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Quantifying solar flux and geomagnetic main field influence on the equatorial ionospheric current system at the geomagnetic observatory Huancayo

Jürgen Matzka[a], Tarique A. Siddiqui[a,b], Henning Lilienkamp[b], Claudia Stolle[a,b], Oscar Veliz[c]

[a]GFZ German Research Centre for Geosciences, 14473 Potsdam, Germany
juergen.matzka@gfz-potsdam.de

[b]Institute of Earth and Environmental Sciences, University of Potsdam, 14469 Potsdam, Germany

[c]Instituto Geofísico del Perú, Jicamarca Radio Observatory, Lima, Peru

Corresponding author: Jürgen Matzka, juergen.matzka@gfz-potsdam.de

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Abstract

In order to analyse the sensitivity of the equatorial ionospheric current system, i.e. the solar quiet current system and the equatorial electrojet, to solar cycle variations and to the secular variation of the geomagnetic main field, we have analysed 51 years (1935 to 1985) of geomagnetic observatory data from Huancayo, Peru. This period is ideal to analyse the influence of the main field strength on the amplitude of the quiet daily variation, since the main field decreases significantly from 1935 to 1985, while the distance of the magnetic equator to the observatory remains stable. To this end, we digitised some 19 years of hourly mean values of the horizontal component (H), which have not been available digitally at the World Data Centres. Then, the sensitivity of the amplitude ΔH of the quiet daily variation to both solar cycle variations (in terms of sunspot numbers and solar flux F10.7) and changes of the geomagnetic main field strength (due to secular variation) was determined. We confirm an increase of ΔH for the decreasing main field in this period, as expected from physics based models

(Cnossen, 2016), but with a somewhat smaller rate of 4.4 % (5.8 % considering one standard error) compared with 6.9 % predicted by the physics based model.

Keywords

Magnetic field; equatorial ionosphere; geomagnetic secular variation; solar cycle

Introduction

On time scales of decades to centuries, the thermosphere and ionosphere have undergone long-term changes like cooling and contraction. Possible drivers discussed in the literature are changes in greenhouse gases or the geomagnetic main field and the forcing from the lower atmosphere as well as long-term trends in solar activity and geomagnetic activity (e.g. Cnossen, 2012; Cnossen, 2016). To better understand these long-term changes in the upper atmosphere, it is important to know the sensitivity of the system to the secular variation of the geomagnetic field as well as changes in solar flux. There are two ways to study long-term trends. One is by modelling the physics of the coupled thermosphere-ionosphere-magnetosphere system by using geomagnetic main field models at different epochs to introduce a time dependency and by taking into account different solar activity levels, parameterised by the F10.7 solar flux index (e.g. Cnossen et al., 2012; Cnossen and Richmond, 2013; Cnossen and Matzka, 2016). The other approach is by analysing homogenous time series of observations that are sensitive to ionospheric processes such as geomagnetic observatory data (e.g. Sellek, 1980; Schlapp et al., 1990; Macmillan and Droujinina, 2007; de Haro Barbas et al., 2013, Shinbori et al., 2014).

The quiet daily variation at a station close to the magnetic equator (defined as the line around the globe with geomagnetic inclination I = 0° or vertical component of the geomagnetic field Z = 0 nT) combines contributions from the solar quiet (Sq) current system and the equatorial electrojet (EEJ). The EEJ is a current ribbon (e.g. Chapman, 1951; Marriot et al., 1979; Stening, 1985, Lühr et al., 2004) limited to a few degrees in latitude along the magnetic equator. Since both the Sq currents at low latitudes and the EEJ current system are east-west oriented, their magnetic field at ground level is oriented northerly and simply adds to the horizontal component of the geomagnetic field H. Hence the H component is usually studied to quantify Sq and EEJ at the equator. The Sq and EEJ currents and their magnetic effects are assumed to be zero during night time and they assume a maximum at local noon (corresponding to 17:00 UT at HUA).

In order to study the effect of the secular variation of the Earth's magnetic field on the strength of the equatorial ionospheric current systems, we investigate the amplitude of the magnetic variation measured at Huancayo, Peru. The geomagnetic observatory Huancayo (IAGA code HUA, latitude -12.05°, longitude 284.67°, geomagnetic inclination I =-0.53° in 2017, operated by Instituto Geofísico del Perú) has been very close to the magnetic equator since it was established in 1922. This is expressed by its consistently small geomagnetic inclination (Fig. 1a). At the same time, the geomagnetic field strength has decreased considerably in the region during this period due to secular variation (Fig. 1b). Indeed, this is the strongest decrease in geomagnetic field strength observed at any location where the magnetic equator remained stationary over the last 100 years or so (see, e.g. Figure 1 and Figure 2 in Cnossen and Richmond, 2013). For our investigation, we had to digitise significant amounts of handwritten data to fill in data gaps in the existing digital datasets for Huancayo.

A scaling law has recently been derived by Cnossen (2016) that predicts that the daily magnetic variation of the H component at the magnetic equator is proportional to $M^{-0.7}$, with M being the dipole moment of the Earth's magnetic field. This is based on results by a Coupled Magnetosphere-Ionosphere-Thermosphere (CMIT) model (Cnossen et al, 2012) which consists of a magneto-hydrodynamic magnetosphere model and the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM) and is in agreement with an earlier scaling law for the Cowling conductance (Glassmeier, 2004). We will compare our analysis of Huancayo data to the physics-based approach by Cnossen (2016). Note that for model-based studies often a simple dipole geomagnetic field is used, for which the local geomagnetic field strength F everywhere scales linearly with dipole moment. The Earth's magnetic field, however, is more complex, and therefore we compare the quiet daily variation with the field strength F at Huancayo rather than the dipole moment M.

Material and Methods

Geomagnetic ground data come with different levels of quality, calibration and time resolution. Data from geomagnetic observatories have the highest level of quality and are absolutely calibrated (e.g. Matzka et al., 2010, Chulliat et al., 2016). These data can be used to study secular variation (the slow changes of the geomagnetic main field due to processes in the core of the Earth) as well as long-term trends in the magnetic signature of ionospheric and magnetospheric currents (e.g. Cnossen and Richmond, 2013). For secular variation studies, annual means of observatory data already contain the major information of its variability, while ionospheric or magnetospheric studies typically require hourly mean values or minute means, e.g. to properly describe daily and seasonal variations. For the geomagnetic observatory HUA, which is operated since 1922, there exists a continuous series of annual means, but there are significant gaps in data coverage for hourly mean values at the World Data Centres in the 1960ies to mid 1980ies (see Fig. 1 d). The hourly mean values in the period considered here (1935 to 1985) were produced with the original instrument installed at Huancayo in 1922, the Eschenhagen-type magnetograph DTM CIW Nr. 2 with a photographic recorder by Otto Toepfer und Sohn, Potsdam (Choque et al., 2014).

We have digitised existing scans of the handwritten, monthly tables of hourly mean values of the H component from Huancayo or their microfilmed copies obtained from the World Data Center for Solar-Terrestrial Physics, Boulder, and scanned as digital images. To this end, about 19 years of HUA data have been digitised recently by us by typing from the digital images, corresponding to more than 150,000 hourly mean values for the H component with 1 nT resolution. However, for 1992 to 1997 no such handwritten data exists and this gap could not be filled in.
During some periods, mainly 1964 to 1967 and some shorter intervals in the end of the 1960ies, there is now both newly digitised data as well as already existing values from the World Data Centre (WDC) for Geomagnetism, Kyoto, available. The data from these two sources are not always identical, and, except for the period August 1966 to December 1966 (here, the data from WDC showed unexpectedly large amplitudes in the daily variation when normalised to the solar flux), we used the data from the WDC for the analysis here (Matzka et al., 2017).

Daily total sunspot numbers R were taken from WDC-SILSO, Royal Observatory of Belgium, Brussels (http://www.sidc.be/silso/DATA/SN_d_tot_V2.0.txt), dataset after revision from July 1st, 2015 (SISLO, 2017). The Kp index and the International Quiet Days were taken from GFZ German Research Centre for Geosciences, Potsdam (ftp://ftp.gfz-potsdam.de/pub/home/obs/kp-ap/). The definitive Dcx index (Mursula and Karinen, 2005; Mursula et al, 2008) was taken from University Oulu (http://dcx.oulu.fi). The Dcx index is an extended (back to 1932) and seasonally corrected version of the Dst index. Solar radio flux values F10.7 are provided from Natural Resources Canada (http://www.spaceweather.ca/solarflux/sx-en.php), we have used daily observed F10.7 values.

Calculation

We performed two independent analyses to calculate the annual mean of the daily variation amplitude and then subtracted the solar cycle variation from it. This is done for the years 1935 to 1985, when inclination at Huancayo was rather constant (Fig. 1a), but magnetic field strength was decreasing (Fig. 1b).

In the first approach, labelled A_1, the Dcx index was subtracted from the H component to remove the effect of the magnetospheric ring current from the data. To characterise the amplitude ΔH of the daily variation, for every day a quiet night time value was subtracted from the mean of H for the time from 11 to 14 LT. The quiet night time values were determined for each month by taking the mean of the night time values (from 23 to 03 LT) for the 5 International Quiet Days published by GFZ. Thus the geomagnetic main field was removed from the data and ΔH represents the amplitude of both the Sq and the EEJ signal. Only days with $\sum Kp \leqq 18$ were selected to calculate the annual mean of ΔH.

In the next step of approach A_1, the linear regression between annual means of ΔH and the annual means of daily total sunspot number R was determined and subtracted from the annual means of ΔH. This yields annual means of the residual $\Delta H_r = \Delta H - \Delta H_p$ (ΔH_p are predicted from R by the obtained linear fit) independent from solar cycle variations.

In the second approach, denoted here A_2, first the Dcx index was subtracted from the H component and hourly mean values were kept only for periods with $Kp < 3$. Then, quiet night time levels were determined by calculating the median value of H from 23 LT to 04LT (the same approach as used by Yamazaki (2010)) for each night and linearly interpolated between the nights to have continuous time series of quiet night time values. The quiet night time levels were subtracted from the H component, removing the main field and yielding an hourly mean value time series representative of the EEJ and Sq signal and being close to zero at night time. For each day, the daily maximum was reconstructed from these hourly mean values by fitting a cubic spline to the 7 values around noon (09:30 LT to 15:30 LT). The maximum of the spline fit then represents ΔH. Annual mean values of ΔH were then calculated.

In the second step of approach A_2, the linear regression between annual means of ΔH and the annual means of square root of a reconstruction of solar flux F10.7 was determined and used to predict ΔH_p, which was subtracted from the annual means of ΔH to yield annual means of the residual of ΔH. Since F10.7 values only go back to 1947, and the relationship between F10.7 and sunspot number in Siddiqui et al. (2015) is only valid for the superseded (pre 2015) sunspot time series, we have updated the relationship for reconstructing daily observed F10.7 from the revised daily total sunspot number:

(1) $$F10.7 = 0.59 * R + 66.65$$

and use this to calculate annual means of F10.7 from 1935 to 1946.

Results

The annual means of ΔH for 1935 to 1985 calculated by approach A_1 and A_2 are shown in Fig. 1c and Fig. 1d, respectively. Both show clearly the signatures of 5 solar maxima (solar cycles 17 to 21). Approach A_1 yields lower ΔH values than approach A_2. The same can be seen in Fig. 2. Approach A_1 yields ΔH values that are one-third (for lowest solar activity) to one-fourth (for highest solar activity) lower than those by approach A_2 (Fig. 2). There exists a well-defined linear relationship between the results of the two approaches

(2) $$\Delta H(A_1) = 0.84 * \Delta H(A_2) - 14.0 \text{ nT}$$

with a linear correlation coefficient r = 0.99.

Both approaches show a linear relationship that predicts annual mean ΔH_p, i.e. the solar cycle dependency of ΔH, from sunspot numbers R for approach A_1 and from $\sqrt{F10.7}$ for approach A_2:

(3) $$\Delta H_p \text{ (nT)} = 0.358 * R + 58$$

(4) $$\Delta H_p \text{ (nT)} = 15.22 * \sqrt{F10.7} - 39$$

Hence, ΔH_p subtracted from the corresponding ΔH (shown in Fig 1c and Fig 1d, respectively), results in the residual ΔH_r plotted in Fig 3, which show a tendency to increase with time. Plotting the same annual means of ΔH_r versus the corresponding geomagnetic main field strength shows a tendency of decreasing ΔH_r with increasing magnetic main field strength (Fig. 4).

The red lines in Figs. 3 and 4 are linear least square fits to the residuals, parameters of these fits are given in Table 1. A t-test was performed with the null-hypothesis that the slopes and intercepts are zero. In each case, the resulting p-value is smaller than $\alpha = 0.05$ which leads to rejection of the null-hypothesis. Thus, we find the trends in ΔH_r to be statistically significant.

Table 1

Linear least square fit and statistical analysis.

Method	slope+- std. error	95 % confidence interval	p-value
A_1 vs. year	0.082+-0.036 nT/yr	0.010 to 0.155 nT/yr	0.0260
A_2 vs. year	0.133+-0.038 nT/yr	0.056 to 0.210 nT/yr	0.0010
A_1 vs. field	-0.0014+-0.0006 nT/nT	-0.0027 to -0.0020 nT/nT	0.0226
A_2 vs. field	-0.0022+-0.0007 nT/nT	-0.0035 to -0.0008 nT/nT	0.0017

Discussion

The daily variation ΔH and the solar cycle signal dependent prediction ΔH_p are very similar in size and the residual $\Delta H_r = \Delta H - \Delta H_p$ is very small and would likely be affected by artefacts in the computation of ΔH or ΔH_p. Therefore, two independent codes using different methods A_1 and A_2 for calculating both ΔH and ΔH_p are used.

We regard approach A_1 as rather crude, but robust, as it just takes a simple mean value over three hourly mean values around local noon to determine the maximum in daily variation. Thus, we expect it to significantly underestimate the amplitude of the daily variation. Approach A_2 is more sophisticated as it approximates the hourly mean values around the maximum in the daily variation by a cubic spline and the daily variation is determined from the maximum value of the spline, yielding values at least as high as the maximum hourly mean value. We note the well-defined linear relationship (equation 2) with r = 0.99 between the two approaches and attribute the difference in ΔH to the systematic underestimation of ΔH by approach A_1.

We present an updated reconstruction of solar flux F10.7 based on sunspot number R (equation 1) and we present the solar cycle dependency of the daily variation ΔH both as a function of sunspot number (e.g. Elias et al., 2010) and $\sqrt{F10.7}$ (e.g. Yamazaki and Kosch, 2014) in equations 3 and 4. This makes the study comparable to earlier studies, but note that the sunspot numbers have been revised in 2015 by SILSO and we use the revised version.

From the time series of Huancayo, only the years 1935 to 1985 were used, as here the inclination at Huancayo was rather constant between 1.92° and 2.26°, indicating that the magnetic equator and the latitudinal centre of the EEJ were at distance between about 100 to 120 km from Huancayo. Taking the EEJ current profile determined from satellite data by Lühr et al. (2004) and calculating the daily variation ΔH at ground level due to the EEJ alone (neglecting Sq), this distance would correspond to a 10 % drop in ΔH compared to a station exactly below the EEJ. More important here, the variability in ΔH due to the slight movement of the magnetic equator at Huancayo between 1935 and 1985 remains within 2 % (1.7 nT). A similar variability of maximum 2.3 % can be derived from models based on ground measurements of ΔH integrating the effect of the EEJ and Sq (see Figure 6 in Stening (1985)). There is no resemblance between the trends in the inclination I from 1935 to 1985 (Fig. 1 a) to the variations of ΔH_r versus time in Fig 3. This is evidence that our results are only little, if at all affected by movements of the magnetic equator.

The geomagnetic field strength decreased by 2681 nT or 9.05 % from the year 1935 (F = 29628 nT; H = 29606 nT) to the year 1985 (F = 26947 nT; H = 26931 nT) due to secular variation of the Earth's core field (main field). Following the scaling law derived by the CMIT model (Cnossen et al., 2012; Cnossen, 2016), the daily magnetic variation (corresponding to ΔH) should vary with $M^{-0.7}$, with M being the Earth's magnetic field's dipole moment. By running the CMIT with a dipole geomagnetic field of varying strength, the effect of field strength on external current systems can be investigated without any effects from changes in field geometry. In reality, the Earth's magnetic field is more complex, and Huancayo is located in a large-scale main field anomaly, the South

Atlantic Anomaly, that controls its magnetic field strength and geometry. Since the Sq and EEJ current systems are controlled by large-scale processes in the ionosphere, we assume here that the magnetic field strength F in the (large-scale) region around Huancayo affects our ΔH with the same scaling law, i.e. ΔH proportional $F^{-0.7}$. For simplicity, we assume the magnetic field change in the source region (the ionospheric current system) to be the same as measured on ground at Huancayo (F decreases by 9.049 %). Indeed, a large-scale area around Huancayo is affected by the South Atlantic Anomaly and shows a rather homogeneous decreasing magnetic field strength for the investigated time period (Figure 1 in Cnossen and Richmond, 2013). At Huancayo, the magnetic equator somewhat changes its orientation with time (Figure 2 in Cnossen and Richmond, 2013), but for the reasons given above we assume no influence on the amplitude of the daily variation. Thus, the change in ΔH predicted by the CTIM model, i.e. using a scaling law of $F^{-0.7}$ and F changing from 29628 nT to 26947 nT) amounts to an increase by 6.9 %. in the time span investigated.

The observed change in daily variation ΔH is obtained by multiplying the slope from Table 1 with the main field change of 2681 nT, yielding 3.9 nT for A_1 and 5.9 nT for A_2. For comparison with the model predicted change in ΔH, we translate the observed trends into percentage values by dividing the magnitude of variation with the mean value of the observed ΔH (97 nT and 133 nT, respectively), and obtain 4.0 % for A_1 and 4.4 % for A_2.

Thus, two independent analyses, A_1 and A_2, were performed with two independent codes and successfully validated against each other. The good agreement between A_1 and A_2 lends confidence to the employed methods for calculating ΔH and ΔH_p. Our method to calculate the percentage changes in ΔH for a given period is similar in principle to the method used by Elias et al. (2010): calculation of residuals, linear fit of residuals including t-test of significance, and normalisation on the mean value of ΔH.

Our results for the change in ΔH (4.0 and 4.4 % decrease, respectively) have the same sign and are in the same order as the scaling law model prediction, but somewhat smaller. Adding one standard error to the result of A_2 yields 5.8 %, which is close the 6.9 % predicted from the scaling law. However, the observed trends could also be affected by variations in tidal forcing as well as in neutral temperature, density, and composition, which have not been accounted for in the physics-based modelling efforts. Possible effects of the different processes have been reviewed, e.g. in Cnossen (2012).

When comparing our results to previous studies on Huancayo data, there are several limitations. Sellek (1980) didn't find long-term trends in solar daily variation at Huancayo, but he used only a relatively short dataset of 14 years (1948 to 1961). Shinbori et al. (2014) investigated Huancayo data from the World Data Centres for 1947 to 2009 (with data gaps as shown in Fig 1. d), but did not specify a trend because of the data gaps (pers. comm. A. Shinbori, 2017). In contrast, in the analysis of the full dataset including the newly digitised observations presented here, a significant negative trend of the signal with increasing geomagnetic field strengths could be identified.

Conclusion

We have analysed Huancayo geomagnetic observatory data hourly mean values from 1935 to 1985 to determine the annual means of the amplitude ΔH of the quiet daily variation of the H component, which is proportional to the east-west oriented equatorial ionospheric current system. These currents consist of the solar quiet current system and the equatorial electrojet. To this end, we digitised some 19 years of hourly mean values previously not available for this key equatorial station. This data is available as a data publication (Matzka et al., 2017), and will be submitted to the World Data Centres.

For this analysis, we took advantage of the strong decrease in main field strength at Huancayo (due to the South Atlantic Anomaly) and of the unique, long time series of Huancayo geomagnetic observatory. We selected a time interval, 1935 to 1985, in which changes of the magnetic equator relative to the observatory were negligible for our study. The analysis is valid under the assumption, that the slight change in the orientation of the magnetic equator did not affect the amplitude ΔH of the quiet daily variation.

The sensitivity of ΔH to solar cycle variations (in terms of sunspot numbers and solar flux F10.7) and to changes of the geomagnetic main field strength (due to secular variation) was determined. The sensitivity to changes in main field strength determined from Huancayo data are similar, but somewhat (one-third) lower than the changes predicted from the physics based CMIT model (Cnossen, 2016). We note that possible effects from variations in tidal forcing and in neutral temperature, density, and composition have not been accounted in the physics-based modelling and could be responsible for differences in model and observation.

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Contributions

JM designed the study, wrote the manuscript, and contributed to digitizing and analysing HUA data. TAS performed the analysis (A_1) and made the graphs. HL digitized HUA data and performed the analysis (A_2). CS contributed to designing the study. OV contributed to designing the study and provided HUA data.

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Figure captions

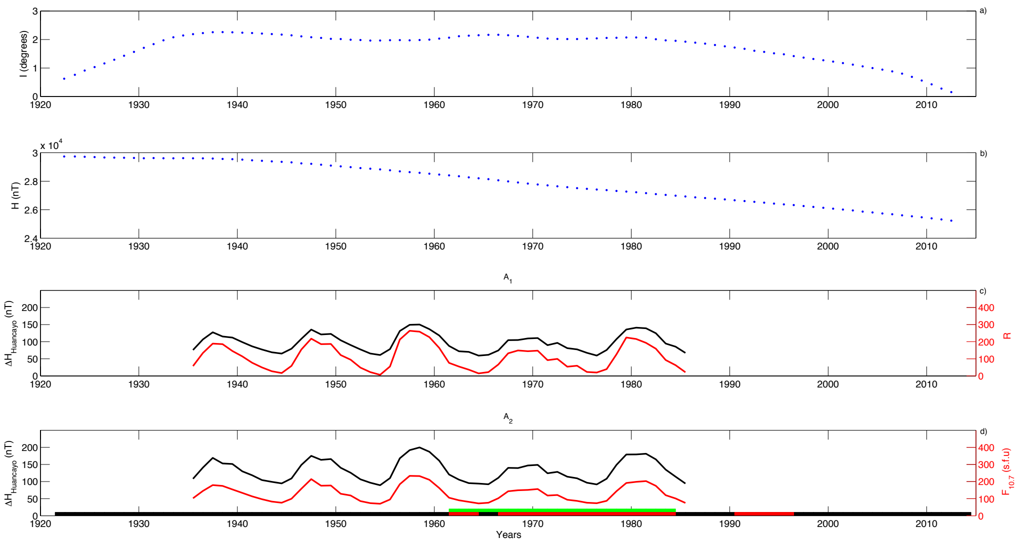

Fig 1. Annual means of geomagnetic inclination I (panel a) and horizontal component H (panel b) measured at Huancayo, Peru. Annual means of the amplitude ΔH of the daily magnetic variation in the H component from 1935 to 1985 calculated with our approach A_1 (together with annual means of sunspot number R, panel c) and our approach A_2 (panel d, together with annual means of solar flux F10.7 in s.f.u = 10^{-22} $Wm^{-2}Hz^{-1}$). Periods with hourly mean values of Huancayo magnetic recordings available at the World Data Centres are marked by black horizontal bars at the bottom of panel d, data gaps indicated by red. The green horizontal bar indicates the newly digitised hourly mean values presented in this study.

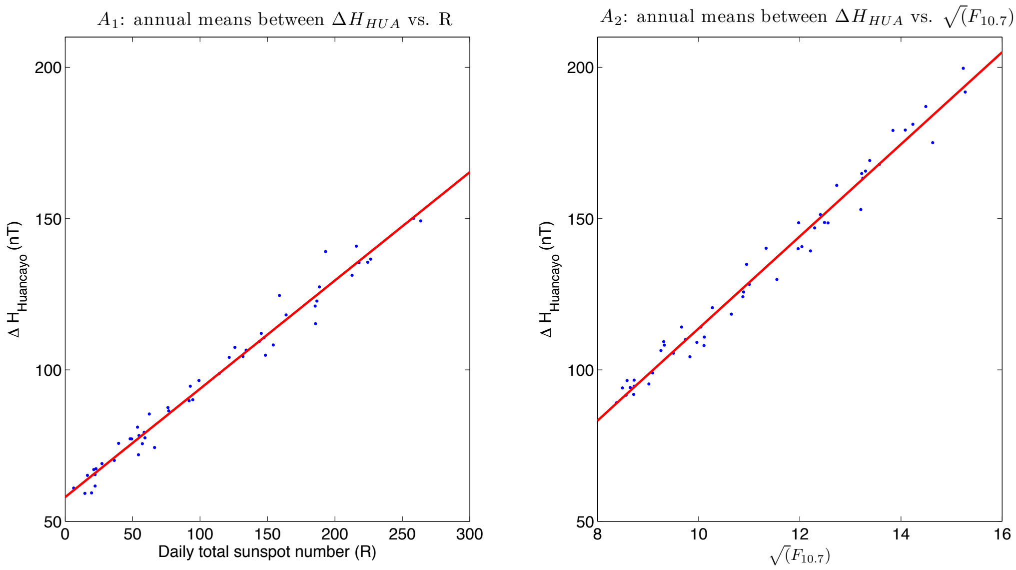

Fig. 2. Annual means of daily variation ΔH from approach A_1 versus annual mean of daily total sunspot number R (left panel) and from approach A_2 versus annual mean of $\sqrt{F10.7}$ (right panel). The red lines are linear least square fits (see equations 3 and 4, respectively).

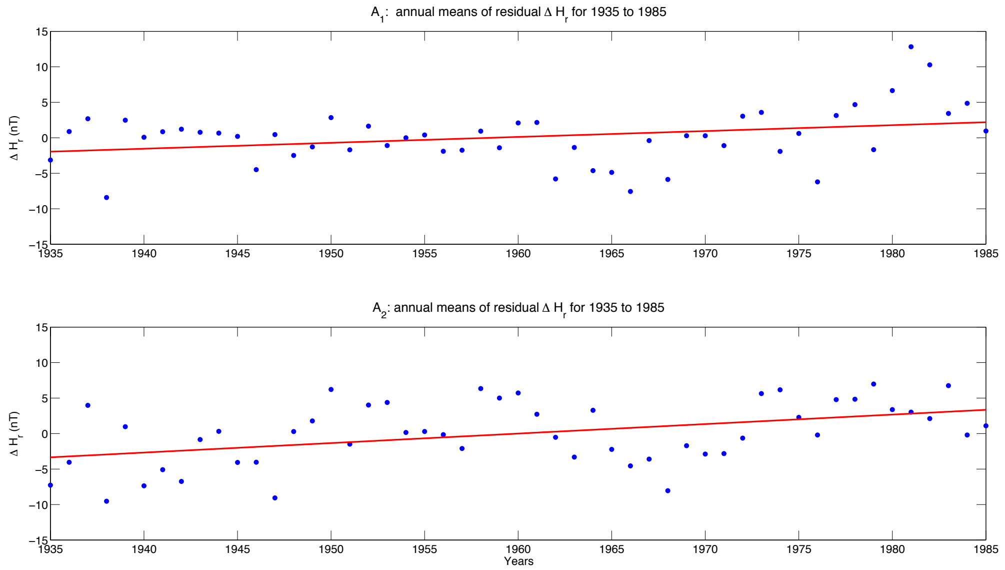

Fig 3. Annual means $\Delta H_r = \Delta H - \Delta H_p$ residual for Huancayo 1935 to 1985 for approach A_1 (upper panel) and approach A_2 (lower panel). The red lines are least square fits (see Table 1).

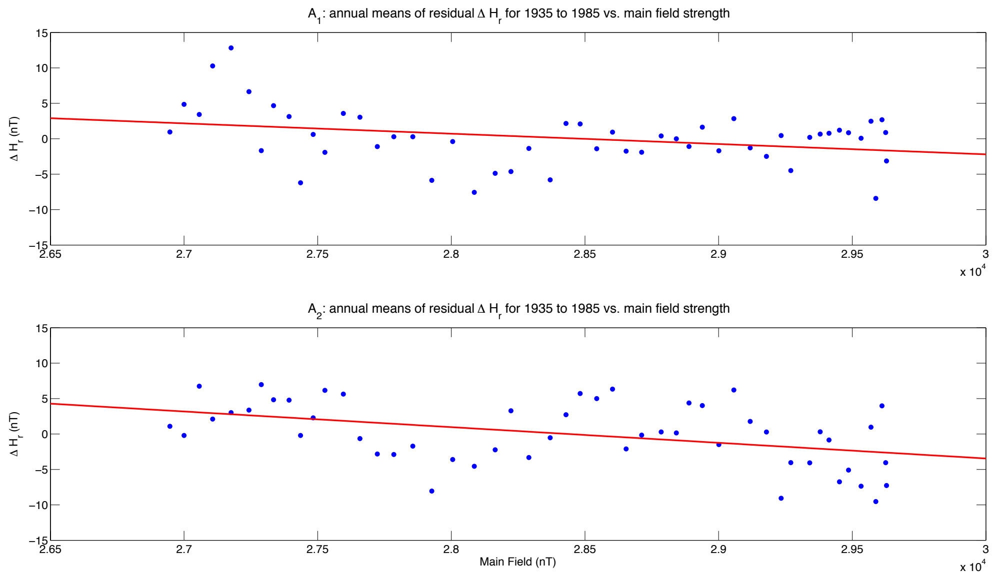

Fig 4. Annual means $\Delta H_r = \Delta H - \Delta H_p$ residual for Huancayo 1935 to 1985 versus main field strength for approach A_1 (upper panel) and approach A_2 (lower panel). The red lines are least square fits (see Table 1).