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Key Points:
- A new inhomogeneity was found in two long-running magnetic observatories from 1930s until 1960s
- We quantified this inhomogeneity and corrected the related geomagnetic activity indices
- This inhomogeneity can modify the long-term trends of SW speed by 20–30% and IMF strength by 10–15%

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Toward more reliable long-term indices of geomagnetic activity: Correcting a new inhomogeneity problem in early geomagnetic data

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Abstract For the time before the space era, our knowledge of the centennial evolution of solar wind (SW) and interplanetary magnetic field (IMF) is based on proxies derived from geomagnetic indices. The reliability of these proxies is dependent on the homogeneity of magnetic field data. In this paper, we study the interhourly (*IHV*) and interdiurnal (IDV_{1d}) variability indices calculated from the data of two British observatories, Eskdalemuir and Lerwick, and compare them to the corresponding indices of the German Niemegk observatory. We find an excess of about 14 ± 4% (5.8 ± 2%) and 27 ± 10% (15 ± 6%) in the *IHV* (IDV_{1d}) in the indices of Eskdalemuir and Lerwick in 1935–1969. The timing of this excess accurately coincides with instrument changes made in these observatories, strongly supporting the interpretation that the excess is indeed caused by instrument related inhomogeneities in the data of Eskdalemuir and Lerwick. We show that the detected excess notably modifies the long-term trend of geomagnetic activity and the centennial evolution of IMF strength and solar wind speed estimated using these indices. We note that the detected inhomogeneity problem may not be limited to the data of the two studied observatories but may be quite common to long series of geomagnetic measurements. These results question the reliability of the present measures of the centennial change in solar wind speed and IMF.

1. Introduction

In recent years, there is growing interest in the long-term evolution of solar activity and solar wind. For the time before the space age, our knowledge on the properties of the solar wind and the interplanetary magnetic field is based on proxies derived from different geomagnetic indices constructed from ground-based magnetic field measurements [*Svalgaard and Cliver*, 2007; *Lockwood et al.*, 2014; *Mursula et al.*, 2015]. The reliability of these reconstructions and proxies is dependent on the long-term homogeneity of related geomagnetic observation and the indices of geomagnetic indices calculated from them.

Some of the longest-running continuous records of geomagnetic activity are the so-called *K* indices [*Bartels et al.*, 1939], which measure the range of variation of the local magnetic field in 3 h intervals at the respective station. An example of a global index of geomagnetic activity is the *aa* index [*Mayaud*, 1972], which is based on the *K* indices of two antipodal stations starting their measurements already in 1868. Unfortunately, the reliability of the early *K* indices is difficult to verify because they were determined from analog magnetographs that are not available in digital format. Instead of the original high-resolution magnetographs, only hourly values of the magnetic field are mostly available in digital format in various databases. Therefore, in recent years, new indices based on hourly values of the magnetic field have been derived and used in long-term studies, along with the *K* indices [*Svalgaard and Cliver*, 2007; *Mursula and Martini*, 2007a; *Lockwood et al.*, 2013a, 2014]. However, generally, the long-term evolution of indices based on hourly data does not completely agree with that of the analog indices [*Mursula and Martini*, 2007b].

Indices based on hourly values also have other problems. The earliest reported hourly values are usually not hourly means but spot values, i.e., momentary magnetograph readings. Naturally, spot values have much (typically 30%–40%) greater variability than hourly means, leading to larger values of geomagnetic indices measuring the hourly variation of the magnetic field [*Mursula and Martini*, 2006] like, e.g., the interhourly variability index (*IHV*) based on the differences of successive hourly values [*Svalgaard and Cliver*, 2007]. Having excessively large indices from spot values typically in the first decades of the twentieth century may lead (and has led) to seriously underestimated centennial trends in geomagnetic activity. Fortunately, this sampling problem is fairly easy to identify and to correct by appropriate scaling [*Mursula and Martini*, 2006].

A different problem with the hourly data of Eskdalemuir (ESK) observatory was noted by *Martini and Mursula* [2006]. The hourly ESK data stored in the World Data Center (WDC), Edinburgh (http://www.wdc.bgs.ac.uk/), were actually 2 h running means of the original hourly means for 1911–1931. This treatment imposed a low-pass filtering to the data, which reduced hourly variability and led to excessively low *IHV* values for these years. The data were later corrected by examination of the original ESK yearbooks [*Macmillan and Clarke*, 2011], and the original hourly data have now been restored in the WDC database.

In this paper we show that even after correcting the above mentioned sampling and filtering problems, the magnetic field data of ESK and Lerwick (LER) observatories and the related indices are still inhomogeneous and exhibit suspicious long-term evolution. In section 2 we first present the data and discuss the known facts on the hourly data of ESK and LER and of the reference observatory Niemegk (NGK). Section 3 discusses the different sources of error in the magnetic field data and how the errors affect different geomagnetic indices. In section 4 we calculate the ratios of different geomagnetic indices between the British observatories and NGK and identify discontinuities in the ratios. In section 5 we suggest an explanation for the observed inhomogeneities, and in section 6 we present the corrected *IHV* and IDV_{1d} indices. Section 7 discusses how the suggested correction affects the reconstructions of solar wind speed and interplanetary magnetic field (IMF) strength based on ESK or LER data. We give our conclusions in section 8.

Finally, we would like to emphasize already at this phase that we did not select ESK or LER data for the present analysis because they are the only stations depicting the new type of inhomogeneity to be discussed here. Rather, we use these data because they are among the best-studied magnetic field data and have already been corrected for the two other, above mentioned problems. ESK and LER data are only used here as a demonstration of the problem, which may be rather common in the long series of magnetic field data covering periods of observations by different instruments. Future studies are needed to examine how common and severe these problems are in the other long-operating stations and what overall effect they have on long-term evolution of solar wind and the IMF properties.

2. Hourly Magnetic Field Data of Eskdalemuir and Lerwick

The British Eskdalemuir (geographic coordinates 55.314°N, 356.794°E) and Lerwick (60.138°N, 358.817°E) observatories have been operating since 1911 and 1923, respectively. The hourly values of ESK are spot values in 1911, but hourly means since 1912, while the whole data set of LER are hourly means [*Macmillan and Clarke*, 2011]. In this paper we use the ESK data only since 1912 in order to avoid the sampling change problem.

Before the start of modern measurements using fluxgate magnetometers in 1985, ESK and LER used classical variometers to measure magnetic field variations. A typical variometer consists of three magnets, perpendicular to magnetic (or geographic) North, East, and vertical directions at equilibrium. Rotation of the magnets is recorded on rolling photographic paper by light beams reflected from mirrors attached to the magnets. Deviations observed on the paper are then converted to physical units by multiplying the deviations by respective scale values. Typically, the scale values are determined by generating a magnetic field of known intensity using coils constructed around the magnets and measuring the resulting deviation on the paper. The hourly values of magnetic field are obtained by determining hourly means of the deviations from the paper and adding them to the baseline of the component measured by an absolute field intensity instrument. Because changes in the baselines are slow (due to, e.g., seasonal or secular changes of the Earth's magnetic field), they can be taken to be constant at the typical timescales of geomagnetic activity events (up to several days for strong geomagnetic storms). Hence, geomagnetic activity measured, e.g., by the range indices (such as *K* indices) or other indices depending only on the rapid variations (such as the *IHV* index) measured by variometers, is not affected by inaccuracies related to baseline measurement.

2.1. Changes in Instrumentation at Eskdalemuir and Lerwick

While the basic design of the variometers used in the early decades before the fluxgate magnetometers remained the same, the instruments and the related measurement accuracy did not. Information on the instrument history of ESK, LER, and some other British observatories can be obtained from the observatory yearbooks available at WDC Edinburgh (http://www.wdc.bgs.ac.uk/; ESK and LER described in the

Table 1. Types of the Variometers Used in the British Observatories[a]

Observatory	Year	Instrument Type
Eskdalemuir (ESK)	1911-1935	Adie
	1936–1967	La Cour
	1968–1983	La Cour (new)
		Adie (new)
Lerwick (LER)	1923-1934	Munro
	1935–1964	La Cour
	1965–1967	Insensitive La Cour
	1968–1983	La Cour (new)

[a]Only those instruments that were used to register hourly data are included.

same yearbooks). The yearbooks state that at Lerwick the horizontal component was measured until the end of the year 1934 using a Munro magnetograph which was replaced by a La Cour magnetograph in 1935 (see a summary of instruments in Table 1). Eskdalemuir started using La Cour instruments 1 year later in 1936 replacing the Adie magnetographs.

At the time, the La Cour magnetograph designed by the Danish Meteorological Institute was probably one of the most used instruments, capable of measuring the large and fast magnetic field variations at high latitudes. Also, different modified versions of the normal La Cour instruments have been used over the years. One modification is the so-called quick-run version in which the recording photographic paper moves at higher speed, providing a higher time resolution (paper speed 3 mm/min) than for the normal instrument (15 mm/h). The hourly means sent to the World Data Centers are, most likely, always based on the lower time resolution (not quick-run) measurements, although this is explicitly stated only in the 1973–1977 yearbooks. Another modification of the La Cour magnetograph is the so-called insensitive (also called the wide range or storm) version [*Jones*, 1940] with lower sensitivity, i.e., a larger-scale value (about 10–25 nT/mm) than in the normal La Cour instrument (about 4 nT/mm). The insensitive instruments were designed to be used during the largest disturbances that sometimes exceeded the measurement range of the normal La Cour instruments.

According to the 1965 yearbook, Lerwick started using insensitive La Cour instruments replacing the older normal La Cour instruments from the beginning of 1965. It remains unclear whether a similar change was made at Eskdalemuir since, unfortunately, no information on the ESK instruments is available in the 1966–1967 yearbooks. However, the yearbook in 1968 mentions that both observatories again operated normal (and insensitive and quick run) La Cour instruments. All these instruments were either new or at least recalibrated, because the reported scale values (3.96 nT/mm for ESK and 3.35 nT/mm for LER) are different or more accurate than earlier reported ("about 4 nT/mm for both observatories" in the yearbooks 1939–1965). At least in LER the scale value of the new La Cour instrument was significantly smaller than in the older (1935–1964) instrument. While at Lerwick all instruments were La Cour, the insensitive magnetograph at Eskdalemuir was an Adie magnetograph since 1968 (having a higher-scale value than earlier Adie instruments). In 1969–1971, yearbooks note that the Adie instruments were also used supplementary to the normal measurements. Both observatories continued using La Cour instruments until 1984 when both Eskdalemuir and Lerwick started using fluxgate magnetometers and automated digital storing of data. Although all details of the measurement history cannot be found in the yearbooks, an important note is that La Cour instruments were installed at the observatories in 1935–1936 and some modifications were made to them in 1965–1968.

3. Sources of Error in Variometer Data

There are at least two different sources of error in variometer measurements, which have an effect on geomagnetic indices. We discuss here the horizontal component H, which is most commonly used to calculate geomagnetic activity indices. The hourly mean of H at hour t is obtained as a sum of the baseline H_0 and the variometer reading h multiplied by the scale value a, i.e.,

$$H(t) = H_0 + ah(t). \tag{1}$$

Thus, the hourly absolute differences used, e.g., in the *IHV* index depend on the variometer readings and the scale value as follows:

$$|H(t+1) - H(t)| = a|h(t+1) - h(t)|. \tag{2}$$

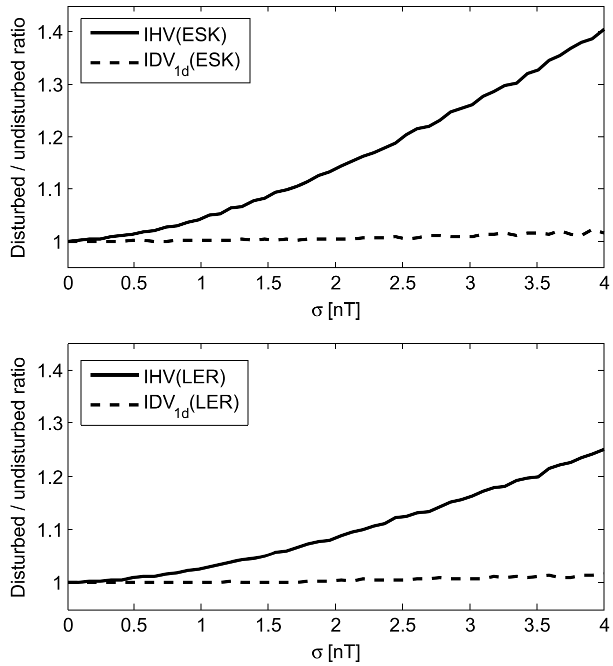

Figure 1. Ratios of simulated and observed *IHV* and IDV_{1d} indices for different levels of random noise added to the hourly magnetic data.

Obviously, an error in the scale value would systematically change all hourly differences and the daily *IHV* index values calculated from the observations in the 21–03 local time (LT) sector

$$\begin{aligned} IHV &= \frac{1}{6}\sum_{t=21\mathrm{LT}}^{02\mathrm{LT}} |H(t+1) - H(t)| \\ &= \frac{a}{6}\sum_{t=21\mathrm{LT}}^{02\mathrm{LT}} |h(t+1) - h(t)|. \end{aligned} \tag{3}$$

Inevitably, there are also errors in the variometer readings, e.g., due to limited reading accuracy of the recorded trace on the paper and uncertainties in estimating hourly means from it. Such errors obviously increase the variance of the hourly differences, leading to a larger average level of $|h(t+1)-h(t)|$ and, hence, to a larger *IHV* index. As long as the value of a, its error, and the error related to the readings remain the same, the derived geomagnetic indices would be homogeneous. However, all of these values are instrument specific, and any change of instrumentation can therefore cause temporal inhomogeneity in the hourly means and the related indices.

While the *IHV* indices are significantly affected by the above problems, it is useful to consider another geomagnetic index that is less prone to random errors in readings $h(t)$. The interdiurnal variability index using data from all local times (IDV_{1d}) is defined [*Lockwood et al.*, 2013a] for day i as

$$IDV_{1d}(i) = |\langle H_i(t)\rangle - \langle H_{i-1}(t)\rangle| = a|\langle h_i(t)\rangle - \langle h_{i-1}(t)\rangle|, \tag{4}$$

where $\langle H_i(t)\rangle$ denotes the daily mean of the 24-hourly values of $H_i(t)$ during the day i. Because the IDV_{1d} index involves averages of 24-hourly means, the random errors in the readings are largely averaged out. If the errors in hourly readings $h_i(t)$ are independent and normally distributed with the standard deviation σ, the standard deviation of the error in their daily means $\langle h_i(t)\rangle$ would be $\sigma/\sqrt{24} \approx 0.2\sigma$. When the difference of two daily means is calculated, as in equation (4), the standard deviation of the error is then increased to $\sqrt{2}\sigma/\sqrt{24} \approx 0.41\sigma$. Similarly, the error of the difference of 2-hourly means in *IHV* index (3) is $\sqrt{2}\sigma$, i.e., almost 5 times larger than the error in the IDV_{1d} index. We will next simulate the effect of the random errors to the *IHV* and IDV_{1d} indices.

3.1. Simulation of Errors in Geomagnetic Indices

Because the *IHV* and IDV_{1d} indices do not measure differences, but their absolute values, the effect of error is not trivial to estimate. In order to roughly estimate the effect of random noise in the readings $h(t)$ to these indices, we recalculate the two indices for the years 1990–2013 (measurements made by fluxgate magnetometers with small errors) from the original hourly means, disturbing them by additional, randomly generated Gaussian white noise. Figure 1a shows the ratios of the disturbed and undisturbed *IHV*(ESK) and IDV_{1d}(ESK) indices for different values of the standard deviation σ of the Gaussian white noise. One can see that while the average level of the *IHV*(ESK) index is significantly enhanced even for moderate values of σ, the IDV_{1d}(ESK) index remains relatively unaffected even for large σ. The increase of *IHV* is nonlinear at small values of σ but linear after the noise becomes greater than the typical (true) hourly differences. The simulation for LER data yields very similar results plotted in Figure 1b. However, since geomagnetic variability is larger in LER than in ESK (see Figure 2 later) the relative increase in *IHV* is larger for ESK than for LER at given noise level.

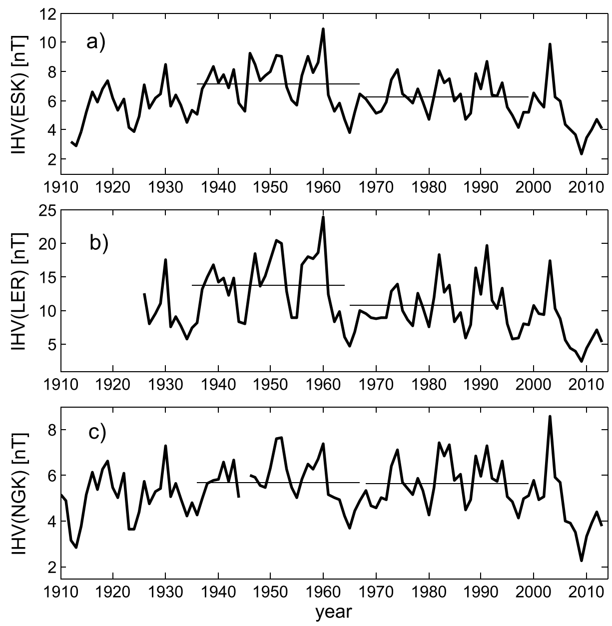

Figure 2. Annual averages of the *IHV* indices of (a) Eskdalemuir, (b) Lerwick, and (c) Niemegk. Horizontal lines denote the average values of the indices during 1936–1967 and 1968–1999 for ESK and NGK, and during 1935–1964 and 1965–1994 for LER.

4. Comparison With Niemegk Data

As a reference, we use the German Niemegk observatory which has been operating since 1890 and has used hourly mean sampling since 1905. However, the location of the observatory has been changed twice: in 1908 the observatory was moved from Potsdam (52.382°N, 13.063°E) to Seddin (52.278°N, 13.01°E) and in 1932 to the current location in Niemegk (52.072°N, 12.675°E). In this paper we call the combined data set NGK for simplicity. New variometers were installed in Niemegk after the movement of the observatory, and these variometers were used until 1996 when they were replaced by fluxgate magnetometers. Note that La Cour instruments were never used in NGK. However, due to the loss of some instruments during the last phase of World War II, some instruments were changed in 1946, but the type of the instruments remained the same. The change of the location and instruments may have an effect for the long-term homogeneity of the early NGK data series, but no changes in instrument sensitivity at NGK are known (H.-J. Linthe, personal communication, 2015). Therefore, the NGK data can be considered a reliable reference at least since 1932.

4.1. Comparison of the *IHV* Indices

Figure 2 shows the annual averages of *IHV*(ESK), *IHV*(LER), and *IHV*(NGK). The three observatories show quite a similar variation in *IHV* after the mid-1960s. However, even then, there are small but systematic differences between the observatories due to their different response to high-speed solar wind streams (HSSs) and coronal mass ejections (CMEs) [*Holappa et al.*, 2014a, 2014b]. From the three observatories studied here, HSSs (CMEs) have strongest (weakest) effects at NGK and weakest (strongest) effects at LER. These differences lead, e.g., to relatively different levels of geomagnetic activity in HSS-dominated years 2003 and 1974 which clearly stand out as high peaks in NGK but lower peaks in LER. On the other hand, LER observes relatively strongest geomagnetic activity close to solar maxima, e.g., in 1982 and 1991, when CMEs are dominant in solar wind [*Holappa et al.*, 2014a, 2014b].

Figure 2 also shows the averages of *IHV* indices for the years when the first La Cour instruments were used in the British observatories (1936–1967 for ESK and 1935–1964 for LER) and for equally long reference periods after the instrumental changes (1968–1999 for ESK and 1965–1994 for LER). For NGK, the averages are plotted for the same years as for ESK. One can clearly see that although all observatories show quite a similar overall evolution for the last 50 years, as discussed above, ESK and especially LER observed much stronger relative activity than NGK during the first time interval.

Figure 3a shows the ratio of the annual means of *IHV*(ESK) and *IHV*(NGK). There is a solar cycle variation in this ratio due to the different response of the stations to HSSs and CMEs, as discussed above. However, the average level of the ratio is clearly elevated from mid-1930s until mid-1960s from the average level either before or after this period. The increase in the ratio closely coincides with the year 1936 when the La Cour instruments replaced the older variometers at Eskdalemuir. A similar increase is observed in LER/NGK ratio (Figure 3b) roughly at the same time, in agreement with LER starting to use La Cour instruments in 1935. Both ESK/NGK and LER/NGK ratios remain elevated until mid-1960s to end-1960s when the first versions of La Cour instruments were replaced by other instruments, as discussed above. (This timing of excessively high values

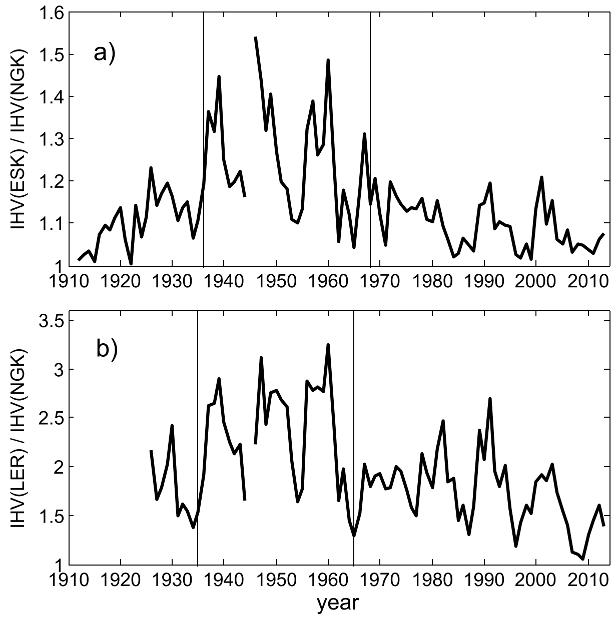

Figure 3. Ratios of the annually averaged *IHV* indices of (a) Eskdalemuir and Niemegk and (b) Lerwick and Niemegk. Vertical lines indicate the dates of instrumental changes in British observatories.

at ESK and LER excludes the possibility that natural changes in space conditions, like the changing magnetic coordinates of the stations, would be the cause.)

In order to estimate the relative excess in the *IHV* indices due to instrument changes, we compare the *IHV*(ESK)/*IHV*(NGK) and *IHV*(LER)/*IHV*(NGK) ratios during and after the era of the first La Cour instrument. We use long (> 25 years) averages in order to smooth out the solar cycle variation in the ratios. The average of the ratio $R_1 = IHV(\mathrm{ESK})/IHV(\mathrm{NGK})$ for years 1936–1967 ($\langle R_1 \rangle$) is 1.255 and 1.103 for years 1968–1999 ($\langle R_2 \rangle$). The ratio $\langle R_1 \rangle/\langle R_2 \rangle$=1.255/1.103=1.138 gives the relative excess of about 14% for the *IHV*(ESK). If we assume $\langle R_1 \rangle$ and $\langle R_2 \rangle$ to be independent from each other, the standard error (or standard deviation) of the ratio $\langle R_1 \rangle/\langle R_2 \rangle$ is approximately [*Kendall et al.*, 1994]

$$\sigma\left(\frac{\langle R_1 \rangle}{\langle R_2 \rangle}\right) \approx \frac{\langle R_1 \rangle}{\langle R_2 \rangle}\sqrt{\left(\frac{\sigma(\langle R_1 \rangle)^2}{\langle R_1 \rangle^2} + \frac{\sigma(\langle R_2 \rangle)^2}{\langle R_2 \rangle^2}\right)}, \tag{5}$$

where $\sigma(\langle R_1 \rangle)$ and $\sigma(\langle R_2 \rangle)$ are estimates for standard deviations of the averages $\langle R_1 \rangle$ and $\langle R_2 \rangle$. Taking into account the effect of autocorrelation in R_1 and R_2 by an autoregressive AR(1) model, we get an estimate [*Wilks*, 2006]

$$\sigma(\langle R_1 \rangle) = \frac{\sigma(R_1)}{\sqrt{n}}\sqrt{\frac{1+\phi_1}{1-\phi_1}}, \tag{6}$$

where n is the number of annual data points in R_1 and ϕ_1 is the autocorrelation coefficient for R_1 at lag 1. For ESK, the standard error of the relative excess $\sigma(\langle R_1 \rangle/\langle R_2 \rangle) = 0.039$. Similar for LER (comparing periods 1935–1964 and 1965–1994), we obtain an estimate of relative excess of 2.359/1.863 = 1.266, i.e., about 27% (with a standard error of 9.6%), for the same time interval.

4.2. Comparison of the IDV_{1d} Indices

Figure 4a shows the ratios of the annually averaged IDV_{1d} indices of Eskdalemuir and Niemegk. One can clearly see that the IDV_{1d}(ESK)/IDV_{1d}(NGK) ratio is rather constant for the recent decades. However, the ratio is clearly different in 1936–1967 when the first La Cour instruments were used at ESK. The ratio is different also before 1935 when the related solar cycle variations are more than twice as large as during recent decades. The latter difference may be related to the relocation (and possible instrument change) made from Seddin to Niemegk in 1932. Comparing the ratios of the indices in 1936–1967 and 1968–1999, we obtain a relative excess of IDV_{1d}(ESK) of 5.8% (with a standard error of 1.5%) in 1936–1967. *Lockwood et al.* [2013a] combined IDV_{1d}(NGK) and IDV_{1d}(ESK) indices into a long-term composite exploiting the high correlation between them in 1911–1920. However, as the IDV_{1d}(ESK)/IDV_{1d}(NGK) ratio shows large variations starting from 1921, the composite IDV_{1d} of *Lockwood et al.* [2013a] is probably not homogeneous.

The IDV_{1d}(LER)/IDV_{1d}(NGK) ratio (Figure 4b) shows an even larger excess in 1935–1964 than the IDV_{1d}(ESK)/IDV_{1d}(NGK) ratio. During the years 1935–1964, the average ratio is 15% (with a standard error of 5.5%) higher than the ratio in 1965–1993. The larger solar cycle variation in the IDV_{1d}(LER)/IDV_{1d}(NGK) ratio than in the IDV_{1d}(ESK)/IDV_{1d}(NGK) ratio is in agreement with the lower correlation between IDV_{1d}(LER) and IDV_{1d}(NGK) (than between IDV_{1d}(ESK) and IDV_{1d}(NGK)), also noted by [*Lockwood et al.*, 2013a]. Note also the

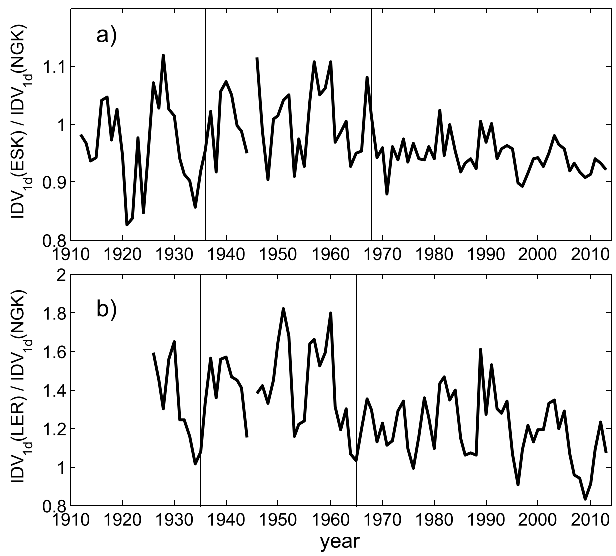

Figure 4. Ratios of the annually averaged IDV_{1d} indices of (a) Eskdalemuir and Niemegk and (b) Lerwick and Niemegk. Vertical lines indicate the dates of instrumental changes in British observatories.

large solar cycle variation before 1935, which supports the above mentioned interpretation (Seddin-Niemegk relocation).

5. Interpretation of the Inhomogeneities

We found in section 4 that both *IHV* and IDV_{1d} indices of Eskdalemuir and Lerwick are increased during the period when measurements were made using the first La Cour instrument, implying an inhomogeneity in the (hourly means of the) horizontal magnetic field strength. The relative excesses in *IHV*(ESK) and IDV_{1d}(ESK) ($\pm$ standard errors) during these times are 14% $\pm$ 4% and 5.8% $\pm$ 2%, and even larger relative excesses (27% $\pm$ 10% and 15% $\pm$ 6%) were found for LER indices. These excesses are most likely due to errors both in the hourly magnetograph readings and in the scale values of the La Cour instruments. We can quantify the effect of these two errors by comparing the relative excesses in *IHV* andIDV_{1d} indices.

Firstly, there must be some error in the scale value since the excesses of the IDV_{1d} indices by many percent cannot be explained by any realistic amount of random noise in the readings of the hourly means (see Figure 1). Secondly, an error in the scale value alone cannot explain the fact that relative excesses are significantly larger in *IHV* than in IDV_{1d}. As discussed above (equations 3 and 4), an error in the scale value should cause equal relative excesses to both indices. If we assume that the scale value error increases *IHV*(ESK) by the factor of 1.058 (being also responsible for the relative increase of 5.8% in IDV_{1d}), the observed total increase factor 1.138 in *IHV*(ESK) can be expressed as the product 1.058 $\cdot$ 1.076, where the factor 1.076 must be due to random error in the hourly means. Similarly, for LER the factor for random error in the hourly means would be 1.097. One can see from Figure 1 that the relative increase of 7.6% (9.7%) in *IHV*(ESK) (*IHV*(LER)) index can be explained by random noise (additional to noise level in 1990–2013) with the standard deviation σ of 1.4 nT (2.2 nT). Despite the larger estimated noise for LER, the noise levels are relatively very similar for both observatories when normalized by the average values of the *IHV* indices of the observatories in 1990–2013: $\sigma(\text{ESK})/\langle IHV(\text{ESK})\rangle = 0.2551$ and $\sigma(\text{LER})/\langle IHV(\text{LER})\rangle = 0.2547$. Thus, the signal-to-noise ratios are the same for both

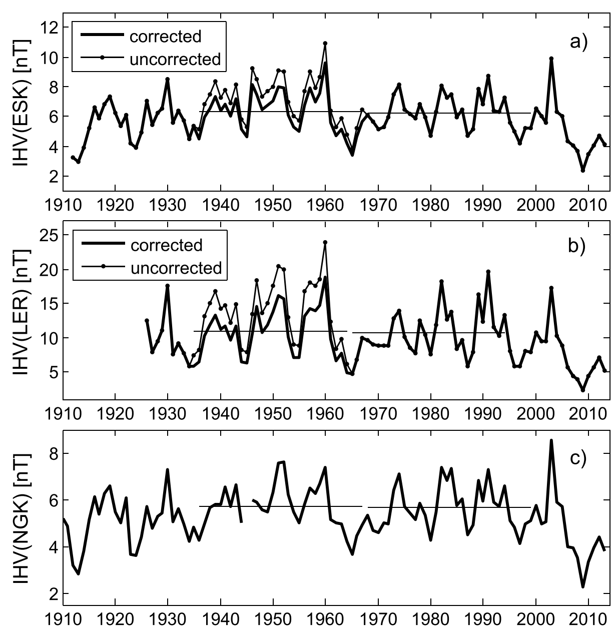

Figure 5. Annual averages of the uncorrected and corrected *IHV* indices of (a) Eskdalemuir, (b) Lerwick, and (c) Niemegk. Horizontal lines denote the average values of the corrected indices during 1936–1967 and 1968–1999 for ESK and NGK, and during 1935–1964 and 1965–1994 for LER.

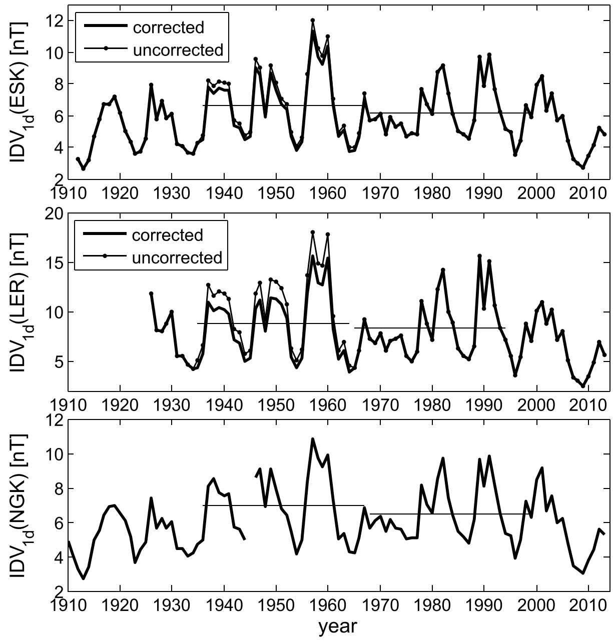

Figure 6. Annual averages of the uncorrected and corrected IDV_{1d} indices of (a) Eskdalemuir, (b) Lerwick, and (c) Niemegk. Horizontal lines denote the average values of the corrected indices during 1936–1967 and 1968–1999 for ESK and NGK, and during 1935–1964 and 1965–1994 for LER.

observatories using similar La Cour instruments. This gives strong support for the method and the obtained results, including the estimated excesses in the *IHV* and IDV_{1d} indices due to the first La Cour instrument.

6. Corrected *IHV* and IDV_{1d} Indices

The simplest way to correct the *IHV* and IDV_{1d} indices of ESK and LER is to scale them down by the observed relative excesses during the years when the first La Cour instruments were used. The corrected *IHV*(ESK) (*IHV*(LER)) index was calculated by dividing the *IHV* index by 1.138 (1.266) for 1936–1967 (1935–1964). Figure 5 shows the corrected *IHV*(ESK) and *IHV*(LER) indices together with uncorrected indices. One can see that after the correction, the observatories show a considerably more similar long-term evolution of geomagnetic activity and the same relative changes in the overall level of activity during the indicated 26 year time intervals. The correction is especially significant for *IHV*(LER), which, without correction, shows anomalously strong geomagnetic activity before the space age.

We apply the same method to correct the IDV_{1d}(ESK) and IDV_{1d}(LER) indices by dividing them by 1.058 and 1.155 in 1936–1967/1935–1964. The corrected and uncorrected IDV_{1d} indices are shown in Figure 6. Although the corrections for the IDV_{1d} indices are not as large as for the *IHV* indices, both corrections affect, e.g., the centennial trends and the reconstructions of the solar wind speed and the IMF strength from these indices, which will be studied next.

7. Effect on Reconstructions of Solar Wind Speed and IMF Strength

Proxies for the IMF strength (*B*) and solar wind speed (*v*) can be derived from any set of at least two geomagnetic indices, which depend differently on *B* and *v*. Most recent reconstructions of the annual means of *v* and *B* [*Svalgaard and Cliver*, 2007, 2010; *Lockwood et al.*, 2009, 2014] use coupling functions of the form Bv^n with different exponents *n* for *IHV* and IDV_{1d}. (*Svalgaard and Cliver* [2010] actually use the *IDV* index based on midnight values, not daily means). In order to reconstruct the annual means of *B* and *v* from the annual means of IHV and IDV_{1d}, we calculate, following the above references, the linear least squares fits

$$IHV = a \cdot Bv^{n_1} + b \tag{7}$$

$$IDV_{1d} = c \cdot Bv^{n_2} + d, \tag{8}$$

where the exponents n_1 and n_2 are selected so that the correlations between indices and the coupling functions are maximized. The optimal values of exponents n_1 and n_2 for ESK (LER) are 2.27 and −0.20 (1.41 and 0.01). These values are close to those published earlier [*Lockwood et al.*, 2014]. Note also that the IDV_{1d} index is almost independent of *v*. The value of n_1 is larger for ESK than for LER because of the stronger response of *IHV*(ESK) to high-speed streams [*Holappa et al.*, 2014b].

Reconstructions for *B* and *v* are calculated by solving *B* and *v* from equations (7 and 8). Figures 7 and 8 show the reconstructed annual means of *B* and *v* derived from corrected and uncorrected *IHV* and IDV_{1d} indices for

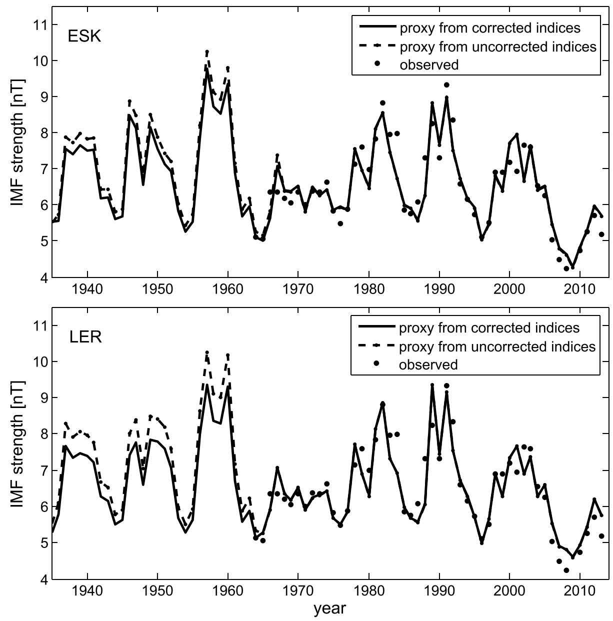

Figure 7. Annual averages of the IMF strength reconstructed from (top) *IHV*(ESK) and IDV_{1d}(ESK) and (bottom) *IHV*(LER) and IDV_{1d}(LER). Observed annual averages are denoted by dots.

the years 1935–2013. The correction to ESK (LER)-based estimates of *v* and *B* values is, on an average, about 19 km/s and 0.3 nT (about 26 km/s and 0.5 nT, respectively). If one compares these values to the average values of the two parameters, about 450 km/s and 7 nT, the corrections would remain rather small, less than 10% even for LER where the changes are larger. However, it is more appropriate to compare the corrections to the typical level of solar cycle variation in these parameters, since this will give the estimate on the relative significance to the long-term trend. For typical solar cycle amplitudes of about 70–100 km/s and 3–4 nT, the corrections would be about 20%–30% for solar wind speed and 10%–15% for IMF strength.

Accordingly, the effect of corrections made to geomagnetic indices have a slightly larger relative effect on the reconstructions of *v* than *B*. This is due to the fact that the reconstructions of *v* depend more on the *IHV* indices, which experienced a more significant correction than on the IDV_{1d} indices. Here we do not attempt to make a detailed comparison of these reconstructions with full error analysis like *Lockwood et al.* [2014] but rather show the effect of the found inhomogeneities when estimating *B* and *v* proxies from uncorrected ESK and LER data. We note that some recent reconstructions [*Svalgaard and Cliver*, 2007; *Lockwood et al.*, 2014] use a composite *IHV* index based on data from several observatories, including Eskdalemuir and Lerwick. Obviously, the effect of inhomogeneities in ESK and LER will be alleviated but will still affect the composite *IHV* and the estimated *B* and *v*. Moreover, it is likely that similar inhomogeneities exist in the data of other observatories as well. Accordingly, most present estimates on the long-term evolution of SW and IMF properties are still pending on the (mostly unverified) homogeneity of the long-term data series. This emphasizes the data from all long-operating observatories should be checked for similar problems as discussed in this paper.

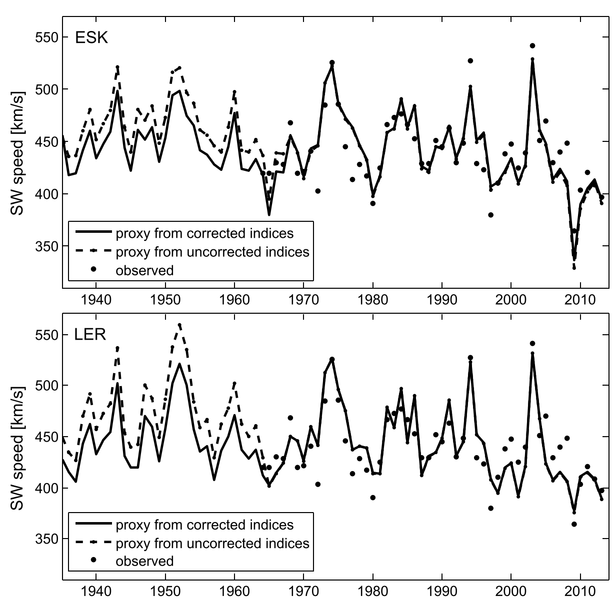

Figure 8. Annual averages of the solar wind speed reconstructed from (top) *IHV*(ESK) and IDV_{1d}(ESK) and (bottom) *IHV*(LER) and IDV_{1d}(LER). Observed annual averages are denoted by dots.

8. Conclusions

In this paper we have presented and discussed a new type of inhomogeneity in the hourly magnetic field data of Eskdalemuir and Lerwick observatories. We found that geomagnetic *IHV* and IDV_{1d} indices of Eskdalemuir and Lerwick are artificially enhanced from mid-1930s until the late 1960s compared to the respective indices of the reference station of Niemegk. Systematic differences in the ratios of the indices are detected between 1935 and

1969. The timings of the enhanced values accurately coincide with the years of instrument changes made at Eskdalemuir and Lerwick, strongly suggesting that they are indeed caused by the inhomogeneities in the Eskdalemuir and Lerwick data due to instrument changes. We find that the *IHV* (IDV_{1d}) indices of Eskdalemuir and Lerwick have an excess ($\pm$ standard error) of about 14 $\pm$ 4% (5.8 $\pm$ 2%) and 27 $\pm$ 10% (15 $\pm$ 6%), respectively, during this time. (There may be inhomogeneities also before 1934, but they were left out of this paper).

The inhomogeneities in the *IHV* and IDV_{1d} indices are large enough, e.g., to significantly affect the long-term trends of geomagnetic activity and the previous reconstructions of IMF strength or solar wind speed derived from the uncorrected data and indices [*Svalgaard and Cliver*, 2007; *Lockwood et al.*, 2013a, 2013b, 2014]. The effect of instrument changes for the analog *K* indices will be investigated in a separate study, but we note that the *K* indices of Eskdalemuir and Lerwick are also used to derive the *Kp* index, causing related inhomogeneity also in *Kp*. Finally, we note that, although only Eskdalemuir and Lerwick are studied here, it is likely that there are similar instrument inhomogeneity problems also at other observatories. In fact, all early and long-term magnetic field data should be carefully investigated and corrected for similar problems before using them in long-term studies.

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