be used as a digital proxy for the analog *Aq* values at auroral latitudes, i.e., for statistical studies of the auroral oval. Due to the vastly different timescale of the two indices one probably cannot use *IHV* at its highest daily resolution reliably, but analysis shows that already using monthly smoothing the differences are averaged out. Since the *Q*/*Aq* index has mostly been used for multi-station statistical studies in the past we would like to raise the community’s attention to the *IHV* index (or any activity index restricted to local night hours only) that should be considered as a possible candidate in future long-term studies of the westward electrojet and current wedge dynamics, by using a number of

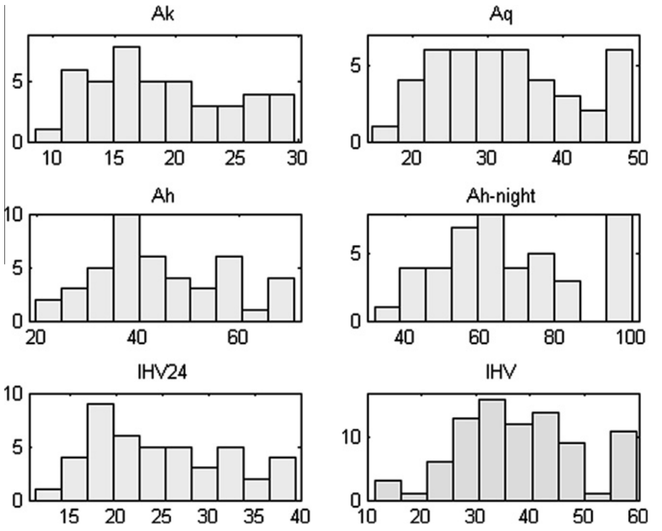

Fig. 8. Number distribution of the annual indices of full-LT coverage (*Ak*, *Ah*, and *IHV*24) in the left column, and night-LT coverage (*Ah*-night and *IHV*) plus *Aq* in the right column. The indices were not normalized, thus the actual effect of the different derivations on quantifying the activity levels is observed from left to right.

station data covering the corresponding UT sectors throughout the day.

5. Discussion and conclusions

We have compared the analog *Ak* index and the more recently implemented digital indices of *Ah* and *IHV* (and their derivatives) at the auroral Sodankylä station. With this selection of indices we have been able to study how the different LT (local time) interval activity is defined and the different sampling (analog vs. hourly mean) affects long-term estimates.

Very importantly there is no evidence that the different derivation methods would lead to observable long-term drifts among the indices, during the later decades of last century with moderate to high average solar activity. On the other hand, however, the observed moderate deviations have very systematic long-term patterns. Digital full-LT indices tend to register somewhat larger irregular variations than the analog *Ak* index at solar cycle maxima, while a lower average level is observed during the declining phases. Indices with only night LT coverage clearly exhibit just an opposite pattern on the long-term.

We have demonstrated that this systematic discrepancy of the residuals is the result of a different coupling to solar wind drivers. Indices based on hourly mean data are somewhat less sensitive than the analog *Ak* index to high-frequency fluctuations due to Alfvén waves in high-speed solar wind streams. Nevertheless, this effect was found to be actually marginal in comparison with the similar effect reported earlier from sub-auroral stations.

We have found that, while the different response of *Ak* and the full-LT indices is the result of their different sampling only, deviations of the night-LT indices (*IHV*, *Ah*-night) are more fundamentally affected by their dissimilar sensitivity to magnetospheric current systems. This leads to their rapidly decreasing correlation with the *Ak* index for shorter averaging timescales. We note that the deviation would even be more pronounced at all time scales, should one compare digital full-LT vs. digital night-LT indices. Night-LT indices are more suitable to measure the indirectly driven disturbances of the magnetosphere, the '*Q*-type variation', especially in the declining phase of the solar cycle when high-speed solar wind streams dominate.

Last but not least we have shown that all other indices registered larger average activity levels than *Ak* in the beginning of the data during the rather low-activity cycles 15 and 16. This necessarily produces a drift between analog and digital indices in these early decades. We suggest that this deviation is due to the large number of quiet days when the original manually scaled *K* values are set to zero while the digital indices are likely to yield a value larger than zero. Therefore, for long-term studies it is essential to take into consideration that digital measure of hourly data are expected to have a somewhat lower century-long increase (by about 10%) in average geomagnetic activity.

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