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Long-term biases in geomagnetic *K* and *aa* indices

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Abstract. Analysis is made of the geomagnetic-activity *aa* index and its source *K*-index data from groups of ground-based observatories in Britain, and Australia, 1868.0–2009.0, solar cycles 11–23. The *K* data show persistent biases, especially for high (low) *K*-activity levels at British (Australian) observatories. From examination of multiple subsets of the *K* data we infer that the biases are not predominantly the result of changes in observatory location, localized induced magnetotelluric currents, changes in magnetometer technology, or the modernization of *K*-value estimation methods. Instead, the biases appear to be artifacts of the latitude-dependent scaling used to assign *K* values to particular local levels of geomagnetic activity. The biases are not effectively removed by weighting factors used to estimate *aa*. We show that long-term averages of the *aa* index, such as annual averages, are dominated by medium-level geomagnetic activity levels having *K* values of 3 and 4.

Keywords. Magnetospheric physics (General or miscellaneous; Instruments and techniques)

1 Introduction

The *K* and *aa* indices (e.g. Mayaud, 1980; Rangarajan, 1989) are widely used summary metrics of geomagnetic-field activity derived from data acquired at ground-based observatories. The "local" *K* index measures the maximum variational range of magnetic disturbance over 3-h durations of time as recorded at individual, mid-latitude, sub-auroral observatories (Bartels et al., 1939). The *aa* index is a "planetary" or "global" index (Mayaud, 1972), derived from *K* values collected from a pair of observatories, one in the Northern Hemisphere (Britain) and one in the Southern Hemisphere (Australia). Together with the source *K* indices, *aa* provides a record of geomagnetic activity from 1868.0 to the present. The *aa* index has been widely used in the analysis of a number of inter-related issues, including: (1) magnetic-storm occurrence statistics and time-series analysis (Courtillot et al., 1977; Gonzalez et al., 1990; Willis et al., 1997), (2) space-weather hazards (Boteler et al., 1998; Thomson et al., 2010), (3) solar-terrestrial interaction (Russell, 1975; Legrand and Simon, 1989; Pulkkinen et al., 2001; Lockwood, 2005), (4) solar activity and its prediction (Thompson, 1993; Hathaway et al., 1999; Fröhlich and Lean, 2004), (5) terrestrial climate change (Cliver et al., 1998; Friis-Christensen, 2001; Le Mouël et al., 2005), (6) atmospheric ozone depletion (Jarvis, 2005), and (7) cosmic rays and atmospheric radionuclide production (Stuiver and Quay, 1980; Beer et al., 1990).

These are subjects of far-reaching consequence, and some of them are controversial. Therefore, it is perhaps not surprising that the fidelities of the *K* and *aa* geomagnetic indices have been discussed and debated in the scientific literature. Joselyn (1970) has described the original process of measuring analog magnetograms for *K*-index estimation as being "subjective". Lanzerotti and Surkan (1974) have noted that the *K*-index time series does not have a well-defined frequency content, especially below diurnal frequencies. And, even the basic physical meaning of the *K* index has remained, long after its introduction, a subject of discussion (e.g. Menvielle, 1979). As for calculating the global *aa* index, Mayaud (1973) identified significant shifts in the statistical distributions of the source *K*-index time series, possibly associated with moving an observatory from one location to another; this motivated him to introduce weighting factors for calculating *aa*. None of this is particularly satisfactory, nor is it surprising. The *K* index was developed before digital-data acquisition, before computer-base time-series analysis, and before we had arrived at our modern understanding of the dynamical interaction of the ionosphere, magnetosphere, and solar wind. In a search for improved quantitative measures of global magnetic-field activity, Svalgaard et al. (2004), and Mursula and Martini (2007), and other researchers, have proposed new indices.

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Still, most studies of long-term secular change in geomagnetic activity rely on analysis of the *aa* index; very few rely on analysis of the original *K* indices used to calculate *aa*. This might be reflective of a perceived need to use a global measure of geomagnetic activity. It might also be due to the easy availability of the *aa* index; it is readily available from several data centers around the world. With respect to *K* index, the British Geological Survey maintains a well-organized database of all of British historical values, 1868.0–2009.0, and Geoscience Australia maintains a database of values from 1980.0 to present. The availability of older Australian *K* values is slightly obscure; we obtained values for 1868.0–1980.0 from colleagues through personal communication. Following on the work of Love (2011), we compare and contrast the independently acquired *K* values from Britain and Australia. We identify long-term inconsistencies that can be considered to be "biases".

2 Data

Observatory data time series record, as a superposition of signals, a wide variety of phenomena (for review, see Love, 2008), including: solar-quiet variation generated by ionospheric electric currents (e.g. Campbell, 1989), magnetotelluric variation generated by currents induced in the Earth's crust and mantle (e.g. Constable, 2007), magnetic-storm variation generated by currents in the coupled magnetospheric-ionospheric system (e.g. McPherron, 1991), and the transient effects of solar flares that result in changes in ionospheric electrical conductivity (e.g. Van Sabben, 1961). Since the middle of the 19th century, and up until the 1980s, magnetic-observatory data were acquired with analog-photographic systems (Chapman and Bartels, 1962, Ch. 2; Schröder and Wiederkehr, 2000). As part of a daily routine, an observatory worker would remove the photographic paper from the recording system, develop it in a darkroom, and, using a scale etched piece of plate glass, make "hand" measurements of the continuous time-series traces recorded on the paper. Since the late 1970s and early 1980s, it has become routine for observatories to operate fluxgate magnetometers with digital acquisition systems (e.g. Forbes, 1987; Jankowski and Sucksdorff, 1996).

2.1 Magnetic-observatory *K* values

It was in an attempt to obtain a separation of the multiple signals recorded in magnetic-observatory data that Julius Bartels developed the *K* index in the 1930s while he was working at Niemegk, outside of Potsdam, Germany. He intended the index 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" (Bartels et al., 1939, p. 411). In practice, however, the *K* index is really just an empirical measure of irregular geomagnetic fluctuations recorded in an observatory time series after an estimated quiet-time baseline has been subtracted (Bartels et al., 1939, p. 412). Unfortunately, in the pre-digital-electronic era of analog data acquisition, it was often difficult for an observatory worker, making hand-scale measurements from paper magnetograms, to draw a fine distinction between disturbance-related variation and quiet-time variation, especially when disturbance was relatively subdued (see, for example, Mayaud, 1980, Sect. 4.4; Papitashvili et al., 1992). Special training was required, but results were not always satisfactory, and, in any case, training of observatory workers was often different from one observatory to another.

Subsequently, and in response to this problem, Bartels (1957) attempted to more clearly delineate the distinction between disturbance that might occur over the course of a day and regular diurnal variation, but some disagreements persisted (see, for example, Mayaud, 1980, p. 3). Some of this confusion could have been avoided if Bartels had (or, indeed, if anybody had) a physical theory with sufficient predictive power to permit tidy separation of disturbance and quiet variation. But mathematics was not actually used by Bartels et al. (1939) to define *K*, therefore, the index cannot be described as being particularly quantitative. And, even though Mayaud (1980, Sect. 4.8) made a strident defense of the *K* index, in the end, he also conceded that the index only provides "loose information". We agree. But we also assert that *K*-index time series contain "useful information", and with multiple *K*-index time series of long duration, consistencies can be interpreted as being physically significant. On the other hand, systematic inconsistencies, or biases, need to be identified and intrepreted with care.

In this study, we use *K* indices from the six magnetic observatories listed in Table 1: two groups of three observatories from Great Britain and Australia that are situated at approximately opposite dipole-geomagnetic latitudes and, even more nearly, opposite corrected-geomagnetic (CGM) latitudes; individual observatories are denoted by their 3-letter IAGA code, for example, Hartland HAD; groups of 3 observatories are denoted by the first letters of each observatory, Great Britain GAH and Australia MTC. 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 operational continuity. Together, these *K*-index time series are among the longest available for studies of secular change in geomagnetic activity. We obtained the British *K* values, 1868.0–2009.0, from the British Geological Survey website (www.geomag.bgs.ac.uk), the Australian *K* CNB 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, from P. G. Crosthwaite (personal communication, 2010), Geoscience Australia, who, in turn, obtained them from M. Menvielle.

Table 1. Summary of observatories for which K index and aa index values are used; w denotes the weighting factors used for making adjustments of a-data for the construction of aa. Geomagntic and corrected geomagnetic (CGM) latitudes, given for qualitative comparison, are for 2008.0.

Group	Observatory	Country	Code	Geom. Lat.	CGM Lat.	Data Years	aa w	Present Institute
GAH	Greenwich	Great Britain	GRW	53.57°	47.75°	1868.0–1926.0	1.007	
	Abinger	Great Britain	ABN	53.35°	47.42°	1926.0–1957.0	0.934	
	Hartland	Great Britain	HAD	53.90°	47.48°	1957.0–2009.0	1.059	British Geological Survey
MTC	Melbourne	Australia	MEL	−45.74°	−48.68°	1868.0–1920.0	0.967	
	Toolangi	Australia	TOO	−45.38°	−48.30°	1920.0–1980.0	1.033	
	Canberra	Australia	CNB	−42.71°	−45.39°	1980.0–2009.0	1.084	Geoscience Australia

Table 2. Scale values used to convert magnetogram ranges to K values, and scaling factors r_K used to estimate a-index values from K.

K	0	1	2	3	4	5	6	7	8	9	
MEL, TOO, GAH	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)
r_K	2.3	7.3	15	30	55	95	160	265	415	667	(nT)

2.2 *K* scaling

A statistician would describe the K index[1] as being “ordinal”; its values are ranked, dimensionless integers. They range 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 a discrete set of magnetic-field ranges measured over 3-h intervals of time at Niemegk. To facilitate inter-comparison of magnetic data from observatories at different locations, especially across a range of latitudes, the long-term statistical distribution of K values collected at a particular observatory is supposed to be normalized so that it is like that realized at Niemegk (Bartels et al., 1940, p. 334–335). 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 to an expected probability for a high-activity range of magnetic-field variation as measured in nT, see Table 2. This scaling is not, itself, derived from any physics-based theory, it is something of an arbitrary quantization. As a result, without applying multiple ad hoc adjustment factors, which would, themselves, be difficult to justify, K-index distributions from different observatories are, inevitably, different from each other.

2.3 Magnetic-observatory *a* and *aa* values

The *aa* index was developed by Pierre-Noël Mayaud (1972), and its regular publication was recommended by IAGA Resolution 1975, No. 3. The *aa* index[2] is calculated from British K_{GAH} and Australian K_{MTC} values by first using the scaling factors r_K given in Table 2 (Mayaud, 1980, p. 47, Table 6 and comments on p. 76) to obtain “redimensionalized” index values[3], for example, $a_{\mathrm{GAH}} = r_{K_{\mathrm{GAH}}}$. These are then weighted using the factors w given in Table 1 to obtain “adjusted” values, for example, $aa_{\mathrm{GAH}} = w_{\mathrm{GAH}} \cdot a_{\mathrm{GAH}}$, that Mayaud (1973) estimated would correct for small differences in measurement procedure and possible site-specific anomalies arising from sub-surface magnetotelluric electric currents (Mayaud, 1980, Sect. 5.3). And, finally, adjusted values are averaged together to form the “standard” *aa* index; $aa = \frac{1}{2}[aa_{\mathrm{GAH}} + aa_{\mathrm{MTC}}]$. As we shall see in Sect. 5, even after Mayaud’s adjustments are made, there are long-term systematic differences between the British and Australian K-index time series. These biases are generally larger than the offsets that Mayaud sought to correct, and they certainly affect the character of the averaged *aa* index. Because we want to compare unadjusted a-values with adjusted *aa* index, we calculate them ourselves, directly from K values going back to 1868 and using the formulas of Mayaud. We acknowledge that standard *aa* values are also available

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[1] “K” stands for “Kennziffer” or “characteristic number”.

[2] “*aa*” stands for “antipodal amplitude”.

[3] We are aware of some slight inconsistencies concerning the scale factor for $K = 1$. A value of 7.5 nT is stated in Mayaud’s book, but algorithms used to calculate *aa* use 7.3 nT. This difference, while annoying, does not affect our conclusions.

from the Service International des Indices Géomagnétiques (http://isgi.cetp.ipsl.fr).

2.4 Sunspot numbers

For comparison of geomagnetic activity 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 should be correlated in time with ground magnetometer data, which were available to Wolf and his colleagues (Hoyt and Schatten, 1998, p. 497). We assert that correlations between data sets that have not been independently acquired are not particularly meaningful (see, also, Mursula et al., 2009). Therefore, we prefer to use G rather than Z. We define the beginning and the end times of each solar cycle, rounded to the nearest year, according to sunspot-number minima.

3 *K* occurrence probabilities

In Fig. 1a we show probability-density functions for K-index occurrence for the British and Australian observatory groups, $p(K_{\mathrm{GAH}})$ and $p(K_{\mathrm{MTC}})$ for 1868.0–2009.0; compare with the shorter durations of time used by Clilverd et al. (2005, Fig. 4) or Lukianova et al. (2009, Fig. 4). Over this long 141-yr period of time, the British observatories tend to show higher K-activity levels than the Australian observatories; the densities $p(3)$ and $p(4)$ are greater for GAH than MTC; the opposite is true for $p(0)$ and $p(1)$. This could be a difference of geophysical significance, or it could be an artifact of the methods used to estimate K values; the important point, which we will now investigate, is the persistence of these differences for different subsets of the available K data from each observatory group.

3.1 Observatory location

In Fig. 1b–f we show K-index density functions corresponding to the 5 durations of time defined by the continuous operation of a British-Australian pair of observatories; years of operation are as specified in Table 1. However, the last duration, Fig. 1f, is a very slight exception: it is shorter by one year than the duration of time defined by the operation of HAD and CNB; 1981.0–2009.0 is the duration of time for which K estimation was made at both British and Australian observatories using only the horizontal magnetic-field elements (discussed below). Viewing all five durations together, global secular change in geomagnetic activity can be seen as a drift in the shape of both the British and Australian K distributions, there is also noticeable variance in the difference between the British and Australian K-probability-density functions. For the first two durations, Fig. 1b, c 1868.0–1926.0, the $p(3)$ and $p(4)$ densities for GRW have slightly higher K-activity levels than MEL/TOO; for the last three durations, Fig. 1d–f 1926.0–2009.0, this difference is more pronounced. The bias towards higher (lower) K-activity level in Britain (Australia) is apparently independent of observatory location. On the other hand, the lowest-activity levels, $p(0)$, occur with relatively high probability for the first two durations, Fig. 1b, c 1868.0–1926.0, but with much lower probability for the last three durations, Fig. 1d–f 1926.0–2009.0; and this change, which amounts to a change in the shape of the K distribution, is rather consistently seen for both British and Australian observatories.

As we have remarked in Sect. 2.2, each observatory's chosen lower-limit for $K = 9$ is supposed to result in similar K distributions from observatories around the world. It appears, however, that the Australian observatories have scale values that are too high, and so their K values are systematically lower than those from Britain. This might be reflective of an inaccuracy in the method Mayaud (1968) developed for fixing the scale values based on an observatory's corrected geomagnetic latitude. From 1868.0–1980.0, the British GAH and Australian MTC observatories were situated on similar corrected magnetic latitudes (CGM), see Table 1. But the transfer of Australian observatory operations from TOO to CNB in 1980.0 corresponded to a move north, farther from the active auroral zone, by about 3° magnetic latitude. For this reason the lower-limit for $K = 9$ for CNB was adjusted down slightly from the value used for TOO, see Table 2. Despite both the observatory move and the required scaling adjustment, biases between the British and Australian K-index distributions, Fig. 1e, f, show persistent patterns. The main difference is for $p(2)$, which is high (low) before (after) 1980.0, the significance of which is difficult to assess; see, for example, Fig. 1d for 1926.0–1957.0. Otherwise, the bias persists with higher (lower) activity levels for $p(3)$ and $p(4)$ in Britain (Australia); low probabilities are seen for $p(0)$ for both British and Australian observatories.

3.2 Induced currents

At first, Bartels defined K according to the maximum range among the three Cartesian magnetic-vector components of magnetic north, magnetic east, and down. This formula was changed in 1963 to the range of just the horizontal components (IAGA Resolution 1963, No. 4), but (confusingly) only for observatories not contributing to the planetary

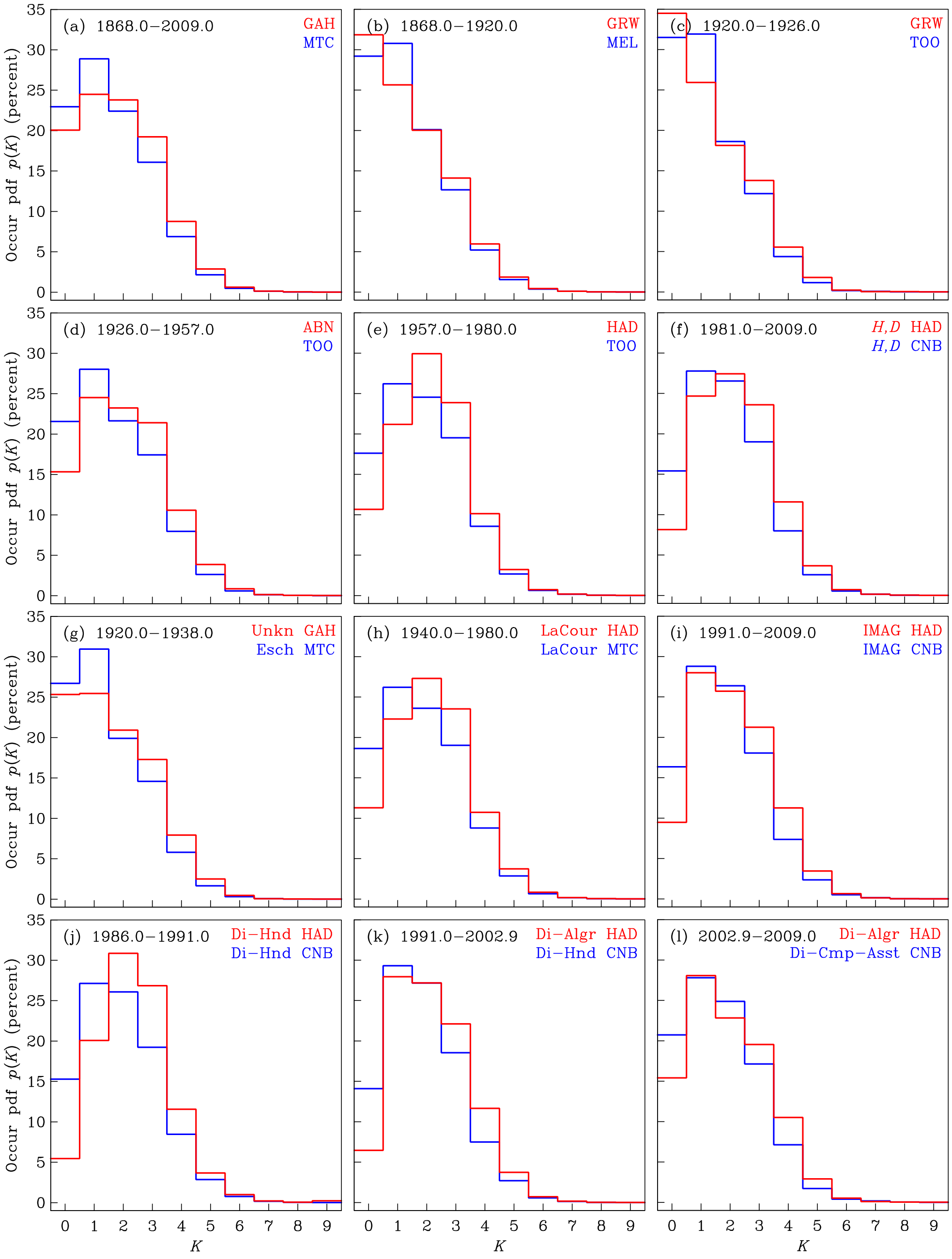

Fig. 1. Probability density functions $p(K)$ for K indices for British (red) and Australian (blue) observatories: **(a)** 1868.0–2009.0 for observatory groups GAH and MTC, **(b–f)** the 5 subset durations of time corresponding to the continuous operation of a British-Australian pair of observatories, **(g)** continuous operation of an unknown type of variometer in Britain and an Eschenhagen variometer in Australia, **(h)** continuous operation of La Cour variometers in both Britain and Australia, **(i)** Intermagnet-certified digital data production, **(j)** hand-scaling for K-value estimation in Britain and Australia using printed digital magnetograms, **(k)** K-value estimation in Britain by a computer-algorithm and using digital data and in Australia by hand-scaling using digital data, **(l)** K-value estimation in Britain by a computer-algorithm and using digital data and in Australia by computer-assistance using digital data. Compare with Fig. 3.

index Kp, a matter of relevance that is not clearly made in Mayaud (1980, p. 27). With the transition from full-vector to horizontal-component estimation, K values were expected to be less sensitive to inductive magnetotelluric signals that dominate the downward magnetic-field component, and which can be very different from one observatory to another because of localized electrical conductivity in the crustal and mantle (e.g. Parkinson, 1983, Ch. 5.3). Although

British HAD is a Kp station, the transition was made anyway, and apparently without the prompting of any IAGA resolution, in 1981.0; compare p. 44, in each case, of Institute of Geological Science (1982, 1983). Horizontal-component estimation was used at Australian TOO for 1979.0, the last year that observatory operated, and at CNB since 1980.0 (P. G. Crosthwaite, personal communication, 2010).

The effects of changing the vector components used for estimating K values can be judged by comparing the British and Australian K values before 1980.0 (full vector) and after 1981.0 (horizontal components). As we have already noted, the probability-density functions in Fig. 1e, f are generally similar; they both show bias towards higher (lower) K-activity level in Britain (Australia), $p(3)$ and $p(4)$, and they both consistently show low probabilities for $p(0)$. It is noteworthy that Mayaud (1973, p. 8) discussed the bias towards higher (lower) reported magnetic-activity levels in Britain (Australia), which, at one point, he described as being "without physical meaning". By this, we believe, he meant that the bias might not represent an accurate measure of hemispherical difference in geomagnetic activity that is generated externally by asymmetric source electric currents in the ionosphere and magnetosphere. Mayaud discussed the presence of possible localized sub-surface "inductive effects", but which we appreciate cannot be explored in much detail with data from only two stations. In general, localized "inductive effects" always contribute to the disturbance field measured at an observatory, and these tend to predominatly seen in the vertical-component. But changing K-estimation methods, from full-vector to horizontal component, did not much affect the persistence of the British-Australian bias in K-activity levels. This might, therefore, indicate that the bias is due to more than just localized inductive anomalies.

3.3 Magnetometer technology

Over the many years of observatory operation in Britain and Australia, the instruments used for acquiring magnetic-field data have occasionally been changed. So, for example, when the Australian TOO observatory was established, K values began to be estimated in 1920.0 using magnetograms produced by an Eschenhagen (1900) variometer system (Baldwin, 1926). This was later replaced by a La Cour (e.g. Chapman and Bartels, 1962, Sect. 2.9–2.10) variometer system in 1940.0 (Baldwin, 1940), which remained in operation through 1958 (e.g. van der Waal and Sorensen, 1960) and, it seems, until the observatory closed in 1980.0. The variometers used in Britain prior to 1938.0 are well described in yearbooks, but they are not specifically identified; we surmise that they were custom-made. After 1938.0, and until it closed in 1957.0, a La Cour variometer was operated at ABN; a similar system was operated at HAD (Forbes and Riddick, 1984) when it was opened as a replacement of ABN. In 1979.0, digital acquisition systems were introduced at HAD, these were operated in parallel with analog systems for several years. Digital systems have been used at CNB since it began operations in 1980.0. Both HAD and CNB were part of the Intermagnet (Kerridge, 2001) when that organization produced its first certified digital data in 1991.0.

In Fig. 1g–i we show K-probability-density functions for three durations of time corresponding to the operation of continuous magnetometer technologies and, presumably, similar operational standards. For Fig. 1g 1920.0–1938.0, with an Eschenhagen variometer in Australia and an unknown variometer type in Britain, low-activity levels, $p(0)$, occur with relatively high probability, although we note from Fig. 1b, c that earlier $p(0)$ probabilities for British GRW are even higher. For Fig. 1h 1940.0–1980.0, when La Cour variometers were operated in both Britain and Australia, $p(0)$ occurs with relatively low probability; this persisted into the Intermagnet era, Fig. 1i 1991.0–2009.0. Clilverd et al. (2002) have examined, in detail, the change over time in the occurrence of $K = 0$ values, concluding that the change to La Cour type variometers resulted in fewer low-activity values being reported. We will return to this subject in Sect. 4 when we examine K-index time series. For now, we simply note that the changes in magnetometer technology represented in Fig. 1g–i do not substantially affect the bias towards higher (lower) activity levels, $p(3)$ and $p(4)$, for K values from Britain (Australia).

3.4 Hand and computer scaling

With the commencement of widespread production of 1-min-resolution digital data in the 1980s, observatory institutes began to use computers for estimating K values, with algorithms designed to mimic the original procedures of hand measurement of analog magnetograms (e.g. Riddick and Stuart, 1984; Menvielle et al., 1995). To some extent, this preserved continuity with the older K-index time series, but research on K-algorithm development continues to this day. In Britain in 1986.0, K values for HAD began to be hand-scaled from paper printouts of digital data (consistent with IAGA Resolution 1983, No. 4; and E. Clarke, personal communication, 2010); computer-algorithm estimation from digital data began at HAD in 1991.0 (Clark, 1992). In Australia, with the opening of CNB in 1980.0, K values were hand-scaled from paper printouts of digital data (Hopgood and McEwin, 1996, p. 20). The method was changed on 1 December 2002, when observatory staff began to use an computer program for making "assisted" estimation of K values (Hopgood, 2004, p. 2); this method continues to be used to this day for estimation of CNB K values.

In Fig. 1j–l we show K-probability-density functions for three durations of time corresponding to K estimation by different methods. It is only for the first duration, 1986.0–1991.0, that the K-estimation methods were the same for the British and Australian observatories, otherwise they are different. In each case, qualitative differences are seen for $p(0)$ and $p(1)$, and in Fig. 1j for $p(2)$, but bias persists with higher (lower) activity levels for $p(3)$ and $p(4)$ in Britain (Australia); low probabilities are seen for $p(0)$ for both British and Australian observatories. Some of this might be relevant for analysis of changes in geomagnetic activity over the past couple of solar cycles, but, as we shall see, it does not significantly affect analysis of long-term change, nor does it much affect average values of *aa*. We note that IAGA Resolution 1983, No. 4 called for computer-generated K values to be given a different name, so that they could be distinguished from values estimated by traditional means. This has not been done, and, in some respects, is not that relevant given the differences that exist in hand-scaled K values from different observatories and the variety of roles played by computers in estimating K values.

4 Time series of *K* exceedance and sunspots

We define the annual exceedance $e(5,t)$ as the number of times per year that $K \geq 5$ for a particular observatory group. In Fig. 2b we show the time dependence of $e(5,t)$ for British GAH and Australian MTC observatories. For comparison, in Fig. 2a we show annual averages of sunspot group number $G(t)$. A secular increase in both geomagnetic disturbance and sunspot number is apparent over the 141-yr duration of time for both the British and Australian K-index time series (Love, 2011). We can quantify this in simple terms by comparing, for example, cumulative exceedance counts from 2 separate periods of time, each encompassing 6 solar cycles. For solar cycles 11–16, 1868.0–1934.0, the cumulative counts from GAH, and MTC are, respectively, 5031 and 4034, while later on, for cycles 18-23, 1944.0–2009.0, they are 8716 and 6550; an increase of 73 and 62 %. For the same two periods of 6 solar cycles, the cumulative number of sunspots G increased from 2649 to 4852 or 83 %. The causal connection here is, of course, well-known; geomagnetic activity is driven by solar activity. These results can be compared with those 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), and with results based on analysis of observatory hourly values (e.g. Mursula and Martini, 2006).

We define the annual count rate $n(0,t)$ as the number of times per year that the low-activity level $K = 0$ for a particular observatory group. In Fig. 2c we show the time dependence of $n(0,t)$ for British GAH and Australian MTC observatories. For solar cycles 11–16, the cumulative counts from GAH, and MTC are, respectively, 58951 and 55234, while later on, for cycles 18–23, they are 19254 and 32272; a decrease of 67 and 42 %. Insofar as geomagnetic activity is increasing, as measured by $e(5)$ Fig. 2b, then it is not, in some respects, too surprising that there is a corresponding decrease in low-activity, as measured by $n(0)$ Fig. 2c; these are, after all, the opposite ends of the K-probability-density functions. In detail, we note that the British GAH (Australian MTC) observatories, which show a greater (lesser) relative increase in $e(5)$, also show a greater (lesser) relative decrease in $n(0)$; compare the slopes of the time series in Fig. 2b, c. These results can be compared with those based on the *aa* index (e.g. Legrand and Simon, 1989, Fig. 5; Clilverd et al., 1998, Fig. 2; Ouattara et al., 2009, Fig. 3).

The correlation between the annual exceedance $e(5)$ rates of the two observatory groups, GAH and MTC, can be clearly seen in Fig. 2b. This observation can be quantified in terms of ρ_K, the Pearson correlation coefficient (Press et al., 1992, algorithm: "pearsn"); $\rho_K = 0.95$. Correlations of G with $e(5)$ are somewhat smaller, for GAH: $\rho_K = 0.51$, for MTC: $\rho_K = 0.57$; these correlations can be slightly improved (results not shown) by introducing a time lag of a year or two to $e(5)$, consistent with the well-known tendency for peak geomagnetic activity to occur during the declining phase of a solar cycle, just after sunspot maximum (e.g. Legrand and Simon, 1989; Richardson et al., 2002). With respect to the annual low-activity count rates $n(0)$ for GAH and MTC, their correlation is clearly seen in Fig. 2c, $\rho_K = 0.90$. Correlations with G are negative (anti-correlated): for GAH: $\rho_K = -0.53$, for MTC: $\rho_K = -0.55$.

The differences between the British and Australian K-probability-density functions seen in Fig. 1 are manifest as differences in the sizes of the trends in $e(5)$ and $n(0)$ seen in Fig. 2. But despite the several factors considered in Sect. 3, each of which, if significant, could introduce offsets in the K-index time series, such offsets are not obvious. There are year-to-year differences between British and Australian K values as well, some of which are to be expected, since geomagnetic activity can take on a complicated geography, especially during large storms.

5 Time series of *aa* and *K* biases

The redimensionalized and adjusted aa_{GAH} and aa_{MTC}, together with the standard *aa* index, are plotted in Fig. 2d. Despite the use of Mayaud's adjustments, the linear trend rates for the British aa_{GAH} and Australian aa_{MTC} data remain somewhat different, although increasing geomagnetic activity is, again, obvious in data from both observatory groups. In Fig. 2e we plot the ratio of the annual averages of the adjusted values $aa_{\mathrm{MTC}}/aa_{\mathrm{GAH}}$ (compare with Mayaud, 1973, Fig. 1). If the K values had been correctly scaled, then, at the very least, we would expect this ratio to be approximately constant over time; even better would be a ratio equal to unity. Instead, there is obvious bias, with the British data tending to record higher activity levels than the Australian data, and with obvious secular drift in the ratio over time. In Fig. 2e we also plot the ratio for unadjusted values $a_{\mathrm{MTC}}/a_{\mathrm{GAH}}$. It is evident that Mayaud's adjustments have most affected the period from 1926.0–1957.0, the duration of the operation of the ABN observatory in Britain, but the ratio is still not particularly close to unity. It is also noteworthy that Mayaud's adjustment factors (Table 1) lead to a

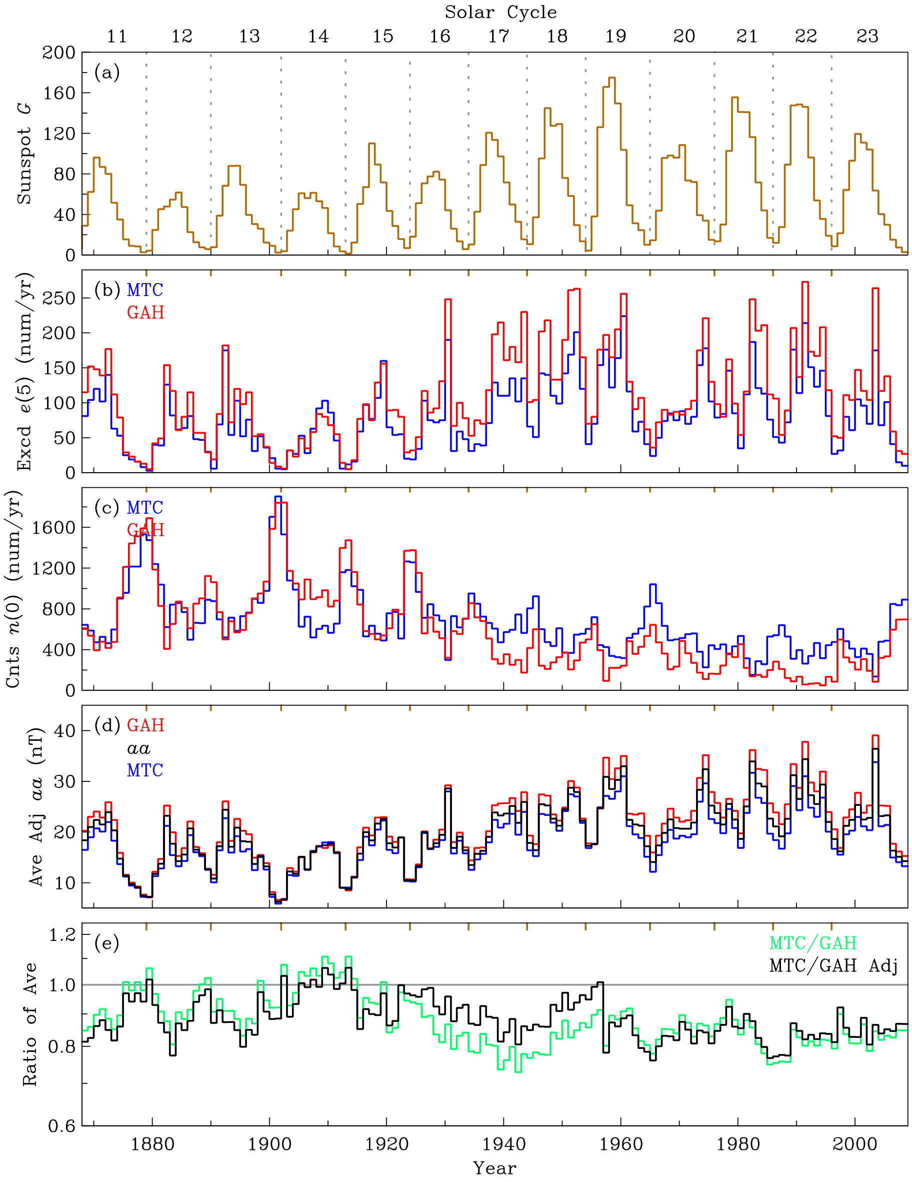

Fig. 2. Time series for 1868.0–2009.0 and solar cycles 11–23 of **(a)** annual means of sunspot group number $G(t)$, **(b)** annual exceedance count rates $e(5,t)$ for British GAH (red) and Australian MTC (blue) observatory groups, **(c)** annual occurrence count rates $n(0,t)$ for British GAH (red) and Australian MTC (blue) observatory groups, **(d)** annual average of adjusted aa_{GAH} (red), aa_{MTC} (blue), and the standard *aa* index (black), **(e)** ratio of annual averages of unadjusted $a_{\mathrm{MTC}}/a_{\mathrm{GAH}}$ (green) and adjusted $aa_{\mathrm{MTC}}/aa_{\mathrm{GAH}}$ (black).

rather large discontinuity in the adjusted ratio $aa_{\mathrm{MTC}}/aa_{\mathrm{GAH}}$ at 1957.0 corresponding to the opening of the HAD observatory. From the standpoint of estimating geomagnetic activity on a global scale, Mayaud's adjustments do not correct for noticeable differences in activity levels recorded at British and Australian observatories.

6 Activity-level contributions of *K* to *aa*

In Fig. 3a we show, as a function of K_{GAH} (K_{MTC}), the contribution to long-term averages of adjusted aa_{GAH} (aa_{MTC}), which, for each observatory, equals $w \cdot r_K \cdot p(K)$. From 1868.0–2009.0, the low-activity $K = 0,1$ values are common, for example, Fig. 1a, but their contributions to long-term averages of the standard *aa* are actually relatively minor. Medium activity $K = 3,4$ values contribute most to average *aa* levels. Since similar observations can be made for Fig. 3b–f, where we show results for the 5 durations of time defined by the continuous operation of a British-Australian pair of observatories, artificial factors that mostly affect low-activity K estimation, such as change in observatory location or instrumentation, do not significantly affect running

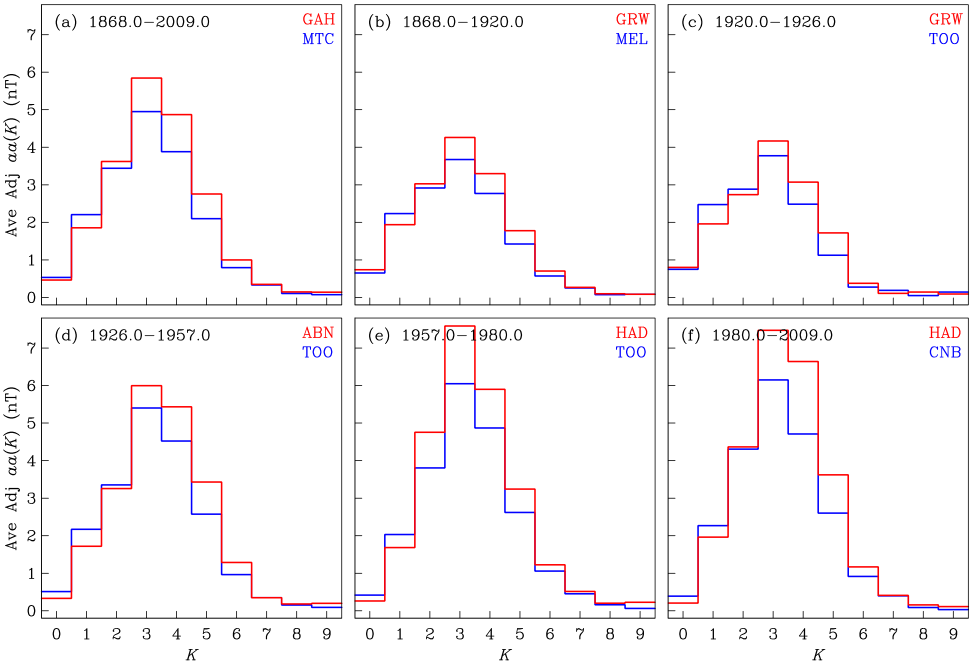

Fig. 3. The adjusted contribution $w \cdot r_K \cdot p(K)$ to long-term averages of the standard *aa* index, each for British (red) and Australian (blue) observatories: **(a)** 1868.0–2009.0 for observatory groups GAH and MTC, **(b–f)** the 5 subset durations of time defined by the continuous operation of a British-Australian pair of observatories. Compare with Fig. 1.

averages of *aa*. The trend of increasing geomagnetic activity that we observe in Fig. 2c is also seen across Fig. 3b–f for each duration defined by an observatory pair. And while the bias for high (low) scaled aa_{GAH} (aa_{MTC}) values makes it difficult to confidently estimate the absolute rate of increase in geomagnetic activity, the qualitative consistency seen here makes it clear there has been a general increase in geomagnetic-field activity over the past 141 yr; see, also, Love (2011).

7 Conclusions

To minimize the effects of statistical noise or unwanted variation, scientists often average together independently acquired data sets. For this, care must be taken to ensure that results are not residual artifacts. Given two data sets drawn from two different types of distributions, or two distributions of the same type but having different means and variances, averaging together pairs of data will result in a distribution that does not resemble either of the two source distributions. The average distribution will be a biased representation of the two source distributions. In general, averaging is most appropriate if the source distributions are almost identical. Furthermore, if adjustments are to be made to independent data distributions, then these should be done on the basis of a quantitative physical theory. In the context of the analysis presented here, where we have shown that higher (lower) *K*-activity levels tend to be reported at British (Australian) observatories, the two *K* distributions used to calculate *aa* are obviously different. The resulting bias means that it is probably best to regard the *aa* index as a qualitative measure of global geomagnetic activity. We have not explored, here, the complex issue of geographic bias, but given that the *aa* index is derived from data from only two observatories, any geographic bias would only reinforce our conclusion about the qualitative nature of this index.

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