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Secular trends in storm-level geomagnetic activity

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Abstract. Analysis is made of K-index data from groups of ground-based geomagnetic observatories in Germany, Britain, and Australia, 1868.0–2009.0, solar cycles 11–23. Methods include nonparametric measures of trends and statistical significance used by the hydrological and climatological research communities. Among the three observatory groups, German K data systematically record the highest disturbance levels, followed by the British and, then, the Australian data. Signals consistently seen in K data from all three observatory groups can be reasonably interpreted as physically meaninginful: (1) geomagnetic activity has generally increased over the past 141 years. However, the detailed secular evolution of geomagnetic activity is not well characterized by either a linear trend nor, even, a monotonic trend. Therefore, simple, phenomenological extrapolations of past trends in solar and geomagnetic activity levels are unlikely to be useful for making quantitative predictions of future trends lasting longer than a solar cycle or so. (2) The well-known tendency for magnetic storms to occur during the declining phase of a sunspot-solar cycles is clearly seen for cycles 14–23; it is not, however, clearly seen for cycles 11–13. Therefore, in addition to an increase in geomagnetic activity, the nature of solar-terrestrial interaction has also apparently changed over the past 141 years.

Keywords. Magnetospheric physics (Solar wind-magnetosphere interactions)

1 Introduction

In considering the possibility of trends in data time series, careful consideration should be given to: (1) the meaning of the word "trend". It is context-dependent. It might be defined as a general direction or tendency, or as the longest, non-periodic movement of a time series (e.g. Dagum and Dagum, 1988). And while many people might claim to recognize a trend when they see one, a more precise, but still usefully general, definition is difficult to pronounce (e.g. Preece, 1987). We are reminded of the limerick by Cairncross (1969): "A trend is a trend is a trend …". To which we would unpoetically add the hope that a graph of the data would have a visually-compelling slope. Of course, needed specificity for what is meant by "trend" can be obtained through (2) measuring and testing. These typically involve either deterministic or stochastic analysis, with limitations imposed by data quantity and quality, and the possible presence of superimposed signals. Here, the notion of significance is important, as is the timescale over which the trend is supposed to apply. And there are practical considerations, why we might be interested in a trend: its (3) utility. An estimated trend can serve as a summary property of available data. But for many applications, prediction is the goal, or to paraphrase Cairncross: does the trend bend, and come to an end? The combination of describing data collected in the past, predicting future data or, at least, predicting those that have yet to be seen, and, then, making objective comparisons is the basis of hypothesis testing. This formal approach is often conducted in laboratory settings, where experiments can be actively controlled, but it is not always so straightforward for many of the "natural" sciences, where we only observe the phenomena provided by Nature.

Magnetic-field measurements, made at ground-based observatories since the middle of the 19th century (Jankowski and Sucksdorff, 1996; Macmillan, 2007; Love, 2008), record activity and disturbance signals generated by electric currents in the ionosphere and magnetosphere. Geomagnetic activity indices, derived from observatory data, are simple, scalar-summary metrics of disturbance (e.g. Mayaud, 1980; Rangarajan, 1989). Among those that are most frequently used are the "local" K index, which measures the range of magnetic-field variation at an individual observatory over 3-h periods of time, and the "planetary" aa index, which is derived from a weighted average of K-index values from two nearly-antipodal, mid-latitude observatories,

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Table 1. Summary of the observatories for which K indices are used.

Group	Observatory	Country	Code	Geomag. lat.	CGM lat.	Data years	Present institute
PSN	Potsdam	Germany	POT	52.11°	48.32°	1890.0–1908.0	
	Seddin	Germany	SED	52.02°	48.21°	1908.0–1932.0	
	Niemegk	Germany	NGK	51.88°	47.97°	1932.0–2009.0	GeoForschungsZentrum
GAH	Greenwich	Great Britain	GRW	53.57°	47.75°	1868.0–1926.0	
	Abinger	Great Britain	ABN	53.35°	47.42°	1926.0–1957.0	
	Hartland	Great Britain	HAD	53.90°	47.48°	1957.0–2009.0	British Geological Survey
MTC	Melbourne	Australia	MEL	−45.74°	−48.68°	1868.0–1920.0	
	Toolangi	Australia	TOO	−45.38°	−48.30°	1920.0–1980.0	
	Canberra	Australia	CNB	−42.71°	−45.39°	1980.0–2009.0	Geoscience Australia

one in Britain and one in Australia. The *aa* index is the longest-running, standard, geomagnetic-activity time series available. It records several signals, including solar-cycle modulation of geomagnetic activity and an apparent long-term trend of increasing geomagnetic activity. Both of these signals are of numerous and far-reaching consequence for (1) magnetic-storm occurrence statistics and time-series analysis (Delouis and Mayaud, 1975; Clilverd et al., 1998; Echer et al., 2004), (2) space-weather hazards (Oler, 2004; Welling, 2010), (3) solar-terrestrial interaction (Schatten and Wilcox, 1967; Feynman and Crooker, 1978; Lockwood et al., 1999), (4) solar activity and space-weather prediction (Feynman and Gu, 1986; Rangarajan and Barreto, 1999; Hathaway, 2010), (5) terrestrial climate change (Bucha and Bucha, 1998; Friis-Christensen, 2000; Courtillot et al., 2007), (6) atmospheric ozone depletion (Laštovička et al., 1992), and (7) cosmic rays and atmospheric radionuclide production (Stuiver and Quay, 1980; McCracken, 2004).

But the fidelity of the *aa* time series has been the subject of a debate played out in the scientific literature. Its source K-index values can be artificially affected in a number of ways. (1) Localized magnetotelluric signals, which are different from site to site, would factor in observatory relocations (Mayaud, 1973). (2) Changes in observatory instrumentation and accuracy from one analog system to another (Clilverd et al., 2002) and from analog systems to digital systems. (3) Normalization factors needed to accommodate different observatory magnetic latitudes (Clilverd et al., 1998). (4) Changes of convention in the magnetic-vector components used to estimate K values. (5) Changes in K-estimation methods, especially from hand-scaling of analog magnetograms to computer-algorithm estimation using digital data. While various authors (e.g. Clilverd et al., 2005; Lukianova et al., 2009) have concluded that none of these factors significantly affect the long-term trend of increasing geomagnetic activity seen in the *aa* time series, Svalgaard et al. (2004) assert that the *aa* index needs substantial recalibration, and that if this were properly done, any trend of increasing activity would be substantially reduced, possibly so much that it would be of little or no long-term significance. If this were true, then it might also affect interpretations of the relationship between solar activity and geomagnetic activity, since it is clear that sunspot number has exhibited secular change since the middle of the 19th century. Lingering concerns have motivated the introduction of several new global, geomagnetic-activity indices (Mursula and Martini, 2007; Svalgaard and Cliver, 2007; Finch et al., 2008).

With a goal of obtaining an improved understanding of how to measure and how to interpret secular change in geomagnetic activity, here, we focus our attention on the source K indices from Britain and Australia that have been used to calculate *aa* values, and, for comparison, we also examine K indices from Germany that, in some respects, are the international standard. In contrast to the methods used to calculate *aa*, and, indeed, in contrast to many of the methods used to analyze *aa*, we do not adjust the K values in any way. We analyze the K-value data as they were originally reported using standard statistical and time series methods, some of which are used for trend estimation in the hydrology and climatology research communities. Comparison of K values from different observatory groups reveals some significant and, in some respects, unfortunate inconsistencies and biases. They also reveal some prominent and important consistencies and patterns. The latter can help us confidently answer the question of whether or not geomagnetic activity exhibits a long-term increasing trend and, also, change in its phase relationship with sunspot number.

2 Data

2.1 K-index values

The K index was developed by (Bartels et al., 1939, p. 411) to be a "record of the terrestrial effects of solar corpuscular radiation by measuring the intensity of the geomagnetic activity caused by the electric currents produced around the Earth by that radiation". The index is a empirical measure

Table 2. Summary of magnetic-activity ranges associated with each K-index value for each observatory.

K	0	1	2	3	4	5	6	7	8	9	
PSN, GAH, MEL, TOO	0–5	5–10	10–20	20–40	40–70	70–120	120–200	200–330	330–500	500–∞	(nT)
CNB	0–4.5	4.5–9	9–18	18–36	36–63	63–108	108–180	180–297	297–450	450–∞	(nT)

of the range of irregular geomagnetic fluctuations recorded at a magnetic observatory, after solar and lunar quiet-time daily variation and slow variation associated with magnetic-storm recovery have been subtracted (Bartels et al., 1939, p. 412). K values are "ordinal": they are ranked, dimensionless integers, ranging from 0 for the quietest magnetic conditions, through to 5 for what are usually considered to be mild magnetic-storm levels (www.swpc.noaa.gov/NOAAscales), up to 9 for the most disturbed conditions, all according to a scale that is approximately the logarithm of the absolute range of magnetic-field variation measured over 3-h intervals of time at Niemegk. After its introduction, the K index was calculated retrospectively from historical analog magnetograms from several observatories, extending the K time series backwards in time to the 19th century.

To facilitate inter-comparison of magnetic-field variation from observatories at different locations, especially across a range of latitudes, the long-term statistical distributions of K values collected at a particular observatory are supposed to be normalized so that they are like that realized at Niemegk (Bartels et al., 1940, pp. 334-335). But this is not what has actually been done. Instead, K values are derived from a scale developed by Mayaud (1968): a lower-limit for $K = 9$ is assigned according to a phenomenologically-derived formula relating an observatory's corrected-geomagnetic latitude (CGM) to an expected probability for a high-activity range of magnetic-field variation as measured in nT, see Table 2. Since this scaling is not, itself, derived from any physics-based theory, it is an arbitrary quantization, and, as a result, K-index distributions from different observatories will, inevitably, be different from each other.

In this study, we use K indices from the nine magnetic observatories listed in Table 1: three groups of three observatories from Germany PSN, Great Britain GAH, and Australia MTC that are situated at approximately the same corrected-geomagnetic latitudes. The observatories in each group have operated in series; with the closure of one observatory another one was opened at a nearby site in order to maintain continuity. Together, these K-index time series are among the longest available for studies of secular change in geomagnetic activity. We obtained the German K values, 1890.0–2009.0, from H.-J. Linthe (personal communication, 2010), GeoForschungsZentrum, the British K values, 1868.0–2009.0, from the British Geological Survey website (www.geomag.bgs.ac.uk), the Australian CNB K values, 1980.0–2009.0, from the Geoscience Australia website (www.ga.gov.au/geomag/), and the Australian MEL and TOO values, 1868.0-1980.0, values from P. G. Crosthwaite (personal communication, 2010), Geoscience Australia, who, in turn, obtained them from M. Menvielle.

2.2 Sunspot numbers

For comparison of geomagnetic-storm occurrence with solar activity, we use sunspot numbers G: for 1868.0–1995.0, solar cycles 11–22, we use group numbers (Hoyt and Schatten, 1998) obtained from NOAA's National Geophysical Data Center (NGDC) website (www.ngdc.noaa.gov), for 1996.0–2009.0, solar cycle 23, we use international numbers Z obtained from the website of the Royal Observatory, Belgium (www.sidc.be). We note that G is more simply defined than Z, that G is based on more source observations than Z, and that G is generally considered to be an improvement over Z (e.g. Hathaway et al., 2002; Kane, 2002). For 1890.0–1995.0, solar cycles 13–22, G and Z are very consistent, but earlier on there are some significant discrepancies (see Hoyt and Schatten, 1998, Fig. 8). This is due, in part, to Wolf's (1875) practice of adjusting his estimates of sunspot number according to an expectation that they would be correlated in time with ground magnetometer data, which were abailable to Wolf and his colleagues (Hoyt and Schatten, 1998, p. 497). While this might be considered acceptable for some types of research work (e.g. Svalgaard, 2007), such as repair of defective data or filling in gaps, for our work, where we choose to examine and test the correlation between sunspot number and geomagnetic activity, Wolf's adjustments are not acceptable. Correlations between data sets that have not independently acquired are not particularly meaningful (see, also, Mursula et al., 2009). For all of these reasons we prefer to use G rather than Z. In our discussion of results, we define the beginning and the end times of each solar cycle, rounded the the nearest year, according to sunspot-number minimum.

3 K occurrence time series

In Fig. 1b–d we show the time dependence of annual exceedances $e_7(t_j)$ and $e_5(t_j)$, the number of times for each year t_j, respectively, that $K \geq 7$ and $K \geq 5$, and attainments $a_1(t_j)$, the number of times for each year that $K \leq 1$, for the German PSN observatories, since 1890.0, and the British GAH and Australian MTC observatories, both since 1868.0. For comparison, in Fig. 1a we also show annual averages of sunspot numbers G. We will discuss the fitted linear trend in Sect. 4. For now, we simply call attention to the secular

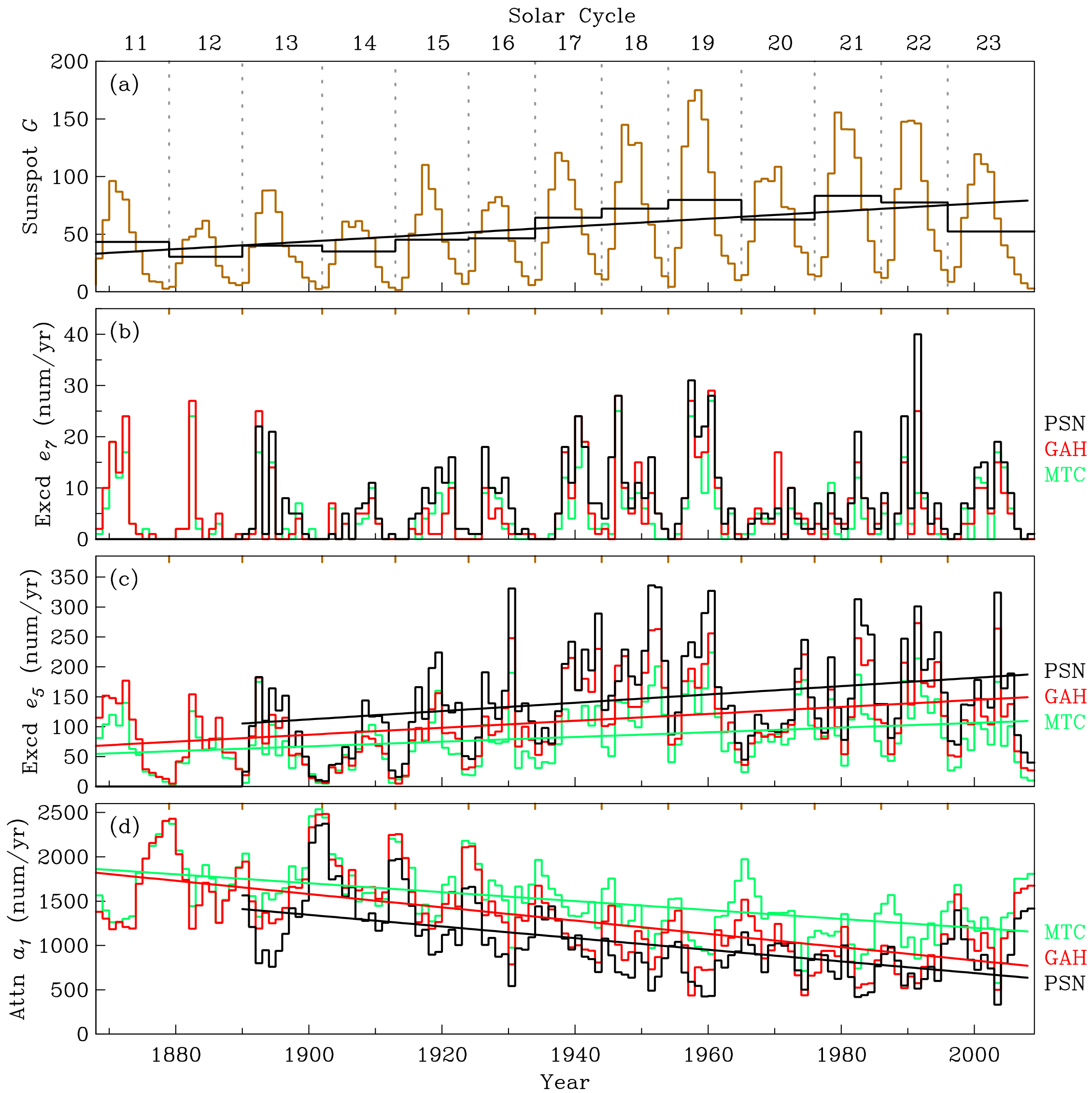

Fig. 1. Time series of **(a)** annual means of sunspot numbers G, and for German PSN, British GAH, and Australian MTC observatory groups: **(b)** annual exceedance count rates e_7, **(c)** annual exceedance count rates e_5, and **(d)** annual attainment count rates a_1. Straight-lines are fitted to solar-cycle averaged data; example histograms shown in **(a)**, but for clarity omitted from **(c)** and **(d)**. Compare with Fig. 4.

change in sunspot number and geomagnetic activity that is apparent over the 141-year duration of the G and K time series. We can quantify this by comparing, for example, the cumulative $\sum_j e_5(t_j)$ of exceedance counts from 2 separate periods of time, each encompassing 5 solar cycles: for solar cycles 13–17, 1890.0–1944.0, the cumulative exceedances are PSN: 6337, GAH: 4667, and MTC: 3553, while later on, for cycles 19–23, 1954.0–2009.0, they are 8719, 6946, and 5310; increases of 37, 48, and 49%. The cumulative e_7 exceedance counts are, of course, smaller than those for e_5 – some years do not have any e_7 occurrences – but the e_7 do show a long-term increase; see Fig. 1b. With respect to low-activity attainment statistics, for solar cycles 13–17, cumulative a_1 attainments are PSN: 69 371, GAH: 83 476, and MTC: 91 392, while later on, for cycles 19–23, they are 45 174, 53 137, and 69 906; decreases of 53, 57, and 30%. From Fig. 1d, we note that many of the maxima of a_1 for cycles 19–23 are less than the minima of a_1 for cycles 13–17. Generally speaking, when geomagnetic activity has increased, geomagnetic quiescence has decreased. For the same two periods, each of 5 solar cycles, the cumulative sunspot numbers G increase from 2290 to 3950, or 73%. This is perhaps the simplest definition we can have of an increasing “trend” in geomagnetic activity (sunspot numbers): the second halves of K-index (sunspot numbers) time series show higher levels of activity (numbers) than the first halves.

Although each of the three independently-acquired PSN, GAH, and MTC K-value data sets show a long-term, secular increase in geomagnetic activity, systematic differences are also noteworthy. Briefly, the statistical distributions of K indices are different from one observatory to another. Many factors can contribute to this, some of which are natural and others of which are certainly artificial. In some respects, this is unfortunate, since this is not what Bartels intended when he designed the K index. Still, consistent signals can be seen in K time series from different observatories, and these can reasonably be interpreted in terms of global, geophysical phenomena.

Focussing on these consistencies, year-to-year cross-correlation is clearly seen between the quantities shown in Fig. 1. This can be quantified in terms of the Pearson correlation coefficient r and probability p that the correlation could be realized from random data (Press et al., 1992, "pearsn"). As examples, Pearson coefficients r between observatory pairs of exceedances e_5 are PSN-GAH: 0.97, GAH-MTC: 0.95, and MTC-PSN: 0.93, where, in each case, $p < 10^{-51}$. These observations are not surprising – magnetic disturbance measured by K indices is usually a global phenomenon, so correlation is expected to be "significant". With respect to cross-correlations between sunspot numbers G and e_5, the Pearson coefficients r are PSN: 0.44, GAH: 0.47, and MTC: 0.57, where, in each case, $p < 10^{-7}$. Geomagnetic activity is driven by solar activity, but it is also well-known that peak magnetic activity lags, by a year or two, sunspot maximum. We will explore this relationship in more detail in Sect. 7. For now, we simply emphasize the apparent long-term correlation that is seen between three independently-acquired K time series and sunspot number. This observation can be compared with others based on the aa index (e.g. Legrand and Simon, 1989, Fig. 1; Clilverd et al., 1998, Fig. 2; Ouattara et al., 2009, Fig. 2).

4 Linear trends in *K*

The straightforward observation, taken from Fig. 1, that there is a trend of increasing geomagnetic disturbance over the past 141 years, motivates the testing of straight-line functional fits to K-index counts. Such fits can serve as estimates of "linear trend" (e.g. Woodward and Gray, 1993; Cohn and Lins, 2005), and they have been used in studies of secular change in geomagnetic activity (e.g. Feynman and Crooker, 1978; Lockwood et al., 1999; Mursula and Martini, 2006). To legitmately accomplish such fits, one must first either remove, as much as is practically possible, serial correlation in the data time series, by, for example, "pre-whitening" or "pruning" the data (e.g. von Storch, 1995, Sect. 2.3), or, alternatively, by using a fitting algorithm that explicitly accommodates serial correlation (e.g. Weatherhead et al., 1998). Year-to-year serial correlation is, of course, especially strong within each solar cycle. We choose to remove it by simply averaging sunspot numbers G, exceedances e_5, and attainments a_1 within each of the N_S solar cycle. For the German PSN observatories this leaves us with 11 data, one for each solar cycle from 1890.0–2009.0, and for the British GAH and Australian MTC observatories it leaves us with 13 data covering 1868.0–2009.0. A straight line, "linear trend" is then fitted to the solar-cycle averaged data using an ordinary least-squares algorithm (Press et al., 1992, "fit"), which minimizes the sum of squared residual differences[1]; fits are shown in Fig. 1.

The fits of linear trends highlight some observations we have already made, namely, that the amount of geomagnetic disturbance has generally increased over the past 141 years. That linear trends can be resolved means that it is necessary that a regressive model be time-dependent. Fitted linear trends are not, however, necessarily sufficient descriptions of the data. One way of checking the adequacy of the linear fits is to measure their Pearson coefficients r with the data; for the exceedances e_5 they are PSN: 0.54, GAH: 0.62, and MTC: 0.64, where, in each case, $p < 10^{-1}$. While these modest correlations are not likely to be accidental, they do invite scrutiny. From inspection of the residuals in Fig. 1, it is not hard to see that secular variation seen in the e_5 and a_1 could be better fitted by a smooth curve instead of a straight line. With respect to the fitted linear trend for sunspot numbers G, the Pearson coefficient r is 0.76, where $p < 10^{-2}$. Here, as well, a smooth curve might provide a better fit (see, for example, Kishcha et al., 1999, Fig. 11; Svalgaard and Cliver, 2007, Figs. 6 and 7), but solar-terrestrial theory is insufficiently developed to provide a specific predictive parameterization for secular change in sunspot numbers and corresponding geomagnetic activity.

The long-term persistence of linear trends can be explicitly checked by fitting subset durations of the available data (see related discussions in Percival and Rothrock, 2005; Koutsoyiannis, 2006). In Fig. 2 we show linear fits to different durations of the British GAH exceedance data e_5 and an example of fits to subset durations of the sunspot data. While fits to data across all 13 solar cycles seem to show a linear trend of increasing geomagnetic disturbance, fits to shorter durations, such as for 6, 4, 3, or 2 cycles, do not consistently show persistence. Indeed, Figs. 1 and 2 show that the time-dependence of past geomagnetic activity has been complicated. Clearly, our observation of a long-term linear trend of increased geomagnetic disturbance is due, in part, to the time span we have considered, the span of the available geomagnetic K time series, 13 solar cycles. This is a simple, but important, observation that has been made by others (e.g. Richardson et al., 2002, Fig. 1; Mursula et al., 2004, Fig. 3). If we had chosen to analyze the time span of (say) the past 6 solar cycles, we would, instead, be discussing a decreasing trend in geomagnetic disturbance!

[1]The linear trends we report here, estimated by an least-squares algorithm, are nearly the same as those that can be obtained with an algorithm the minimizes the sum of absolute residuals.

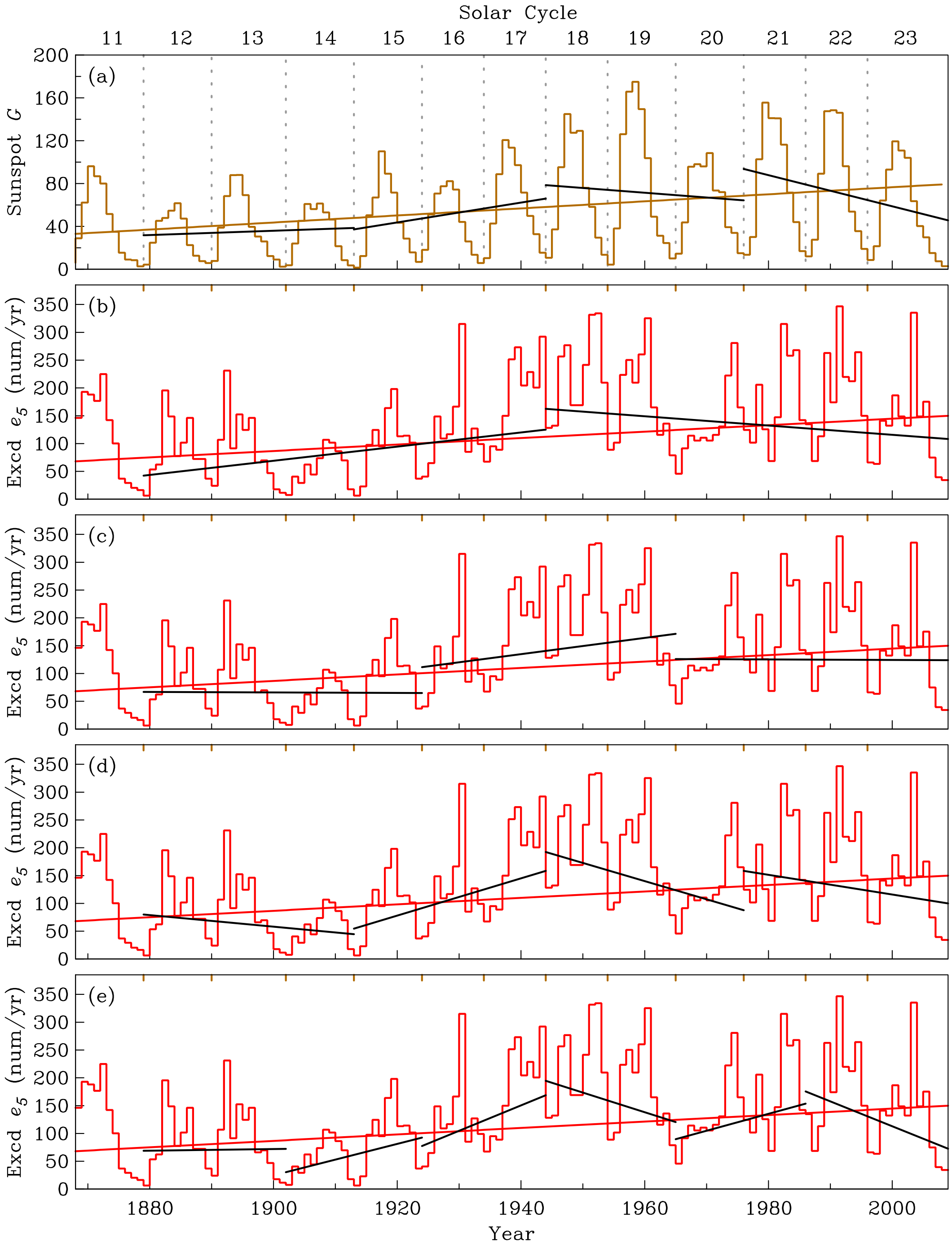

Fig. 2. Comparisons of straight-line fits to sunspot numbers G using 13 solar cycles of data and **(a)** 3-solar-cycle subset durations of the data. Similarly, comparisons of straight-line fits to exceedances e_5 from British GAH observatories using 13 solar cycles of data and **(b)** 6, **(c)** 4, **(d)** 3, and **(e)** 2-solar-cycle subset durations of the data.

The slopes of the linear fits shown in Fig. 1 for the annual exceedances e_5 are PSN: 0.69, GAH: 0.58, and MTC: 0.39 number/yr/century; annual attainments a_1 are PSN: −656.84, GAH: −749.17, and MTC: −503.23 number/yr/century. Thus, the observatory group with the most rapidly increasing rate of disturbance, as measured by e_5, German PSN, is not the observatory group with the most rapidly decreasing rate of quiescence, as measured by a_1, British GAH. Some of this might simply be related to differences in K scaling from one observatory group to another.

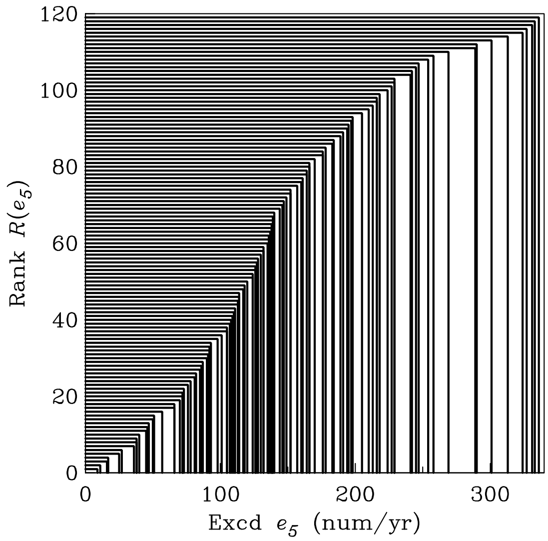

Fig. 3. Schematic representation of the mapping between the ordered set of German PSN K-exceedance count rates e_5 and their ranks $R_j(e_5)$.

It might also be evidence that secular change in geomagnetic activity is a function of geographic location, as found, for example, by Mursula and Martini (2006, Table 3) in their analyses of observatory, hourly-vector data spanning the 20th century.

5 Ranks of *K* over time

Given that the distributions of K values are different for each observatory group, a nonparametric inter-comparison is appropriate (e.g. Ferguson, 1965). For this, we rank the data. For N_Y exceedances e_5, one for each year $j = 1, 2, 3 \cdots N_Y$, the largest has the highest rank and is assigned the number N_Y, the next largest is assigned the number $N_Y - 1$, etc. We represent the operation of assigning ranks to the exceedance data by the mapping $e_5(t_j) \rightarrow R_j(e_5)$; see Fig. 3. Similar rankings are be made for the exceedances e_7, attainments a_1, and sunspot numbers G. By plotting ranks in place of the data themselves, Fig. 4, K-exceedance counts are now neatly normalized, year-to-year correlation is very clear, despite the different K-occurrence rates at each observatory; compare with the dimensional results shown in Fig. 1.

Data ranking can also be used to confirm the relative increase in geomagnetic disturbance that has occurred over the past 141 years. In Table 3 we list the 10 years from 1868.0–2009.0 with the highest (lowest) levels of geomagnetic activity, as measured by ranks of e_7 and e_5 (a_1) from British GAH and Australian MTC observatories; we also list the 10 years with the highest (lowest) sunspot numbers G. With very few exceptions, which we highlight in Table 3, the most (least) active years measured in terms of e_5 (a_1) tend to occur in the second (first) half of the time series, after (before) 1938.0. The situation is slightly less clear-cut for e_7, which might be real or might be an artifact of relatively small occurrence numbers. These observations are consistent with those made in Sect. 3, and they can be compared with others based on the *aa* index (Stamper et al., 1999, amplitude-normalized results in Figs. 2 and 3; Clilverd et al., 2005, theshold results in Fig. 3). In more detail, we note that the most active years for e_5 are not necessarily those for e_7.

Year-to-year cross-correlation of ranked time-series values can be quantified in terms of the Kendall correlation coefficient τ and probability p that the correlation could be realized from random data (Press et al., 1992, "kendl1"). The Kendall coefficients τ between observatory pairs of ranked exceedances are PSN-GAH: 0.86, GAH-MTC: 0.81, and MTC-PSN: 0.77, where, in each case, $p < 10^{-34}$. With respect to cross-correlations between ranks of sunspot numbers G and e_5, the Kendall coefficients τ are PSN: 0.36, GAH: 0.39, and MTC: 0.47, where, in each case, $p < 10^{-9}$. We note that the Kendall coefficients are lower than the Pearson coefficients, an indication of the lower information content of data ranks as compared to the dimensional data themselves. Still, the correlations of ranks appear to be "significant".

6 Monotonic trends in *K*

More general than a linear trend is a monotonic trend, by which we mean a persistent increase (or decrease) over a certain duration of time, but where the functional form is, otherwise, unspecified. Statistical analysis of monotonic trends can be made using Kendall's nonparametric approach. Instead of analyzing the correlation between a dimensionalized data time series and a linear fit to those data, as we did in Sect. 4, we analyze the correlation between the ranked time series and an arbitrary monotonically increasing trend represented by a perfectly ordered increasing linear progression, such as the positive integers $1, 2, 3, \cdots N_S$, one for each of the N_S solar cycles. With this, nonparametric Kendall statistics reduce to Mann-Kendall statistics, often used for measuring the significance of trends in the hydrological sciences (e.g. Helsel and Hirsch, 1992; Hipel and McLeod, 1994) and in the climatological sciences (e.g. Luterbacher et al., 2004). For the exceedances e_5, the Mann-Kendall coefficients τ are PSN: 0.45, GAH: 0.46, and MTC: 0.49, where, in each case, $p < 10^{-1}$, indicating, again, that a secular trend of increasing geomagnetic activity, linear or otherwise, is modestly significant. With respect to sunspot numbers G, the Mann-Kendall coefficient τ is 0.61, where $p < 10^{-2}$. As we suggested in Sect. 4, better descriptions of the data are available, especially if strict monotonicity is not expected.

Since the exceedances e_5 from each observatory group seem to record a long-term trend of increasing geomagnetic activity, one might wonder whether or not their consistency could be used to reinforce the confidence we have that

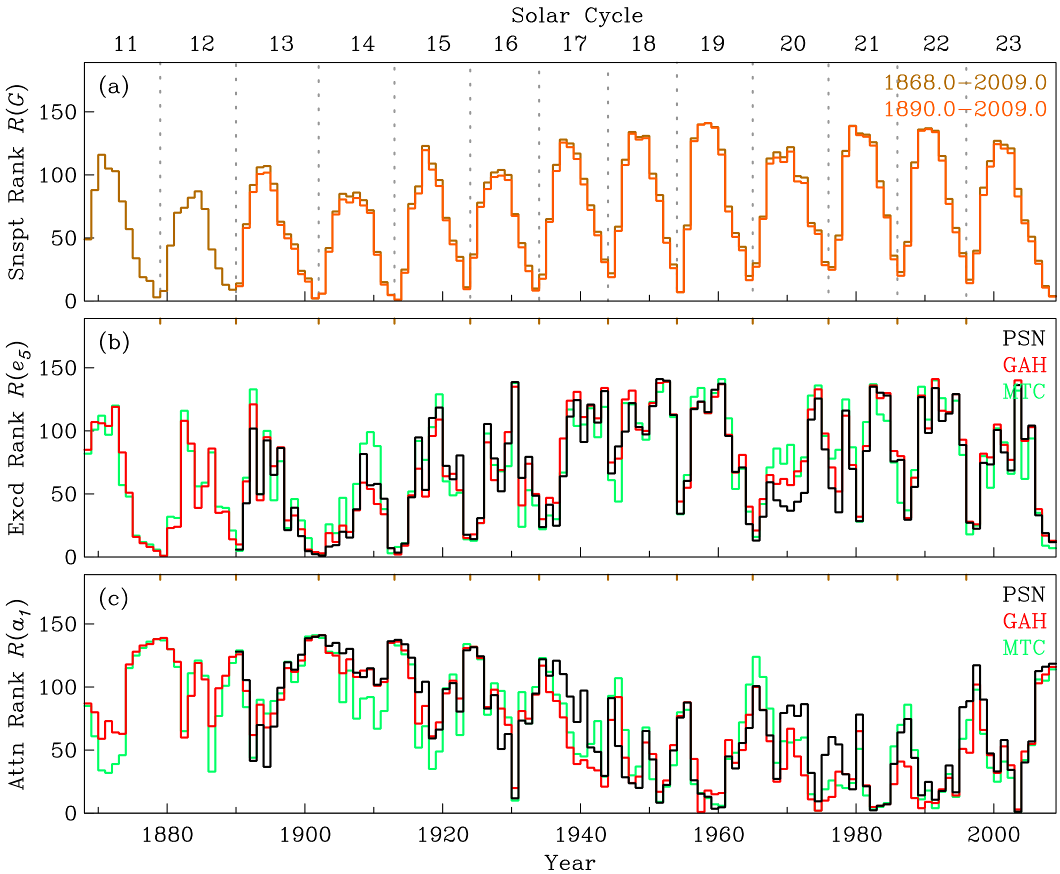

Fig. 4. Time series of ranks of **(a)** annual means of sunspot numbers G for two durations of time: 1868.0–2009.0 and 1890.0–2009.0, and for German PSN, British GAH, and Australian MTC observatory groups: **(b)** annual exceedances $R(e_5)$, and **(c)** annual attainments $R(a_1)$. In **(a)**–**(c)** the ranks of the German PSN data have been adjusted to account for their shorter duration. Compare with Fig. 1.

Table 3. The years with the greatest (least) activity as measured by average sunspot numbers G, and highest (lowest) K-index exceedances e_7 and e_5 (attainment a_1) for British GAH and Australian MTC observatories. Ranks are relative to the 141 years of 1868.0–2009.0. Active (Quiet) years before (after) 1938.0 are shown in bold font.

Rank	Active years					Quiet years		
R	G	GAH e_7	MTC e_7	GAH e_5	MTC e_5	G	GAH a_1	MTC a_1
141	1957	1960	1960	1991	1960	1913	1902	1901
140	1958	1946	1946	2003	1991	1901	1901	1900
139	1959	1957	**1882**	1952	1952	**2008**	1879	1902
138	1989	**1882**	1957	1951	**1930**	1878	1878	1878
137	1979	1991	**1870**	1960	1982	1912	1900	1879
136	1980	**1892**	1941	1982	1974	**1954**	1913	1877
135	1947	**1872**	2003	**1930**	1989	1902	1912	1912
134	1991	1940	**1892**	1943	1957	1933	1877	1923
133	1990	1941	**1872**	1974	**1892**	1911	1876	1913
132	1956	**1870**	1958	1947	2003	1923	1924	1925

global-scale, geomagnetic activity has an increasing trend. In particular, with Mann-Kendall significance probabilities $p < 10^{-1}$ for each observatory, would not their joint significance be less than $10^{-1} \times 10^{-1} \times 10^{-1}$, or a small and extremely definitive 10^{-3}? The answer is "no" because K values from Germany, Britain, and Australia, while independently acquired from different locations, measure essentially the same global-scale, geomagnetic activity. They are not

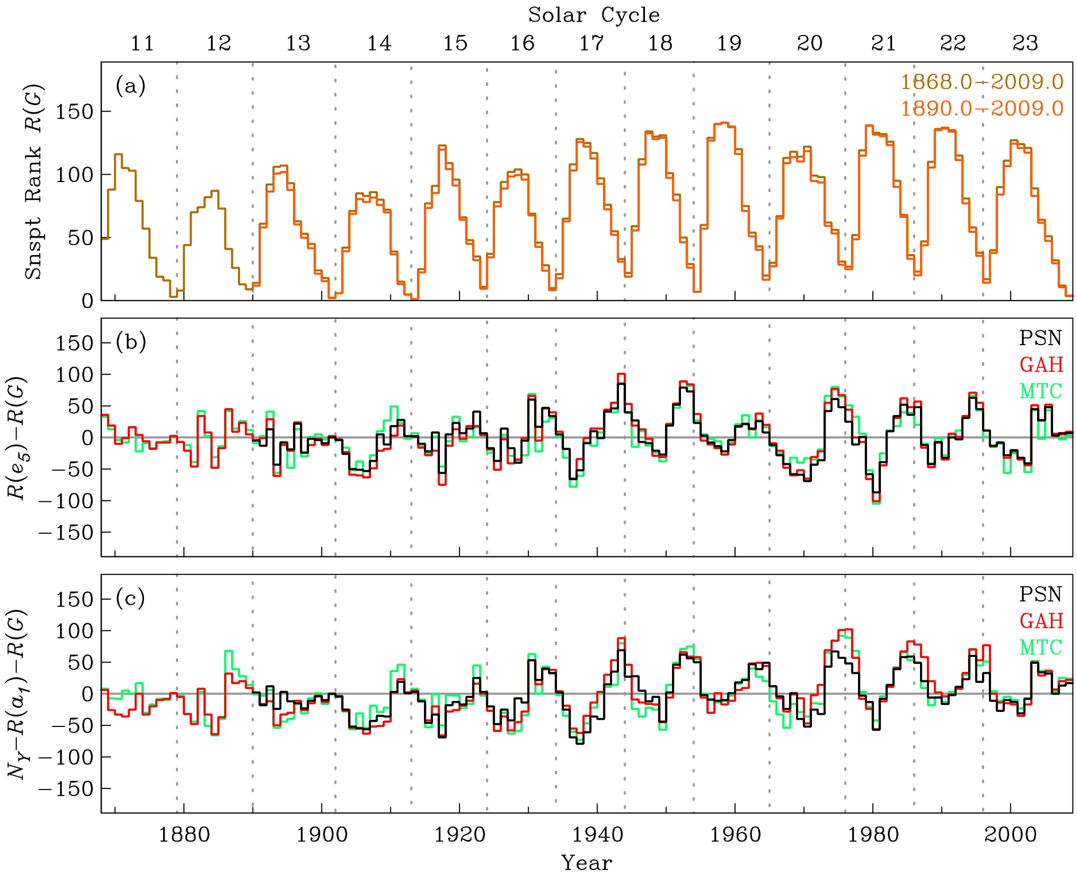

Fig. 5. Time series of ranks of **(a)** annual means of sunspot numbers G for two durations of time: 1868.0–2009.0 and 1890.0–2009.0, **(b)** annual residuals $R(e_5)-R(G)$, and **(c)** the differences $N_Y - R(e_5) - R(a_1)$, for German PSN, British GAH, and Australian MTC observatory groups. In **(a)–(c)** the ranks of the German PSN data have been adjusted to account for their shorter duration.

statistically independent. And, indeed, as we have documented in Sect. 3, PSN, GAH, and MTC K values are rather tightly cross-correlated. As a result, it is likely that their joint significance probability is not much smaller than 10^{-1}; an estimate can be obtained through a detailed bootstrap analysis (not pursued). The situation, here, is analogous to that encountered in hydrology, where multiple rivers in a continental region are monitored for flow-rate trends in order to estimate regional, climatological change (e.g. Lettenmaier et al., 1994). The redundant information in the three K time series considered here provides qualitative reassurance that their secular change has geophysical meaning. While this is important, it is also difficult to quantify with simple rank statistics.

7 Secular change and the Sun

We consider, now and in more detail, the temporal relationship between solar and geomagnetic activity. The Kendall coefficients τ, measuring cross-correlation between ranks of solar-cycle-average exceedances e_5 and sunspot numbers G, are PSN: 0.67, GAH: 0.74, and MTC: 0.77, where, in each case, $p < 10^{-2}$. These coefficients are higher than the Pearson coefficients measuring linear trends, Sect. 4, and higher than the Mann-Kendall coefficients measuring monotonic trends, Sect. 6, and so, as an hypothesis test, we might reasonably reject simple trend parameterizations in favor of a sunspot-number parameterization. This does not contradict our observation that geomagnetic disturbance has shown an increase over the past 141 years. It just means that geomagnetic activity has changed over time in a way that is neither particularly linear nor particularly monotonic. Like the solar activity that drives it, geomagnetic activity has had a complex evolution.

Details of this evolution are important. In Fig. 5b we plot, for each observatory group, residual differences between ranks of exceedances and sunspot numbers $R(e_5) - R(G)$, and in Fig. 5c we plot residual differences between ranks of complementary attainmeents and sunspot numbers $N_Y - R(a_1) - R(G)$. Clearly seen is the well-known lag of a year or so in geomagnetic disturbance relative to sunspot number (Bartels, 1963; Rangarajan and Iyemori, 1997), caused by co-rotating interactive regions in the solar wind that are

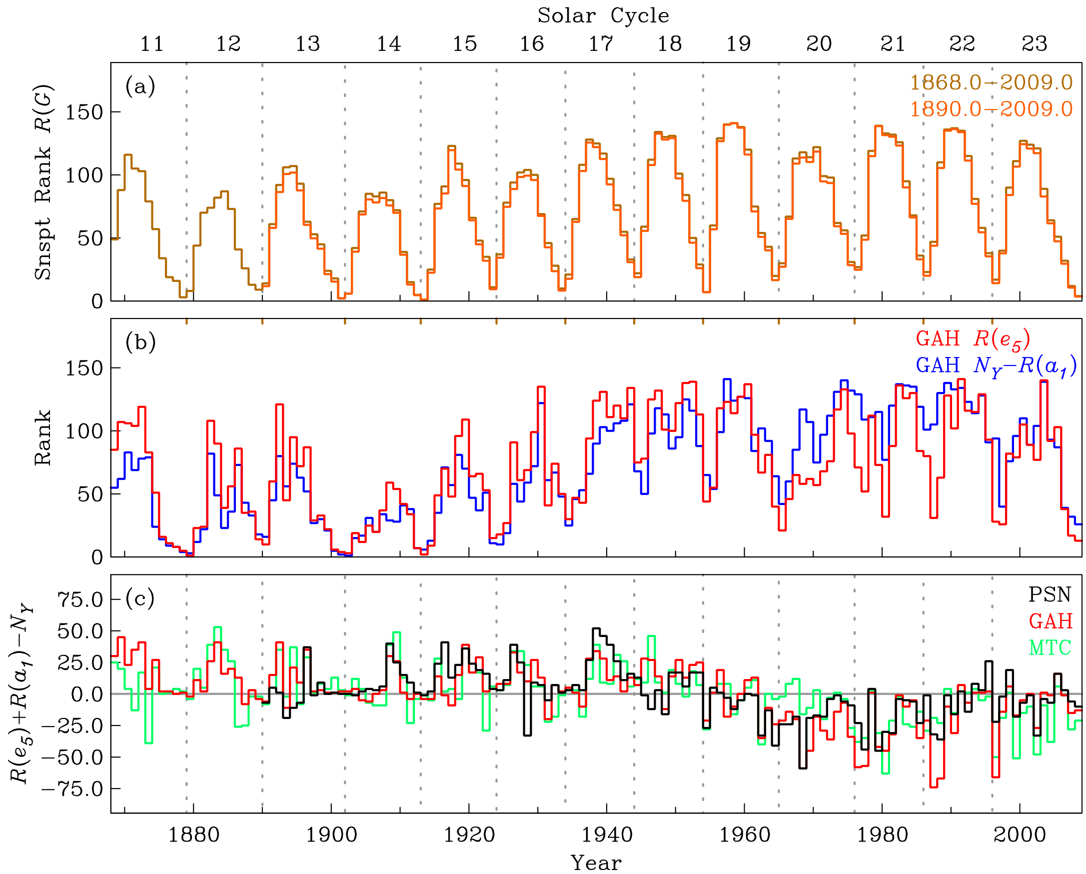

Fig. 6. Time series of ranks of **(a)** annual means of sunspot numbers G for two durations of time: 1868.0–2009.0 and 1890.0–2009.0, **(b)** annual exceedances $R(e_5)$ and the complements of annual attainments $N_Y - R(a_1)$, for the British GAH observatory group, and **(c)** the differences $R(e_5)+R(a_1)-N_Y$, for German PSN, British GAH, and Australian MTC observatory groups. In **(a)–(c)** the ranks of the German PSN data have been adjusted to account for their shorter duration.

geoeffective during the declining phase of the solar cycle, just after solar maximum (e.g. Legrand and Simon, 1989; Richardson et al., 2002b). But also seen, here, is the emergence of this lag after cycle 13 (Bartels, 1932, Sect. 14; Kishcha et al., 1999, Fig. 9; Echer et al., 2004, Fig. 2), an interesting observation that is not, perhaps, as widely appreciated as it should be. It demonstrates that the relationship between sunspot number and geomagnetic activity has changed over time. This should be regarded as cause for caution in making linear extrapolations of parameterizations of recent solar-terrestrial interaction, either forward or backward in time.

Over the past 141 years, the shapes of the K-index distributions for all three observatory groups have changed. As an example of this, in Fig. 6b we compare ranks of British GAH exceedances $R(e_5)$ and the corresponding ranks of complementary attainments $N_Y - R(a_1)$. Although there is substantial correlation between these two time series, as would be expected, close inspection also shows that before (after) 1954, or the start of solar cycle 19, the $N_Y - R(a_1)$ are systematically lower (higher) than $R(e_5)$, an observation that is consistent with those based on the aa index (e.g. Legrand and Simon, 1989, Fig. 6; and Ouattara et al., 2009, Fig. 4). In Fig. 6c, we plot the differences between the two time series shown in Fig. 6b, but for all three observatory groups, $R(e_5) + R(a_1) - N_Y$. After averaging over each solar cycle, the Mann-Kendall coefficients τ indicate the presence of a long-term trend, PSN: 0.42, GAH: 0.49, and MTC: 0.43, where, in each case, $p < 10^{-1}$. In the evolution of geomagnetic activity, the quiescent attainments a_1 have been diminishing faster than magnetic activity e_5 has been increasing. This conclusion should be compared with those of Feynman and Crooker (1978) and Vennerstroem (2000), who, in analyses of the aa time series, suggested that the long-term increase in geomagnetic activity has as much to do with an increase in the activity during periods of relative quiescence as it has to do with an increase in the occurrence of magnetic storms.

8 Conclusions

While we can conclude that geomagnetic activity has increased, as a "trend", over the past 141 years, the detailed evolution of geomagnetic activity since 1868.0 is not well-described as being approximately linear, nor, even, monotonic. Since geomagnetic activity is controlled by the Sun and its solar wind, a physics-based parameterization of the evolution geomagnetic activity should be tied to heliophysical parameters. Over the past 141 years, the only directly-measured heliophysical parameter available is sunspot number, and this too has shown secular change. Given these observations, and the understanding that solar-terrestrial interaction is generally "non-linear", it is, perhaps, not surprising that the relationship between sunspot number and geomagnetic activity has evolved; since solar cycle 14, geomagnetic activity has lagged behind sunspot number by a year or two, but before then the phase-lag was not very pronounced. Apparently, the nature of solar-terrestrial interaction has changed over time. Therefore, predicting the long-term future of geomagnetic activity is bound to remain difficult if not impossible.

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