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Long-term external field contributions in geomagnetic repeat station results

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ABSTRACT
Geomagnetic repeat station measurements are carried out in several countries to provide additional information on secular variation or to map the field regionally. These measurements are continuously monitored by geomagnetic observatories. However, clear separation of magnetic variations from the different field sources remains a challenge in all geomagnetic observations. This is particularly true for repeat station data, where measurements are only available from one or a few days at a time. Contributions from large-scale magnetospheric fields remain in repeat station data despite careful data processing, and they are modulated by solar activity variations on time scales of several years to decades. Here, the influence of magnetospheric field contribution in repeat station data from Germany and Southern Africa over the past ten years is shown and strategies are discussed to eliminate them by using existing or custom-made geomagnetic activity indices. The disturbed storm time (Dst) index, its derivatives and the CM4 external field extrapolated to recent times clearly do not capture the multi-annual trends accurately. For the satellite era, since about 2000, global spherical harmonic models based on satellite and ground data give the best description of the large-scale magnetoshperic field and can be used to correct ground data time series for long-term external field contributions. It would be desirable to develop a Dst-like index with correct long-term variability and baseline to correct data series further back in time.

Keywords: Repeat station surveys, Decadal variations, Magnetospheric field variation.

INTRODUCTION

Geomagnetic repeat station measurements, observations of the absolute magnetic field vector at well-defined locations over one or a few days at time intervals of one to a few years (*Newitt et al., 1996*) are carried out in several countries to provide information on secular variation on a denser network of stations than provided by permanent geomagnetic observatories. Nowadays modern global geomagnetic core field models based on observatory and satellite magnetic data describe the detailed regional secular variation to high accuracy (*Korte and Lesur, 2012*). Nevertheless repeat station data are still valuable, e.g., to allow regional field mapping independent of the availability of global data or models or to provide information about the lithosphere. Moreover, the modern satellite era only started with the launch of the Ørsted and CHAMP satellites in 1999 and 2000 (e.g. *Olsen and Kotsiaros, 2011*). Long time series of regular repeat station observations that extend back in time well beyond the modern satellite era can be valuable resources to study secular variation on decadal timescales.

The separation of the individual contributions originating inside and outside of the Earth in geomagnetic data remains a challenge for all kinds of magnetic measurements. This is particularly true for repeat station data, where the observations span a few hours to a few days at the most. Short period ionospheric and magnetospheric variations (from seconds up to a few days) can be eliminated by standard data processing (see *Newitt et al., 1996*) ideally using a variometer installed temporarily near the repeat station for that particular purpose, or by comparison with the variations recorded at the nearest observatory. Variations with periods from several days to a year can be eliminated fairly well in most cases by comparison with the nearest observatory recordings, if necessary, taking secular variation gradients into account. However, large-scale magnetospheric fields show additional variations on time scales of several years to decades, e.g. from modulation of the always present magnetospheric ring current by solar activity on time-scales of the 11 year solar cycle. Such variations do not average out in observatory annual means (*Yukutake and Cain, 1987, Verbanac et al., 2007*) and therefore are also present in the repeat station data reduced to annual means. In the following I show that this is also the case for repeat station results reduced to quiet night time values. Elimination of this contribution might not be necessary or not even desirable if repeat station data are used for regionally mapping field components for practical purposes like navigation, but it is important when the data are used for core field secular variation studies as, e.g., for the detection and detailed description of geomagnetic jerks. In the following, German and southern African repeat station and observatory data are used as examples to demonstrate the influence of such long-term magnetospheric field contributions. Some existing geomagnetic activity indices and models aimed at describing the magnetospheric field variation are discussed and methods are suggested to reduce the long-term magnetospheric influence in repeat station data and observatory annual means.

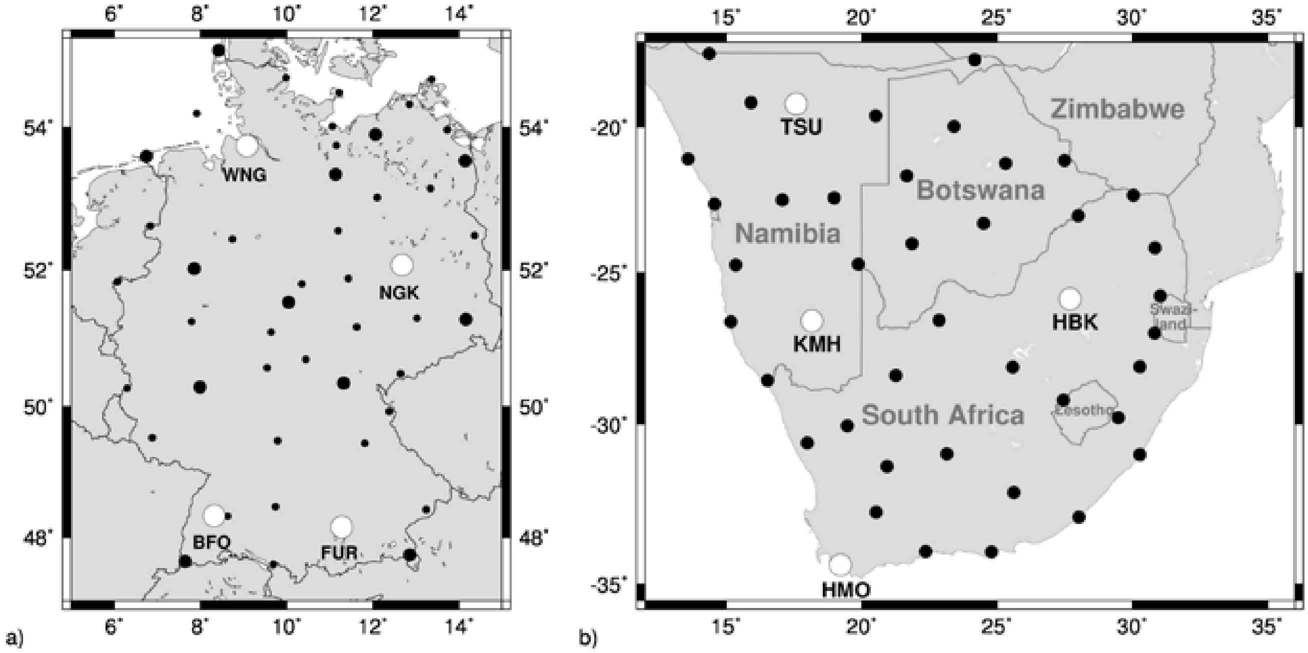

Figure 1. Maps of geomagnetic observatory (white dots) and repeat station (black dots) distribution for a) Germany and b) southern Africa. For Germany, large black dots are first order repeat stations with on-site variometer, small symbols are second order stations not considered in this study.

LONG-TERM MAGNETOSPHERIC SIGNAL IN GEOMAGNETIC GROUND DATA

Data from two regions have been included in this study: from Germany and Southern Africa,encompassing South Africa, Namibia and Botswana. Both regions include four geomagnetic observatories and networks of up to 40 repeat stations. Given the different size of the regions, the data coverage is much denser for Germany. Minimum and maximum distances between the four German geomagnetic observatories Wingst (WNG), Niemegk (NGK), Black Forest (BFO) and Fürstenfeldbruck (FUR) are in the order of 240 to 630 km. The average distance between repeat stations lies in the order of 120 km. For southern Africa, the minimum and maximum distance between the four observatories Hermanus (HER), Hartebeesthoek (HBK), both in South Africa, Tsumeb (TSU) and Keetmanshoop (KMH), both in Namibia, are of the order of 820 to 1680 km, and the average distance between repeat stations of 240 km (Figure 1).

The data are standard data products as made available by the World Data Center for Geomagnetism, Edinburgh. From the observatories, we use the annual mean values from 2001.5 to 2010.5. Observatories BFO and KMH from Germany and Namibia have not been included because they only went into operation in 2004 and 2006, respectively. The repeat station data have been processed in somewhat different ways. From Germany, we only consider a sub-set of 12 repeat stations where a local variometer has been operated for a few days around the absolute measurement. The observations are first reduced to quiet night time values by means of these variometers and then further reduced to annual means by comparison to the NGK observatory recordings (see *Korte and Lesur, 2012*). Repeat station surveys have been conducted bi-annually from 1999 to 2012, and we use the time series from 2001.5 to 2010.5. Repeat station surveys have a long tradition in southern Africa, but here I consider only data from 2005 onwards, when a collaboration between SANSA and GFZ led to intensified survey activity with annual repeat intervals and improved data processing by means of local variometers set up for a full night with absolute observations in the evening and the morning (*Korte et al., 2007*). These data have only been reduced to quiet night time values at the time of observation.

Figure 2 shows the residuals of the data series after a main field and secular variation estimated for the location from a core field model and the constant average value of the remaining signal have been subtracted. The constant average can be seen as an estimate of the lithospheric field contribution which is assumed to be constant over the studied time interval. For the core field and its secular variation the continuous GRIMM3 model spanning the time interval 2001 to 2010 and based on CHAMP satellite and geomagnetic observatory data (*Lesur et al., 2010, Mandea et al., 2012*) was used. The residuals of the annual mean values of the three German observatories and selected six repeat stations very clearly show similar

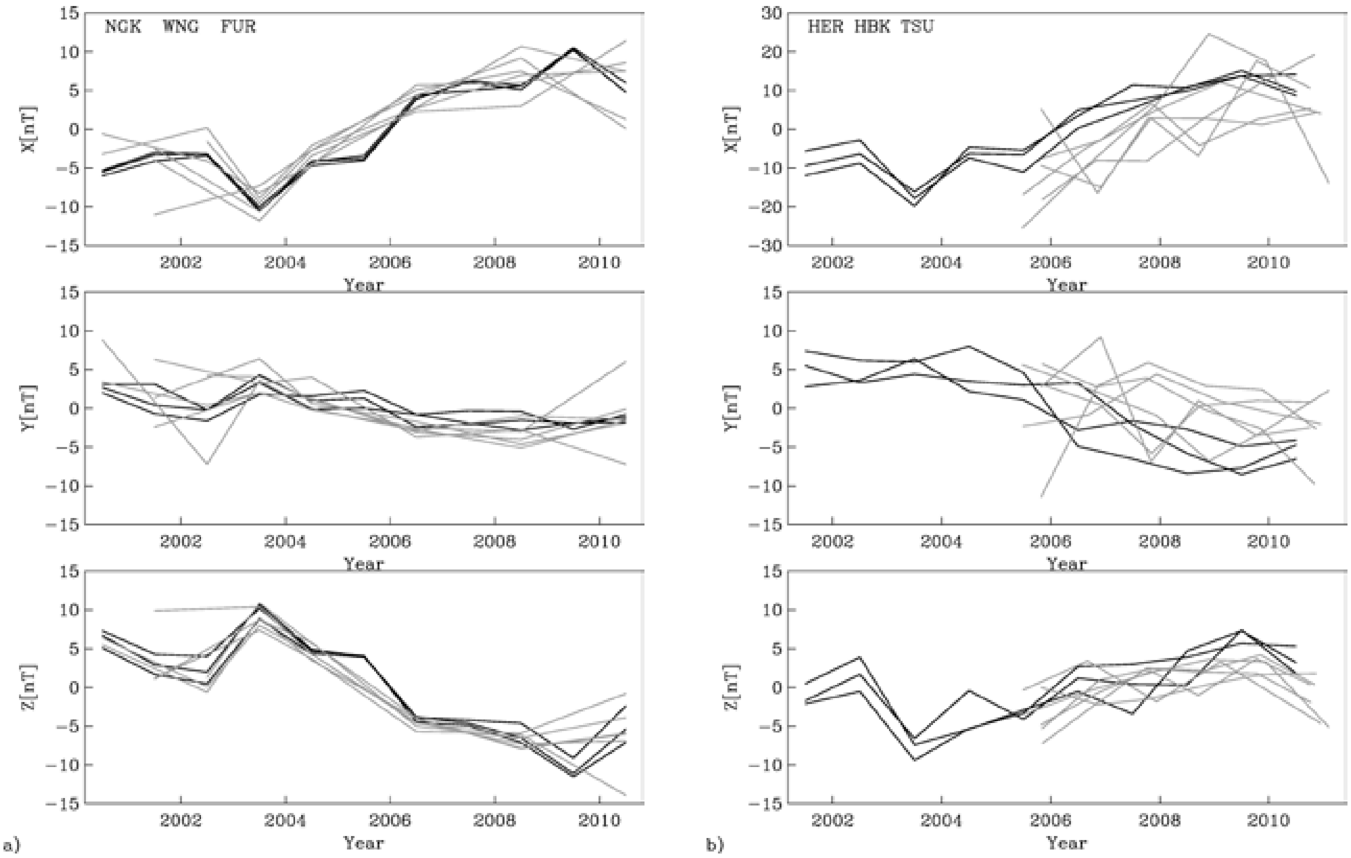

Figure 2. Observatory (black) and repeat station data (gray) residuals after subtraction of core field, secular variation and a constant average to account for lithospheric sources. Geographic co-ordinates are indicated as north (X), east (Y) and vertical (Z) component from top to bottom. a) Annual mean data from the three observatories WNG, NGK and FUR and sixselected repeat stations distributed over Germany. b) Annual means from the three observatories HER, HBK and TSU and night time values from sixselected repeat stations distributed over South Africa, Namibia and Botswana.Scatter in particular in repeat station data is due to data uncertainties or further residual external fields.

long-term trends for the whole area in all components. The residuals from both the annual means of the southern African observatories and the night time values of selected repeat stations, respectively, are noisier but similar trends are obvious. The noise in the repeat station night time values is at least partly due to the fact that these data might contain some further external field influences, which have averaged out better in annual means, indicating that these night time averages may not always be truly quiet time night time averages.

The fact that the residual signal is very similar in northern and southern hemisphere (with slight differences due to different geomagnetic coordinates) of the north (X) and east (Y) component and of opposite sign in the vertical (Z) component indicates a large scale source consistent with a dipole geometry far out in the magnetosphere. Therefore, it is likely due to a modulation of the large-scale magnetospheric currents, mainly the ring current, with solar activity.

ESTIMATING THE MAGNETOSPHERIC CONTRIBUTION

The traditional geomagnetic activity index meant to describe the disturbance field created by a magnetospheric ring current is the Dst (disturbed storm time) index (*Sugiura and Kamei, 1991*), available from the World Data Center Kyoto at *http://wdc.kugi.kyoto-u.ac.jp/dstdir/*. Mursula and Karinen (*2005*) extended the Dst index back in time to 1932 and corrected some errors. Mursula et al. (*2011*) further corrected this index for a semiannual variation arising from seasonal variations at the four contributing geomagnetic observatories that are unrelated to geomagnetic storm activity, which also had an influence on the long-term variability of the index. These two indices, named Dxt and Dcx respectively, are now available derived either from the four traditional observatories or an extended data basis of 17 low- and mid-latitude observatories at *http://dcx.oulu.fi/*.

Two other large-scale magnetospheric indices are obtained by low-degree spherical harmonic analysis of low- and mid-latitude geomagnetic observatories data, the Vector Magnetic Disturbance index (VMD) by Thomson and Lesur (*2007*) and the Ring current (Rc) index by Olsen et al. (*2014*). Both are available upon request from the authors. However, the VMD index is designed to monitor only rapid variations and its long-term average (> 3 months) is close to zero. It thus cannot describe the long-term magnetospheric variation seen in the ground data.

All the indices contain magnetic field contributions originating directly from electric currents in the magnetosphere, but also secondary parts induced in the Earth's crust and mantle by these time-varying fields. A separation of these contributions for the Dst index has been presented by Maus and Weidelt (*2004*), using a one-dimensional conductivity model of the Earth. They have been termed Est (primary external part) and Ist (secondary, induced internal part) and are available at *ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC_DATA/INDICES/EST_IST/Est_Ist_index.lis*. The Rc and VMD indices similarly consist of separate estimates for the direct, external variation and the indirect, internally induced part.

Several recent spherical harmonic global geomagnetic core field models include descriptions of the large-scale magnetospheric variations. The CM4 comprehensive model by Sabaka et al. (*2004*) separately describes the main, large scale lithospheric, primary and induced magnetospheric and ionospheric contributions and toroidal fields generated by field-aligned currents. It spans the time interval 1960 to 2002 and is available at *http://core2.gsfc.nasa.gov/CM/*. The magnetospheric contributions in this model are modulated by the Dst index and thus can be extrapolated to more recent times. (A new model version, CM5, has been published by Sabaka et al. (*2015*) too recently to be included in this study.)

Version 7 of the POMME model series developed by Maus et al. (*2010*) is mainly designed as an internal field model but contains a description of the large-scale magnetospheric currents modulated by the Est/Ist indices and is available at *http://geomag.org/models/pomme7.html*. The latest version of the internal field GRIMM model series, GRIMM3 (*Lesur et al., 2010, Mandea et al., 2012*) co-estimates large-scale magnetospheric fields in the spherical harmonic expansion. It is available at http://www.gfz-potsdam.de/magmodels/.

Predictions for the magnetospheric description included in the spherical harmonic models are obtained for any location on Earth from the respective forward modelling code. Annual means were obtained by averaging hourly values. The POMME7 and GRIMM3 models span approximately the same time interval from 2000 to 2010. They require substantial modification of the provided forward modelling code to obtain the desired time-averaged and purely external annual mean prediction. In particular the POMME7 software requires the implementation of regular input not only of the Est and Ist index, but additionally information on the interplanetary magnetic field By component, the merging electric field and the solar irradiation F10.7 index. While it certainly would be of interest to see the prediction of that model in comparison, it was not possible to include it within the time-frame of this study.

The individual indices (Dst, Dcx, Dxt, Rc, Est, Rc external part) can be considered as describing the strength of a dipolar magnetic field originating from a ring current in the magnetosphere, some with an internally induced dipolar secondary part (Ist, Rc induced part). They can be interpreted as the external and internal (induced) spherical harmonic axial dipole coefficients. Thus their contribution to the magnetic components north (X), east (Y) and vertical (Z) is given by

$$
\begin{aligned}
X &= ext^*\cos(\lambda) + int^*\cos(\lambda) \\
Y &= 0 \\
Z &= ext^*\sin(\lambda) - 2int^*\sin(\lambda),
\end{aligned}
\tag{1}
$$

with latitude λ and (ext,int) one of the index pairs (Dst,0), (Dcx,0), (Dxt,0), (Rc,0), (Est,Ist), (Rc external, Rc internal). To take into account that the ring current is aligned with the main field dipole axis λ is the geomagnetic latitude and the contributions to the components have to be transformed back from the geomagnetic to the geographic reference frame. A comparison of the large-scale residual signal and several of the magnetospheric descriptions is shown in Figure 3 for the two locations of Niemegk, Germany, and Hermanus, South Africa.

DISCUSSION

The similarity between individual observatory data residuals and averages from three observatories in each of the two regions, both for the long-term trend and year to year variation once more confirms a homogeneous large-scale source of this signal.

Differences between the Dxt and Dcx indices determined from four or 17 observatories respectively are very small in the annual means (order of 1 nT) and only the latter versions based on the extended data distribution are included in Figure 3 (labelled Dxt (17) and Dcx (17), respectively). Treating the primary and induced contributions separately in Dst and Rc can cause differences of a few nT in the vertical component, as can be seen in the case of Dst and Est+Int. Dcx and Dxt as expected are also similar to Dst, with Dxt capturing the year to year variations seen in the data better than Dcx. The long-term, decadal trend seen in the data is not explained well by any of these indices. This is not surprising when considering

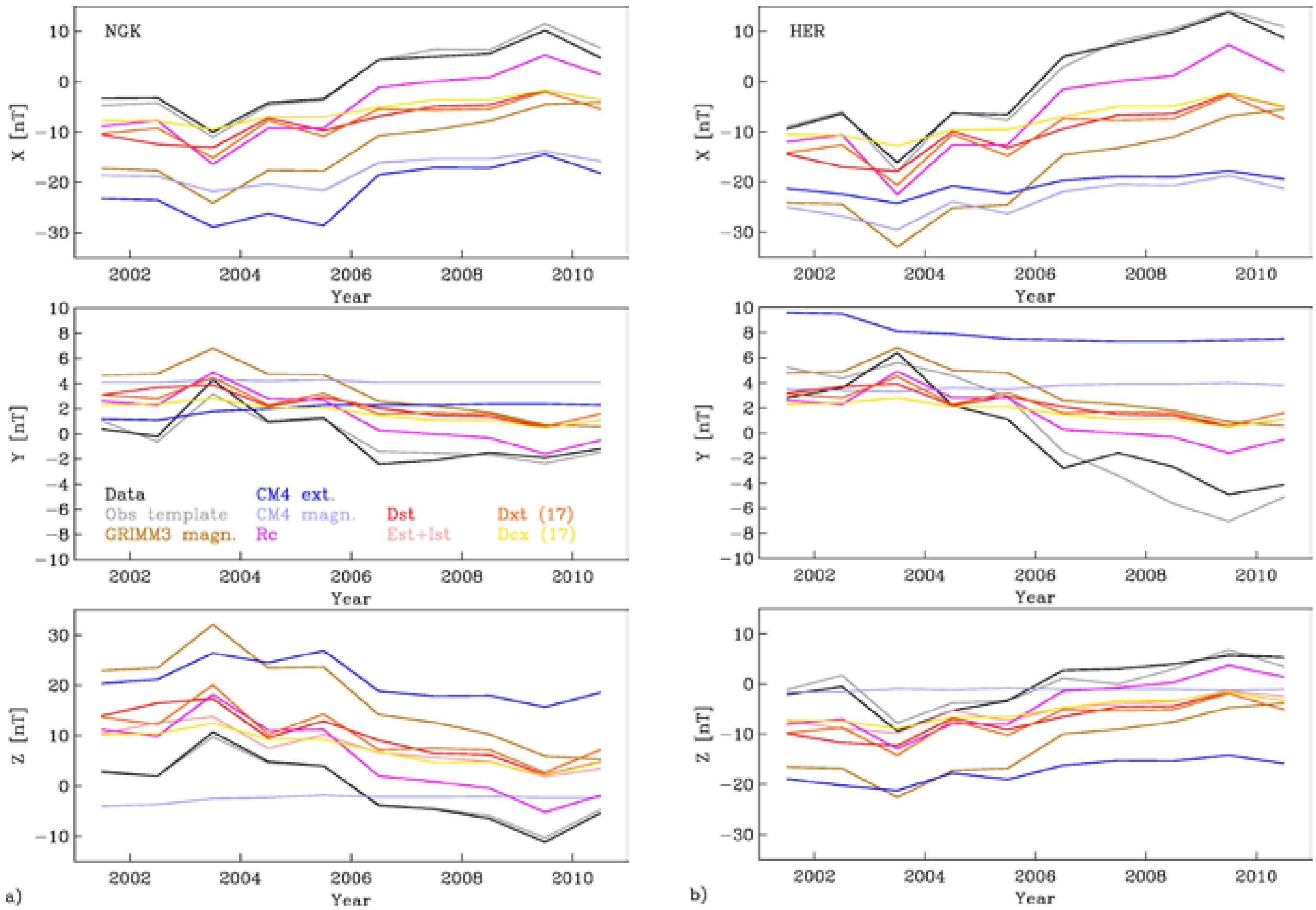

Figure 3. Annual mean observatory residuals (black) as in Fig. 2 for a) NGK (Germany) and b) HER (South Africa) and averaged of the three observatories from each region (gray), respectively, compared to several magnetospheric ring current / large scale external field proxies: based on the GRIMM3 (brown) and CM4 models (light blue: magnetospheric contribution, dark blue: magnetospheric and ionospheric contribution) and using the Dst (red), Est+Ist (light red), Dxt (yellow), Dcx (orange) and Rc(magenta) indices. Geographic north (X), east (Y) and vertical (Z) component from top to bottom.

the derivation of these indices: the core field is subtracted from the data on the basis of a quiet time field estimate on a rather short term basis. The absolute level of the quiet time ring current and long-period variations are not taken into account and the indices have an arbitrary and unstable baseline, as has been noted before by, e.g., Olsen et al. (2005).

The description of primary and induced magnetospheric contribution from the extrapolated CM4 model (CM4 magn.) cannot explain the signal in the Y and Z components, but for X and Z a reasonable description of both long term and year to year variation is given if both magnetospheric and ionospheric contributions are considered (CM4 ext.). However, the recently published CM5 model, which does not rely on a modulation by an independently determined index but co-estimates the magnetospheric contribution (*Sabaka et al., 2015*), would be more appropriate for this time interval and might describe the observed signal better. Among the investigated large-scale external field descriptions the Rc index and the GRIMM3 model describe the observed long-term trend and year to year variation best, however with different constant offsets in all components. It can be assumed that the GRIMM3 model, which co-estimates the large-scale external field in the inversion gives the most accurate description of the true strength of this contribution even during quiet times. The Rc index in contrast has an arbitrary baseline, although with better long-term stability than Dst, as any quiet time background ring current contribution is eliminated in its derivation together with the constant individual lithospheric field estimates for the observatories.

CONCLUSIONS AND OUTLOOK

Observatory annual mean data series contain clear long-term signals of magnetospheric variations . Repeat station data reduced to annual means are subject to the same influence. Similar magnetospheric field contributions are present in repeat station data reduced to quiet night times. Existing magnetospheric field descriptions could be used to eliminate these external field residuals from ground data to provide cleaner data for internal field secular variation studies. This has been investigated by comparing observatory annual mean data after subtraction of core field, secular variation and a constant time averaged lithospheric field estimate to several existing proxies of large-scale external field / magnetospheric field contributions. Accuracy and availability of these descriptions vary and it is not immediately obvious which one to use. The Dst index, its derivatives and the CM4 external field extrapolated to recent times clearly do not capture the trends accurately. For the satellite era, since about 2000, global spherical harmonic models like GRIMM3 and probably also models POMME7 and CM5 (not included in this study), give the best description of the large-scale magnetoshperic field and can be used to correct ground data time series for long-term external field contributions. In the case of a co-estimation of external field without the need for modulation of the description with a magnetospheric index they should even give the correct absolute level of this contribution, which also is present as a background field during magnetically quiet times. The Rc index is easier to apply and does give the correct trend, if not the absolute value. However, it is only available upon request and does not extend back much beyond the satellite era. In order to be able to easily correct multi-decadal time-series of observatory and repeat station data for the external field residual signal it would be useful to develop a new Rc-like index spanning the whole observatory era with correct absolute level.

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