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Geomagnetic secular variation changes in Southern Africa during the SWARM period 2013 - 2018

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Abstract

Geomagnetic field observations from 4 magnetic observatories located in Southern Africa located at Hermanus (HER), Hartebeesthoek (HBK), Keetmanshoop (KMH) and Tsumeb (TSU) have been analysed with the main purpose to identify abrupt secular variation changes on time scales of less than 1 year. Removal of an annual variation resulting from large-scale magnetospheric and ionospheric currents by means of 12-month differences of the respective observatory monthly mean of northward component X, eastward component Y and vertical component Z, revealed clear evidence of several geomagnetic secular variation changes that took place in this region during the period between 2013 and 2018. The geomagnetic field model CHAOS6-x7, based exclusively on SWARM satellite and magnetic observatory data during this period, has been used to determine secular acceleration patterns across Southern Africa. The results obtained revealed that the observed secular variation changes took place over a range of strengths in the respective X, Y and Z components at every magnetic observatory. In addition, the respective observatories in the region also exhibited strong individual characteristics. The findings in this investigation show once again that the southern African region is characterised by unpredictable abrupt geomagnetic secular variation changes that have the potential to render linear prediction models less accurate.

Keywords: Geomagnetism; Secular variation; Geomagnetic jerks; Magnetic observatories.

1. Introduction

The southern African region has been characterised for several years by strong and abrupt changes in the secular variation pattern of the geomagnetic field [Mandea et al., 2007]. Continuous data series from the four INTERMAGNET (www.intermagnet.org) geomagnetic observatories in Southern Africa at Hermanus [Kotzé, 2018], Hartebeesthoek, Keetmanshoop and Tsumeb have been used extensively in the past to study rapid geomagnetic field changes in this region [Kotzé et al., 2007; Korte et al., 2007; Kotzé and Korte, 2016].

Abrupt changes of secular variation trends are also known as geomagnetic jerks [see Mandea et al., 2010 for a review], which make their appearances as distinctive changes of slope in secular variation patterns. They generally occur on timescales of a few months to a few years. Since geomagnetic jerks were discovered in 1969 by Courtillot et al. [1978] and Malin et al. [1983] several rapid changes in the geomagnetic secular variation (SV) pattern have been identified [Mandea et al., 2010; Pinheiro et al., 2011; Brown et al., 2013, 2018]. During the recent past several abrupt secular variation change events appeared in quick succession of each other. In Southern Africa the 2007 abrupt SV change as observed at the Hermanus magnetic observatory [Kotzé, 2010, 2011] has been documented, while the 2012 jerk [Chulliat et al., 2015] exhibits a completely different morphology across the southern African region [Kotzé and Korte, 2016]. A characteristic feature of these most recent events is that they appear to originate from a quick succession of core field acceleration pulses occurring predominantly in West Africa and the South Atlantic region. The 2014 jerk, first reported by Torta et al. [2015] show evidence of intense secular acceleration in the Africa-South Atlantic region extending into Europe, and also regions such as Alaska as pointed out by Brown et al. [2018]. A particularly interesting finding was the variation in strength of the 2014 geomagnetic jerk across Southern Africa [Kotzé, 2017] as revealed by the various field components at each magnetic observatory. In this publication evidence of several abrupt secular variation change events across Southern Africa during the period between 2013 and 2018 will be presented. This period also coincides with the SWARM satellite mission. Although SWARM data started to be collected in November 2013, the first secular variation data became available towards 2014.5. A geomagnetic field model, CHAOS6-x7 [Finlay et al., 2016; http://www.spacecenter.dk/files/magnetic-models/CHAOS-6/], that includes both observatory and data from the SWARM mission will be used to support measurements in this study. We will also show how the amplitudes of these events varied in the different X, Y and Z components at all four magnetic observatories. There exist conference reports for jerk-like feature in late 2014/early 2015 for Alaskan observatories [Brown et al., 2016], and for a Pacific Ocean (Guam) and a Caribbean (San Juan, Puerto Rico) observatory [Brown et al., 2017]. Brown et al. [2018] also reports on an abrupt secular variation change during 2015/2016 that could have implications for the accuracy of global geomagnetic field models like IGRF-12 [Thébault et al., 2015] relying on linear extrapolation-based secular variation routines. These observations elsewhere therefore provide further evidence that abrupt secular variation changes have a global character, but also that the strength as well as the precise timing varies from one location / region to the other.

2. Data, results and discussion

For the purpose of this investigation we selected quiet time data of geomagnetic field variations recorded at the INTERMAGNET magnetic observatories located at Hermanus (HER), Hartebeesthoek (HBK), Hartebeesthoek (HBK), and Tsumeb (TSU) in Southern Africa [Kotzé et al. 2015]. Hourly mean values at HER, HBK, KMH and TSU were required to comply with the Dst ring current index not to change by more than 3nT/h and K-indices less than or equal to 2. This was done in order to eliminate the most disturbed and active geomagnetic conditions as far as possible and in this way provided the best possible compromise between truly quiet times and the amount of data left to derive monthly means based on hourly mean values. These hourly X, Y and Z observations values were additionally corrected for ionospheric (plus induced) fields as well as large-scale magnetospheric (plus induced) fields utilizing the CM4 comprehensive field model [Sabaka et al., 2004]. The model was further updated with the latest f10.7 indices (ftp://ftp.ngdc.noaa.gov) as well as Dst indices till 2018 (http://wdc.kugi.kyoto-u.ac.jp) in order to determine external field effects for the period of this investigation between 2013 and 2018. The latest definitive baseline corrections were also applied, ensuring that the most accurate data were used in this study. Data uncertainty estimates for observatory measurements depend entirely on the accuracy of baselines which at HER are approximately 50% more accurate compared to remote stations such as TSU or KMH where observations are made only once a week in comparison to HER where we perform 3 absolute observations weekly. Error estimates for observatory values for X, Y and Z components therefore vary from ~1 nT at HER to ~1.5 nT for a remote observatory such as TSU or KMH [Kotzé, 2017]. HBK on the other hand has a completely different ground conductivity structure in comparison to the other 3 observatories and therefore behaves differently to external field induction effects. Furthermore, differences between arithmetic mean and median monthly values turned out to be negligibly small. It is, however, suspected that a small amount of external field leakage will still be present in the data in spite of these stringent selection processes. In order to eliminate annual and seasonal variations resulting from magnetospheric and ionospheric currents, including the resulting induction effects, secular variation (SV) values were calculated as first differences of the X, Y and Z monthly means at time t as the difference between those at time $t + 6$ months and

t – 6 months. This procedure is standard when studying abrupt secular variation changes [Mandea et al., 2000; Olsen and Mandea, 2007], however it implies that SV information is limited to 6 months after the beginning of the time series and 6 months before the last available main field measurements. The time interval in this investigation therefore stretches from 2013.0 to 2017.5 and includes data from 2012.5 to 2018.0.

The rates of SV change were subsequently determined from the respective time series by piecewise (segmented) linear fits. The different piecewise linear fit segments cover the full time range from 2013.0 to 2017.5 for all investigated time series. The break points between two consecutive linear segments were determined by using, a software computer algorithm, called SegReg (http://www.waterlog.info/pdf) that searched for an identifiable and distinctive changes in the slope of the respective segments. The breakpoint is numerically found by adopting several potential tentative breakpoints and performing a linear regression at both sides of them. The tentative breakpoint that provides the largest coefficient of determination (as a parameter for the fit of the regression lines to the observed data values) is then selected as the true breakpoint. All breakpoints were determined by applying a 95% statistical confidence level. This procedure also included an iterative method to obtain the best linear fit and the subsequent slope of a particular time interval by optimising the regression coefficient. The scatter in the secular variation data made it almost impossible to obtain a 100% fit of the different linear fits on both sides of some breakpoints. In the present investigation we limited the code to only secular variation data between 2013 and 2017.5 in contrast to a previous investigation where the data ranged between 2006 and 2015 [Kotzé, 2017]. As the code is quite sensitive to the range of data provided the present results are to be regarded as more accurate and representative of the trends observed between 2013 and 2017.5 as we also employed the latest updated observatory baselines.

Results for X, Y and Z components at HER, HBK, KMH and TSU are shown in Figures 1, 2, 3, and 4 respectively as a function of time after applying the procedures described above. Included in these figures are values of R indicating an estimate of the quality of each linear fit. R values are determined using the following formula:

$$R^2 = 1 - \frac{\Sigma\,(SV_{OBS} - SV_{FIT})^2}{\Sigma\,(SV_{OBS} - SV_{AV})^2} \qquad (1)$$

Where: SV_{OBS} = Secular variation observations

SV_{FIT} = Fitted secular variation values

SV_{AV} = Average of observed secular variation values

Therefore R can have values between 0 and 1 with values closer to 1 indicating a better fit estimate. In addition the Standard Errors (SE) of the respective fits are also included in the legends of the respective figures.

We employed the latest CHAOS6-x7 geomagnetic field model to determine secular acceleration (SA) patterns for X, Y and Z across Southern Africa. This particular geomagnetic field model utilises both observatory and SWARM satellite data up to and including August 2018 and is able to calculate field information for the period 1999 till 2019. Figures 5, 6, and 7 respectively show the secular acceleration behaviour of the X, Y and Z components for 2015.5. These plots therefore represent snapshots of the SA for X, Y and Z at 2015.5. Included in these figures are the experimentally determined SA values at the respective observatories for 2015.5 using monthly mean observatory data.

From figures 1 to 4 it is evident that the X-component secular variation follows the same pattern at all observatories. However, at TSU we notice that between 2015 and 2016.5 the secular acceleration differs quite strongly in magnitude from HER and HBK, where it is observed to be much stronger. At KMH, however, between 2015.5 and 2016.5 the tendency is in the opposite direction in comparison to the other 3 observatories. According to CHAOS6-x7 the X-component secular acceleration (Figure 5) in the southern African region is characterised by strong gradients around 2015.5, with the secular variation change across this region characterised by an increasing tendency from East to West. Figure 5 therefore represents a snapshot of SA as determined by the CHAOS6-x7 field model. Next to each observatory the value of SA as determined from experimental data at 2015.5 is presented. In general the model values underestimate observations. The most significant difference between observation and model value is at KMH where we measure a value of -37.0 nT/yr^2, while CHAOS6-x7 predicts a value of ~ 4.5 nT/yr^2. The strength of the sudden 2014 and 2015 geomagnetic secular variation change in the X component (i.e. the difference in slope of dX/dt before and after the event) is found to be the strongest at KMH, while during 2016 it is at TSU.

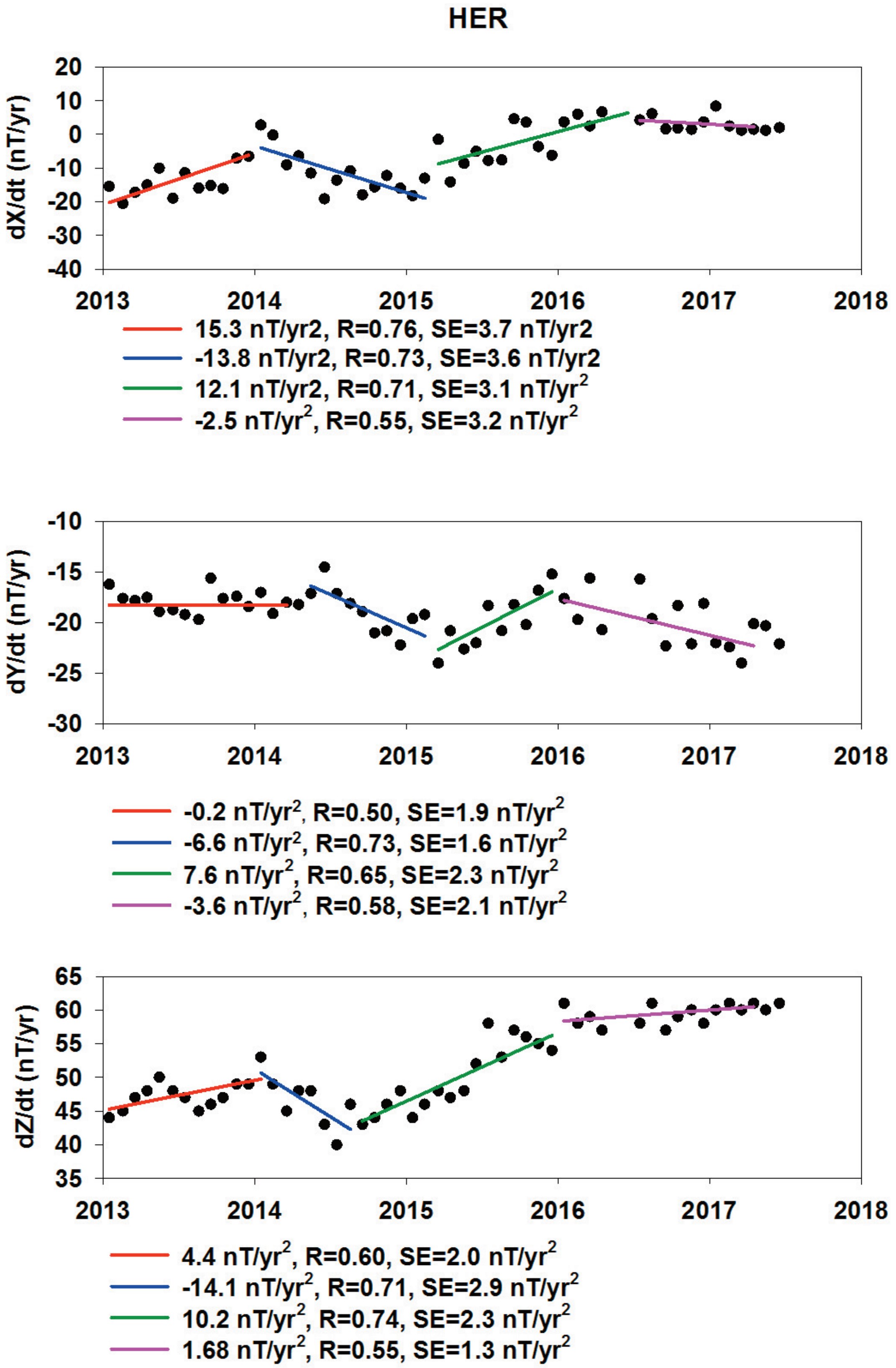

Figure 1. Figure 1. Secular variation of the X, Y and Z components at HER between 2013.0 and 2017.5. The black dots show monthly mean secular variation estimates derived from 12-month differences, while piecewise linear fits to the data provide estimates of secular acceleration as given in the respective legends. Regression coefficients R provide an estimate of the quality for every fit, while Standard Errors (SE) are included for comparative purposes.

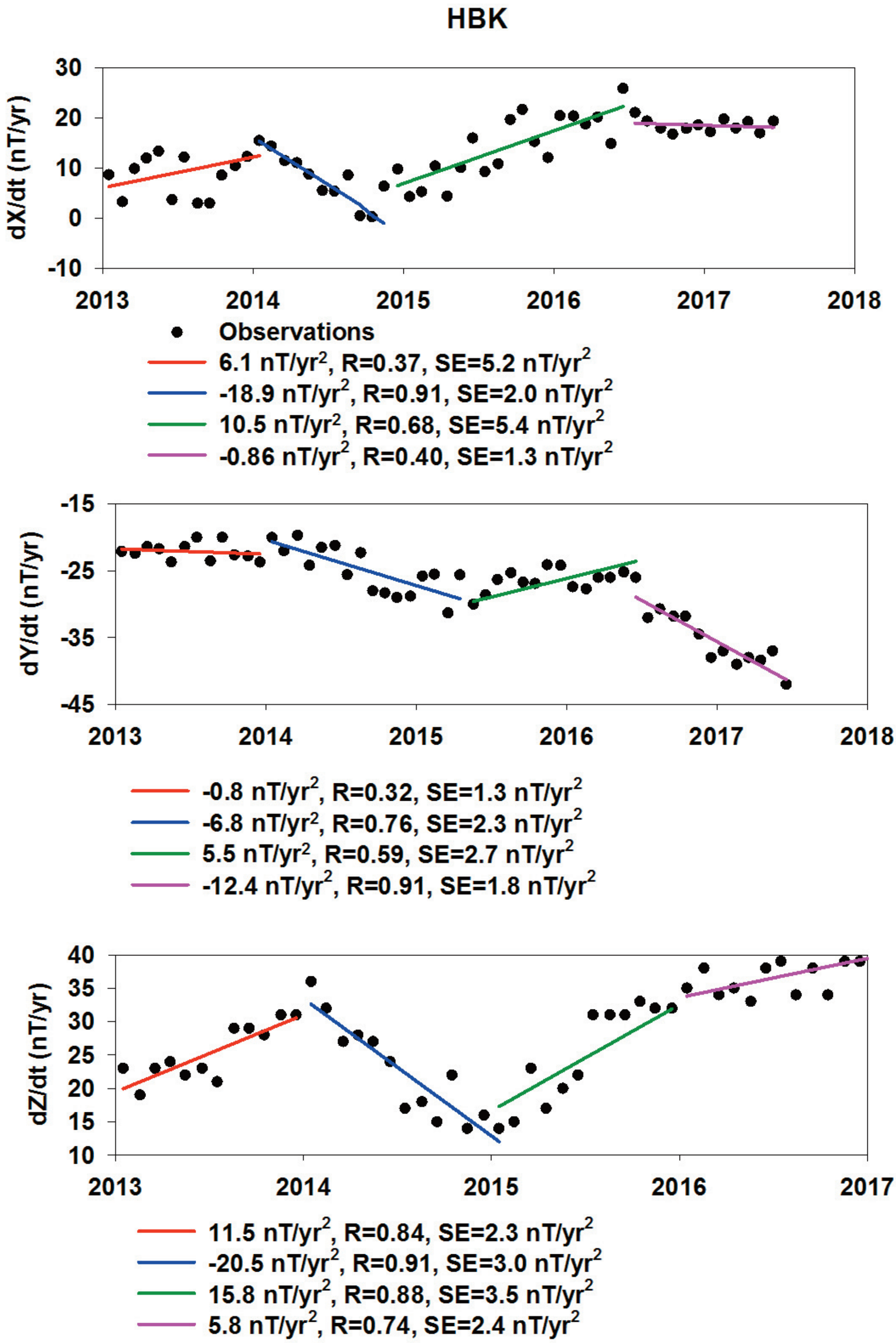

Figure 2. Secular variation of the X, Y and Z components at HBK between 2013.0 and 2017.5 as derived from monthly-mean values. The black dots show monthly mean secular variation estimates derived from 12-month differences, while piecewise linear fits to the data provide estimates of secular acceleration as given in the respective legends. The quality of each fit can be estimated by the respective regression coefficients R, while Standard Errors (SE) are also included.

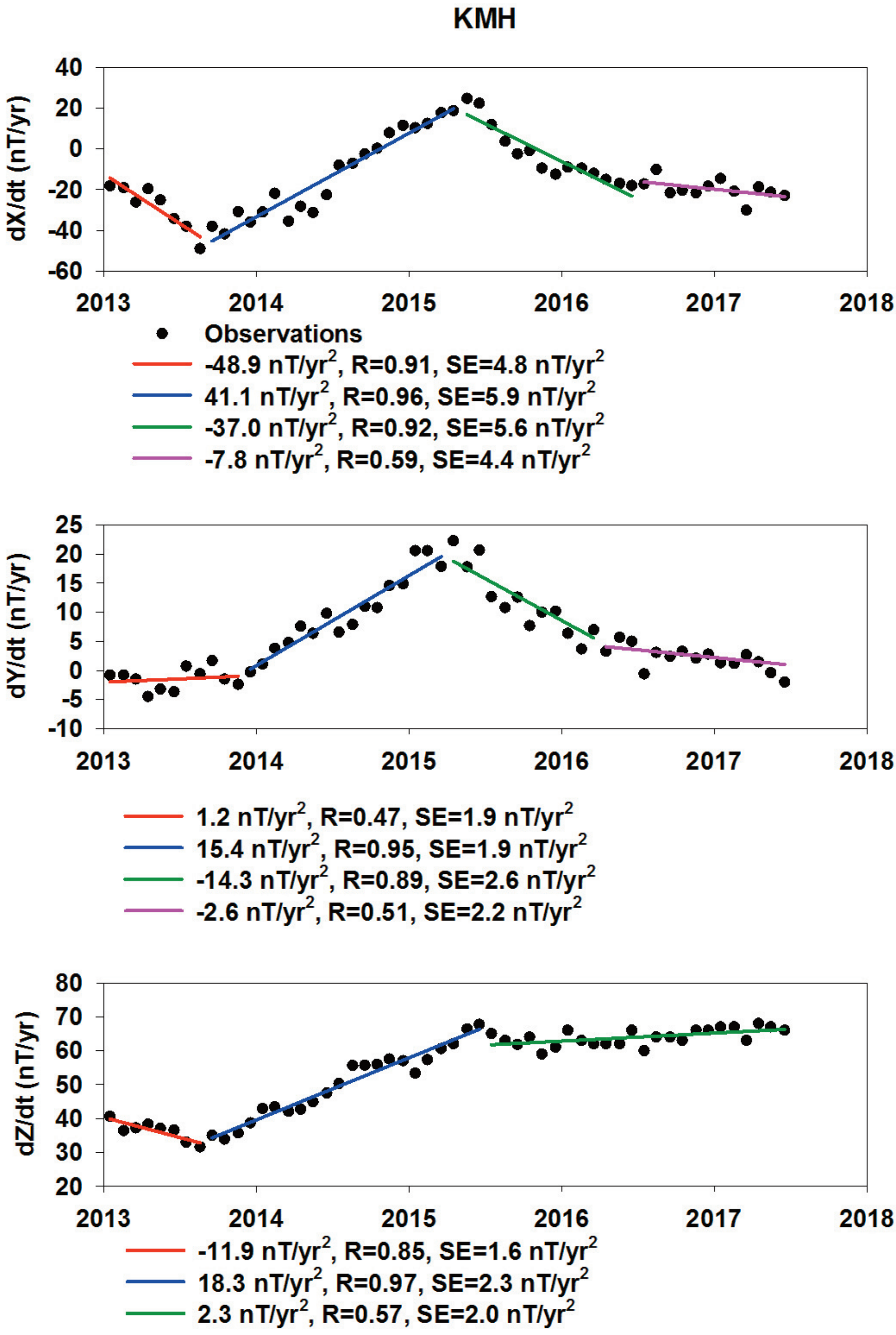

Figure 3. Secular variation of the X, Y and Z components at KMH between 2013.0 and 2017.5. The black dots show monthly mean secular variation estimates from 12-month differences, while automatically fitted piecewise linear fits to the data provide estimates of secular acceleration as given in the respective legends. Regression coefficients R provide an estimate of the quality for every fit, together with Standard Errors (SE).

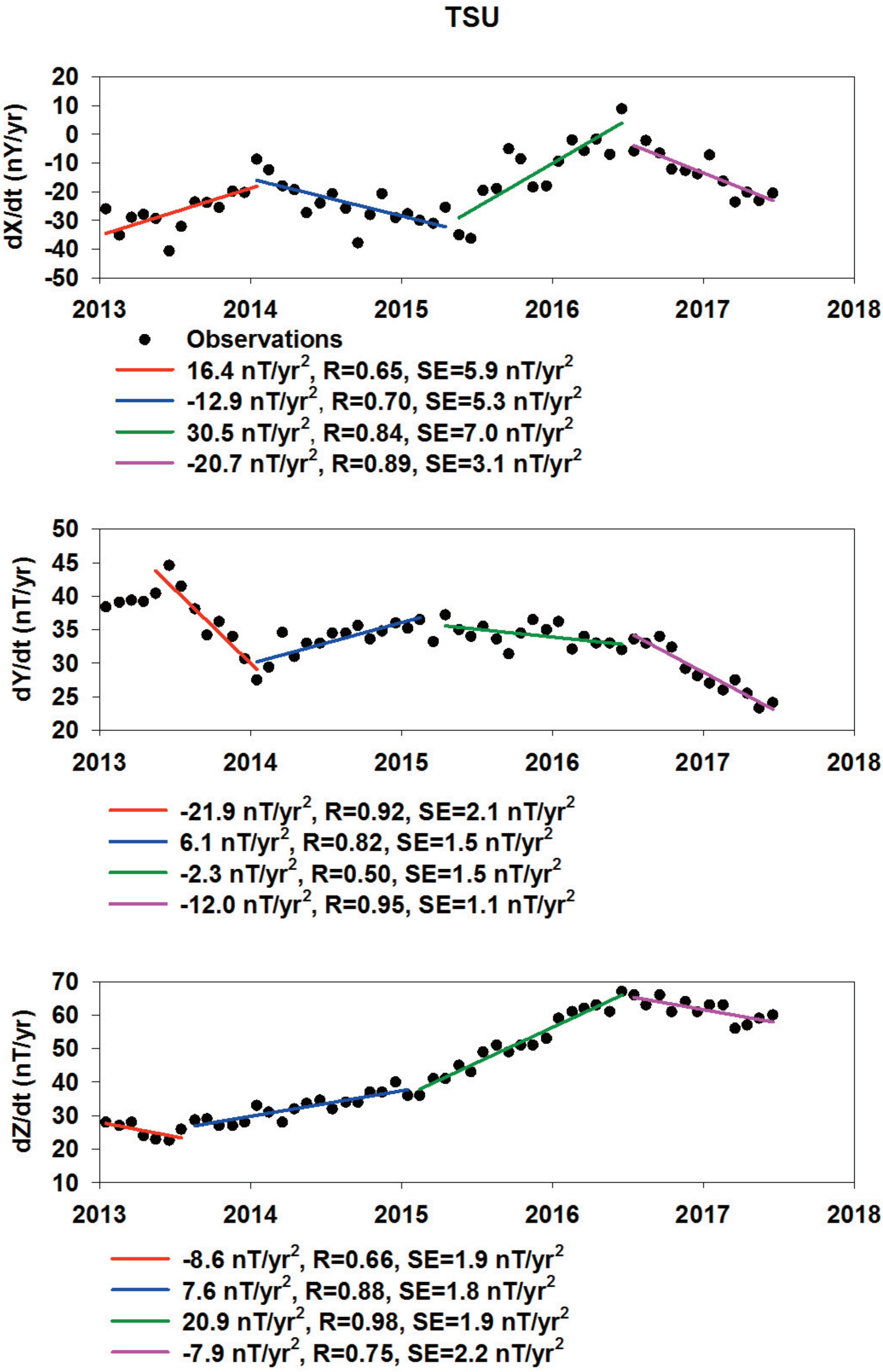

Figure 4. Secular variation of the X, Y and Z components at TSU between 2013.0 and 2017.5 as derived from monthly-mean observations. The black dots show monthly mean secular variation estimates from 12-month differences, while automatically fitted piecewise linear fits to the data provide estimates of secular acceleration as given in the respective legends. The quality of each fit can be estimated by the respective regression coefficients R, while Standard Errors (SE) are provided for comparative purposes.

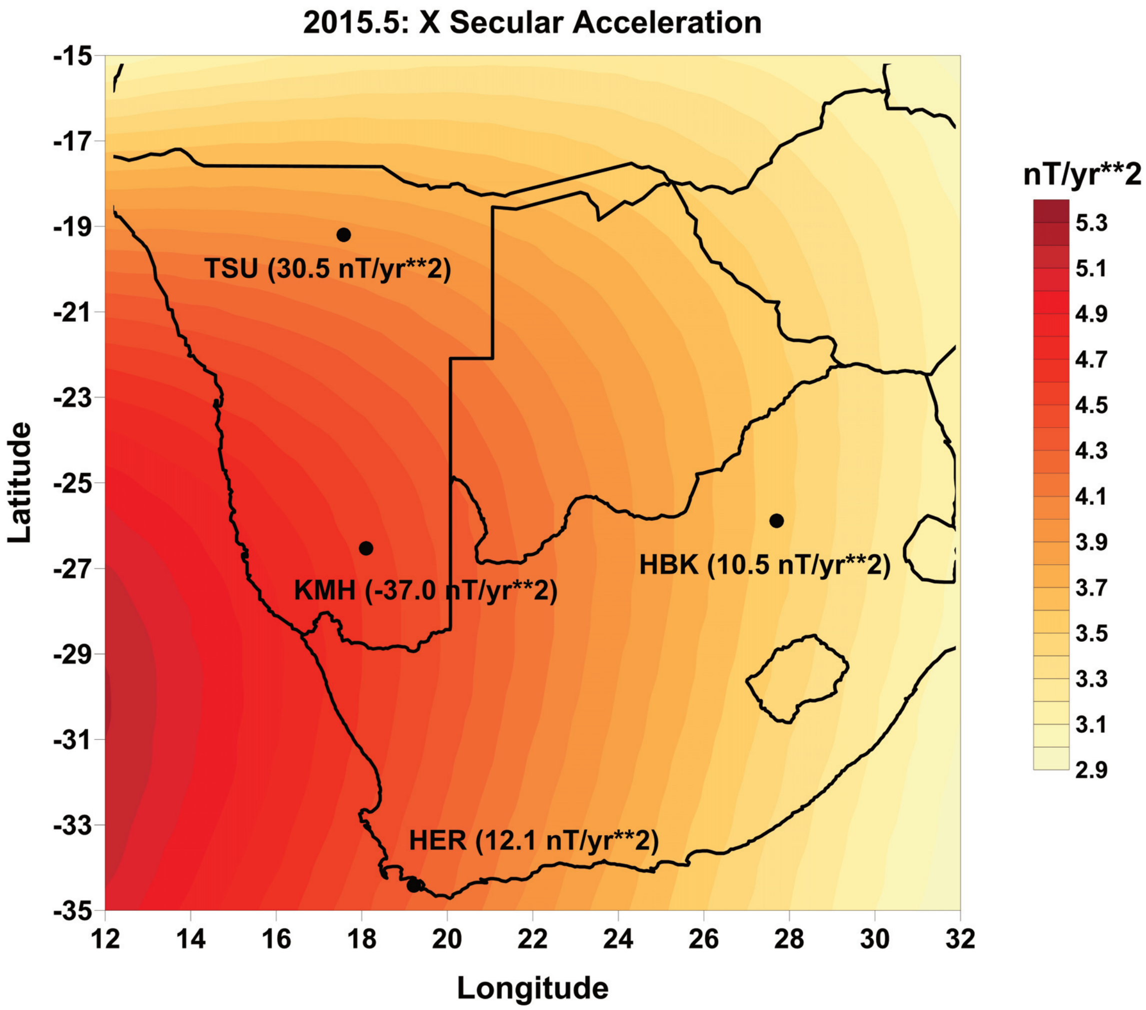

Figure 5. A map showing X-component secular acceleration at the Earth's surface at 2015.5 in the southern African region as determined using the CHAOS6-x7 model. The positions of the different observatories used in the investigation are indicated by their respective IAGA codes and black dots. Values for SA determined form experimental observations at 2015.5 are included for each observatory to serve as reference.

This is supported by CHAOS6-x7 model evaluations. At HER, HBK and KMH observatories we ascertained that the absolute magnitude/strength of the X-component secular variation change during both 2014 and 2015 is more than twice the absolute strength of the 2016 event (see Table 1). At TSU however the absolute intensity of the 2014 event is substantially weaker than during 2015 and also 2016, in contrast to the other 3 observatories where we observe a decreasing tendency in absolute intensity from 2014 to 2016.

On the other hand the Y-component secular variation changes at both HER and HBK are in complete contrast to the behaviour at TSU, and KMH. This is not surprising since the Y secular variation at HER and HBK is of opposite direction to that at TSU and KMH. It is also evident that the absolute strength of the 2015 secular variation change (29.7 nT/yr^2) at KMH is almost double the absolute strength of the 2014 and 2016 events (~14 and 12 nT/yr^2 respectively), while at HER and HBK the 2015 and 2016 SA change is much stronger (~ 2x) than the 2014 change in the Y-component. Figure 6 shows a contour map of the Y secular acceleration at 2015.5 as determined by the CHAOS6-x7 model, showing that SA increases from -1.7 nT/yr^2 in the East to approximately 0.2 nT/yr^2 in the West across Southern Africa. We observe that CHAOS6-x7 in general underestimates the experimental values with the greatest deviations observed at HER and HBK.

The Z-component SV change at all observatories in this investigation showed a positive tendency (Figures 1-4) between 2015 and 2016.5. This is in strong contrast to the 2003 geomagnetic secular variation change in 2003 when Olsen and Mandea [2007] found a strong decreasing secular variation ($d^2Z/dt^2 < 0$) in the southern African continental

Δ SA(nT/yr^2)	HER	HBK	KMH	TSU
		2014		
$\Delta(d^2 X/dt^2)$	29.1	25.0	-90.0	29.3
$\Delta(d^2 Y/dt^2)$	6.4	6.0	-14.2	-28.0
$\Delta(d^2 Z/dt^2)$	18.5	32.0	-30.2	-16.2
		2015		
$\Delta(d^2 X/dt^2)$	-25.9	-29.4	78.1	-42.4
$\Delta(d^2 Y/dt^2)$	-14.2	-12.3	29.7	8.4
$\Delta(d^2 Z/dt^2)$	-24.3	-36.3	17.9	-13.3
		2016		
$\Delta(d^2 X/dt^2)$	14.6	11.3	-29.2	51.2
$\Delta(d^2 Y/dt^2)$	11.2	17.9	-11.7	9.7
$\Delta(d^2 Z/dt^2)$	8.5	10.0	-4.8	28.8

Table 1. Strength of geomagnetic secular acceleration changes (Δ SA) as observed at HER, HBK, KMH and TSU during 2014, 2015 and 2016 for the X, Y and Z components.

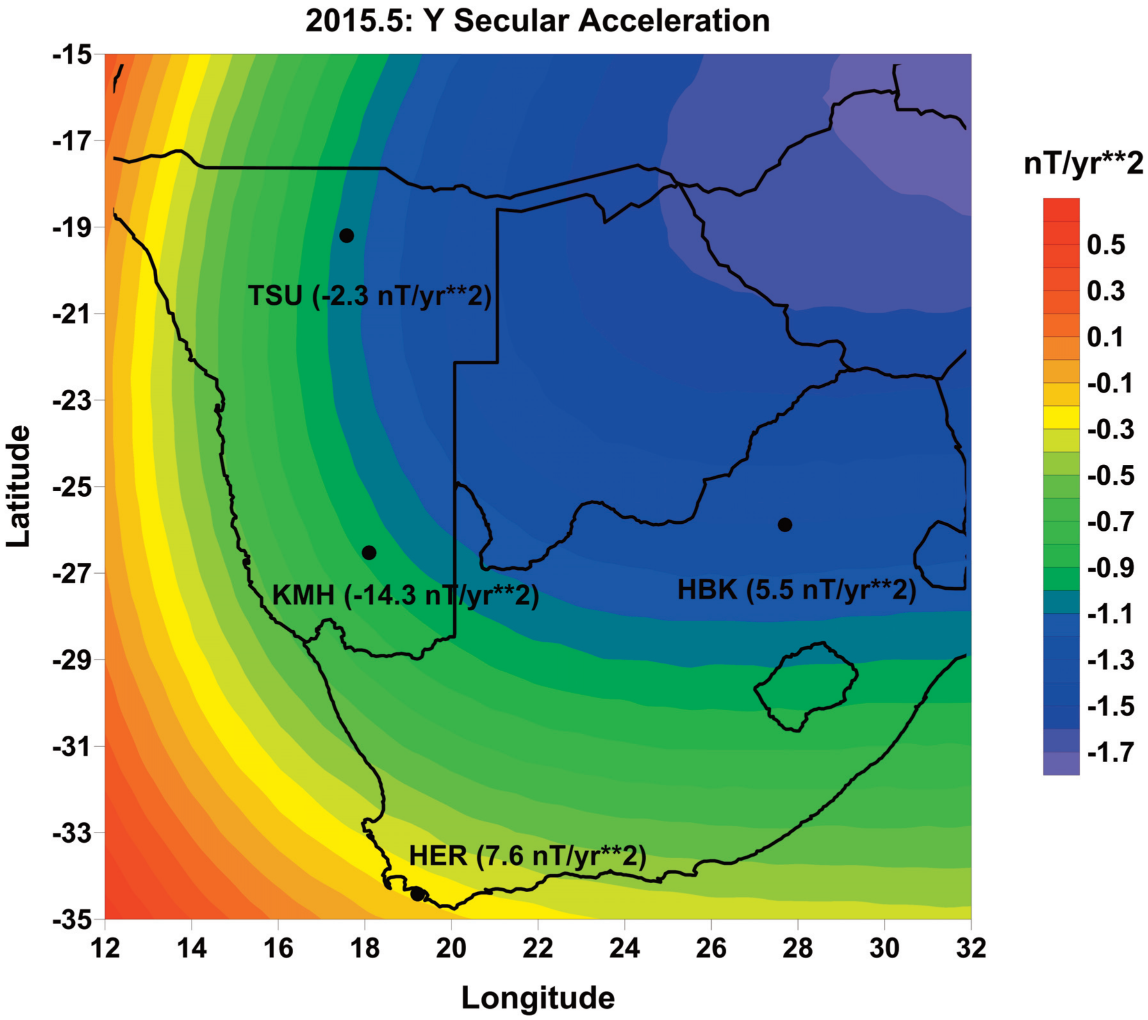

Figure 6. A map showing Y-component secular acceleration at the Earth's surface at 2015.0 in Southern Africa using the CHAOS6-x7 model. The positions of the different observatories used in the investigation are indicated by their respective IAGA codes and black dots. Values for SA determined form experimental observations at 2015.5 are included for each observatory to serve as reference.

and surrounding ocean area using satellite data. In the case of HER, KMH and HBK the secular variation during 2016 changes from an increasing tendency during 2015 to again another positive gradient. This is in strong contrast to TSU where we observe the strongest change in secular variation change for the Z component (20.9 nT/yr^2). The positive tendency of secular variation change observed around 2015.5 at all observatories is consistent with the Z secular acceleration contour map in Figure 7 using the CHAOS6-x7 field model, although the observed strengths are much larger than the modelled values. The behaviour of the Z-component secular variation at TSU around 2015 does not show a change in sign while a similar behaviour could also be observed during 2016 at HER, HBK and KMH.

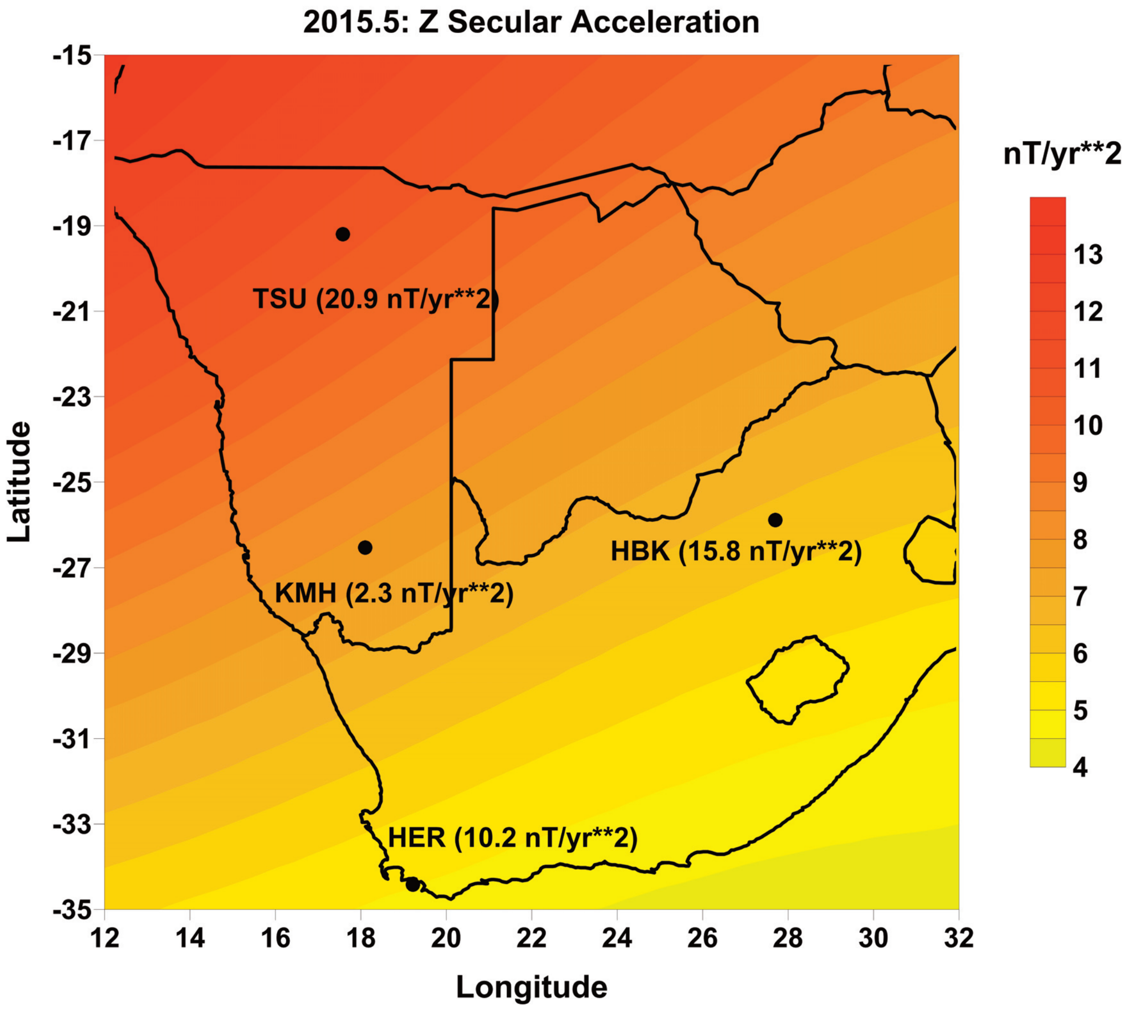

Figure 7. CHAOS6-x7 geomagnetic field model estimates of Z component secular acceleration across Southern Africa for 2015.0. The respective magnetic observatories used in this study are indicated by black dots and their IAGA codes. Values for SA determined form experimental observations at 2015.5 are included for each observatory to serve as reference.

3. Conclusions

We used monthly mean X, Y and Z geomagnetic field observations from 4 magnetic observatories across Southern Africa to identify the occurrence of rapid secular variation changes during the period 2013 – 2018. This is also a period during which data from the SWARM satellite mission were used to derive the CHAOS6-x7 geomagnetic field model. The observatory data covered the period between 2012.5 and 2018.0, allowing us to determine secular variation values between 2013.0 and 2017.5 based on a 12-month difference technique. The 2014 event [Kotzé, 2017] could also be clearly identified employing the latest baselines and data reduction principles. We were able to clearly

identify a secular variation change event in all components at HER, HBK, KMH and TSU observatories during 2015 and 2016, with the exception of KMH showing no secular variation change during 2016. Due to a reduction in noise levels, which was achieved through a stringent data selection process, the upgrading of the CM4 comprehensive magnetic field model with the latest available indices till 2018 and the application of the most recent baselines, e.g. the Z-component at TSU, we are now able to identify changes around 2014 more clearly, which was not possible during the previous analysis. This investigation provides an opportunity to make a comparative analysis of the changing secular variation patterns at 4 different magnetic observatories located in a region characterized by rapid and strong field changes [Mandea et al., 2007], separated in time by only 1 year. Such a short time in between two successive secular variation changes is in contrast to the generally accepted assumption and findings proposed by Chulliat et al. [2010] and Chulliat and Maus [2014] that geomagnetic jerks are the resulting consequences of acceleration pulses at the core surface with a 3-4 year separation as observed during the last 10-15 years [see also Torta et al., 2015]. The 2014 jerk is generally accepted as the result of the descending phase of an intense acceleration pulse during 2012-2013 [Torta et al., 2015]. It is unclear what exactly caused the abrupt secular variation changes during 2015 and 2016, but a possible explanation could be the occurrence of more acceleration pulses at the core surface. Brown et al. [2018] pointed out the occurrence of geomagnetic secular variation changes (jerks) at several locations across the globe during 2015 - 2016 by studying SV patterns obtained from observations and field models. According to the findings by Brown et al. [2013] as well as Chulliat and Maus [2014], successive jerks have opposite signs, i.e. if the slope of secular acceleration increases (decreases) with one jerk it decreases (increases) with the next jerk. This behaviour is confirmed for most observatories and most components. The exception however is the Z-component at TSU during 2015, as well as at HER, HBK, and KMH during 2016 where consecutive increases in secular variation have been observed. On the other hand, KMH is the only observatory during 2016 that exhibited similar patterns in its secular variation changes for both X and Y components, as shown in Figure 3.
Finding the cause of the abrupt SV changes during 2015 and 2016 and to determine the source mechanism in the core is beyond the scope of this paper. Our main purpose was to report some of the abrupt secular variation features as observed in Southern Africa at ground level during the SWARM satellite mission for the period between 2013 and 2018. Recent publications by Aubert [2018] and Aubert and Finlay [2019] provided a new theory to explain the occurrence of geomagnetic jerks. The authors successfully showed in numerical simulations of the geodynamo that rapid changes in secular variation (jerks) can be modelled by taking into account the interaction of the slow convection of the core and rapid hydromagnetic waves. A direct consequence of these successive abrupt changes in secular variation is that predicting secular variation changes in future is more challenging than previously thought [Torta et al., 2015]. Brown et al. [2017, 2018] pointed out that the currently unpredictable occurrence of abrupt SV changes could have an impact on the accuracy of global field models, particularly the International Geomagnetic Reference Field which uses linear prediction secular variation methodology, particularly if a sudden SV change takes place early in the lifetime of such a model. The timely release of accurate ground-based magnetic observatory data is therefore of paramount importance to be integrated with satellite data like SWARM for the derivation of e.g. the CHAOS series of geomagnetic field models in order to obtain the most accurate and up-to-date description of the temporal behaviour of the Earth's field.

Data archive. All geomagnetic data used in this investigation are located at: https://sandims.sansa.org.za/.

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