Long-term changes in solar quiet (Sq) geomagnetic variations related to Earth's magnetic field secular variation

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[1] The daily amplitude of the solar quiet (Sq) magnetic variation of the horizontal intensity, *H*, of observatories at low and midlatitudes is analyzed, in search of significant long-term trends. These trends are expected based on secular variations of the Earth's magnetic field (**B**) and increasing concentrations of greenhouse gases which can affect Sq for instance through their effect on ionospheric conductivities and E-region electron concentration. The hourly horizontal geomagnetic field component, *H*, measured at Apia, Fredericksburg, Hermanus, Bangui, and Trivandrum was analyzed for the period 1960–2000. The solar activity effect was filtered out from the daily Sq amplitude of *H*, and then linear trends were calculated and compared to trend values obtained from the Coupled Magnetosphere-Ionosphere-Thermosphere model. Linear trends were calculated separately for periods of different secular trends in the magnetic field intensity, *B*. We found significant trends in experimental data for Apia, Fredericksburg, Hermanus, and for the period 1960–1983 for Bangui. There is reasonable quantitative agreement between experimental and simulated trends, and a qualitative agreement with trends expected from the secular trend in *B*.

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1. Introduction

[2] As a consequence of the increasing interest in global changes, trends in the upper and middle atmosphere have become a main subject of study since the beginning of the 1990s [*Aikin et al.*, 1991; *Roble*, 1995; *Ulich and Turunen*, 1997; *Jarvis et al.*, 1998; *Lastovicka*, 2005, 2009]. In the case of the ionosphere, long-term trends have been linked to various possible causes, including the increasing concentration of greenhouse gases [*Roble and Dickinson*, 1989; *Rishbeth*, 1990; *Hall and Cannon*, 2002], long-term solar variability [*Torta et al.*, 2009], long-term variation of geomagnetic activity [*Danilov and Mikhailov*, 1999; *Mikhailov and Marin*, 2000], and the secular variation of the Earth's magnetic field [*Foppiano et al.*, 1999; *Elias and Ortiz de Adler*, 2006; *Cnossen and Richmond*, 2008, 2013; *Yue et al.*, 2008; *Elias*, 2009; *Elias et al.*, 2010; *Cnossen et al.*, 2012].

[3] The solar quiet (Sq) geomagnetic field variation is caused by ionospheric currents flowing in the E-region, driven by electric fields generated by the atmospheric dynamo. The Sq current system consists of two large current vortices on either side of the magnetic equator, flowing anticlockwise in the northern hemisphere and clockwise in the southern hemisphere. As the Earth rotates underneath this current system, a given geographic location samples the magnetic perturbations associated with different parts of the current system over the course of a day, which results in a characteristic daily variation. The main variables that determine the daily amplitude of the Sq variation are the ionospheric conductivities, the dynamo electric field, the solar diurnal tide, and the E-region electron concentration. The currents flowing in the ionosphere also induce counterpart currents in the Earth's conducting interior and in the oceans, approximately mirroring the electric current flow in the ionosphere. This produces a secondary magnetic field that is about 30% of the inducing amplitude, although this also depends on the local interior conductivity.

[4] On one hand, the Earth's main magnetic field, **B**, generated in the Earth's core, presents long-term variations in its strength and orientation [*Bloxham and Gubbins*, 1985; *Hongre et al.*, 1998; *Korte and Constable*, 2011; *Korte et al.*, 2011], and since the ionospheric conductivity depends on the intensity of the magnetic field, *B*, some effect may be expected on the Sq daily variation. Also, changes in the orientation of the field, and especially involving a shift in the geographic location of the magnetic equator, can affect the Sq system [*Cnossen and Richmond*, 2013]. On the other hand, the increase in the concentration of greenhouse gases, which is expected to produce an increase in the peak electron

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Table 1. Geographic and Geomagnetic (in Brackets) Coordinates of the Stations Considered, Period Considered for the Linear Trend Calculation, Linear Trends of the Sq Amplitude Residuals in % per Year Calculated From the Experimental Data (Sq Data Column) and From the CMIT Simulations (Sq Model Column), Percentage Trend of Earth's Magnetic Field Intensity *B*, and Mean *B* for the Period Considered[a]

Station	Geog. Latitude (Geom. Lat.)	Geog. Long. (Geom. Long.)	Period	Sq Data %/year	Sq Model %/year	B %/year	Mean B $\times 10^3$ [nT]
Apia (API)	13.8°S (15.3°S)	188.2°E (262.2°E)	1960–2000	0.17 (99%)	0.11 (95%)	−0.07	37.4
Hermanus (HER)	34.4°S (33.5°S)	19.2°E (83.3°E)	1960–2000	0.23 (99%)	0.14 (NS)	−0.34	27.5
Fredericksburg (FRD)	38.2°N (48.7°N)	282.6°E 352.8°E)	1960–2000	0.13 (99%)	0.36 (95%)	−0.16	52.1
Bangui (BNG)	4.4°N (4.3°N)	18.6°E (89.6°E)	1960–1983	−0.11 (95%)	−0.11 (NS)	0.03	31.7
			1983–2000	0.02 (NS)	−0.01 (NS)	−0.02	
Trivandrum (TRD)	8.5°N (0.7°S)	77.0°E (148.7°E)	1960–1983	0.01 (NS)	−0.08 (NS)	−0.03	37.7
			1983–2000	−0.09 (NS)	−0.12 (NS)	0.05	

[a]The statistical significance of the trend is indicated in brackets besides the corresponding value. NS: not statistically significant.

density of the E-layer [*Rishbeth and Roble*, 1992; *Bremer*, 2004, 2008], could affect the daily Sq variation as well.

[5] A decreasing trend in the Earth's main magnetic field intensity, *B*, should induce increasing trends in Sq [*Elias et al.*, 2010], and vice versa. This result can be deduced considering a uniform current sheet **J** of infinite extent. The Sq variation of *H*, ΔH, is then proportional to $|\mathbf{J}|$, where **J** is given by $\mathbf{J} = \Sigma\,(\mathbf{V}\times\mathbf{B}+\mathbf{E_p})$. Σ is the integrated layer conductivity tensor, **V** the tidal wind, **B** the main magnetic field, and $\mathbf{E_P}$ the polarization electric field. Theoretically, a decrease in the intensity of **B**, *B*, would result in a Σ increase. *Rishbeth* [1985] and *Takeda* [1996] obtained that the increase in Σ outweighs the decrease in *B*, so a net increasing effect in $|\mathbf{J}|$ should be expected, which in turn means an increase in the amplitude of the Sq variation.

[6] In this work, long-term trends in the daily amplitude of the Sq variation are analyzed with the aim of contributing to elucidate the origins of global changes in the ionosphere. So far, controversies have mainly arisen between the role of anthropogenic changes and the Sun's effects. Here we demonstrate that secular changes in the Earth's magnetic field can also induce measurable changes and should enter in the global change debate.

[7] Trends in Sq variation linked to the Earth's main magnetic field, to movements of the equatorial electrojet, and to solar long-term variations, have already been analyzed by many authors since the 1980s [*Sellek*, 1980; *Schlapp et al.*, 1990; *Macmillan and Droujinina*, 2007; *Torta et al.*, 2009; *Elias et al.*, 2010; *Cnossen et al.*, 2012]. Among them, only *Macmillan and Droujinina* [2007] and *Torta et al.* [2009] linked Sq trends to long-term variation in solar activity. *Sellek* [1980] found significant secular changes in Sq amplitude for Huancayo, Hermanus, and San Juan, which are in qualitative agreement with the predictions of a simple theory that considers changes in the Earth's main magnetic field. *Schlapp et al.* [1990] studied data from 11 observatories and attributed trends to changes in the Earth's main magnetic field after comparing their observational results with a mathematical model of the ionospheric dynamo developed by them. *Elias et al.* [2010] obtained significant trends for Apia, Fredericksburg, and Hermanus and explained more than half of their trend values by secular changes in the Earth's main magnetic field through a very rough theoretical assessment, and less than 10% by the effect of increasing greenhouse gas concentrations.

[8] *Cnossen et al.* [2012] were the first to analyze the role of the Earth's dipole moment on the Sq amplitude using the Coupled Magnetosphere-Ionosphere-Thermosphere (CMIT) model. They obtained decreasing trends in Sq for an increasing dipole moment and a good agreement of their theoretical values with experimental ones obtained by other authors, based on a rough assessment. *Cnossen and Richmond* [2013] performed CMIT simulations with more realistic magnetic field changes between 1908 and 2008, and stressed that their results should be compared to observed trends to determine the relative contribution of magnetic field changes to those trends more precisely. The present study contributes to that effort. We estimate the linear trend of the Sq variation of the horizontal intensity, *H*, of five magnetic observatories located at low and midlatitudes. We add to previous work by comparing the trends calculated from experimental data measured at each observatory with trends calculated from simulations

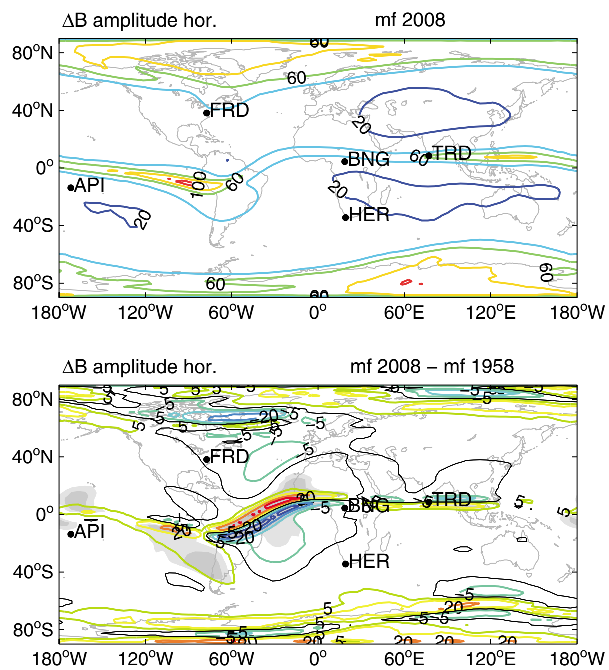

Figure 1. (a) Sq amplitude of the horizontal component of **B** obtained with the CMIT model for March–April 2008, and (b) the difference between the 2008 and 1958 Sq amplitudes. Stations analyzed are marked: Apia, Fredericksburg (Fred), Bangui (Bang), Hermanus (Herm), and Trivandrum (Triv). The light (dark) shading indicates statistical significance at the 95% (99%) level according to a *t* test.

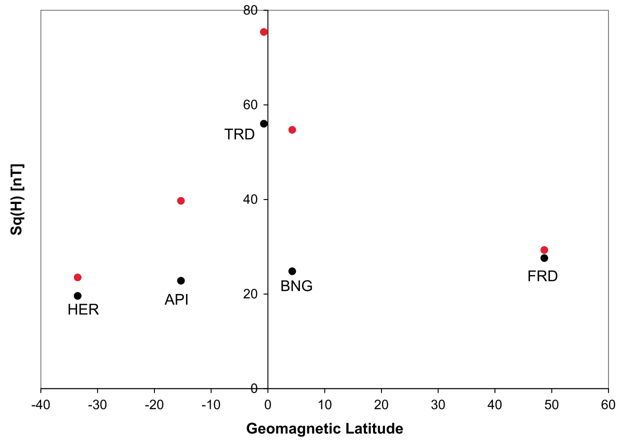

Figure 2. Mean Sq amplitudes obtained with experimental data (red dots) and with the CMIT model (black dots). The experimental Sq amplitude was calculated using the five quietest days in March and April for years with low solar activity levels during the period of analysis of each station. The simulated Sq amplitude was calculated for the five quietest days in March and April 2008.

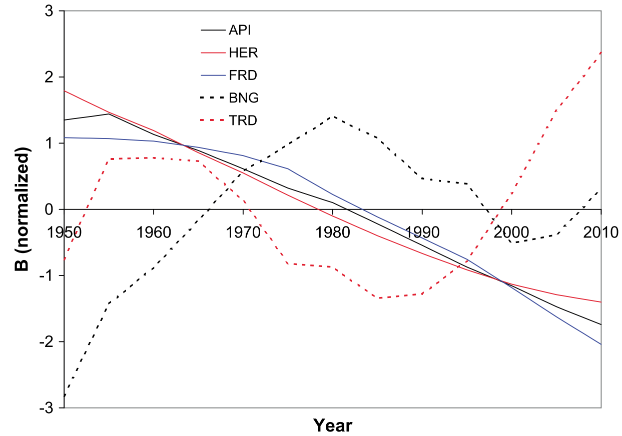

Figure 3. Secular trend of the Earth's magnetic field intensity B in nT obtained from the International Geomagnetic Reference Field (IGRF) for (a) Apia (black solid line), (b) Hermanus (red solid line), (c) Fredericksburg (blue solid line), (d) Bangui (black dashed line), and (e) Trivandrum (red dashed line). B for each location has been normalized [(B-Bmean)/standard deviation].

with the CMIT model. This will allow us to estimate to what extent the observed trends in Sq variation are likely to be associated with changes in the Earth's magnetic field.

[9] The paper is organized as follows. In section 2, the analysis of the experimental data to calculate trends is described, followed by the data analysis from the CMIT model. Results are presented in section 3, followed by the discussion and conclusions in section 4.

2. Methods

2.1. Experimental Data Analysis

[10] The horizontal component of the hourly geomagnetic field, H, obtained from the Space Physics Interactive Data Resource of the NOAA World Data Center was analyzed for five stations: Apia, Fredericksburg, Hermanus, Bangui, and Trivandrum. Their coordinates are given in Table 1. The period considered is 1960–2000, except for Bangui, which covers the period 1960–1992. The stations and period of analysis were selected according to data availability and completeness of the data record. The station locations are indicated in Figure 1, which shows a map of the daily Sq amplitude of H obtained with the CMIT model for 2008 (top) and the difference between 2008 and 1958 (bottom). According to these maps, stations located between 60°W and 30°E near the dip equator would be ideal to analyze since the largest changes occur there. However, the stations with data available close to this area do not have records long enough to assess trends or they have too many gaps.

[11] To obtain the Sq amplitude of H, the daily amplitude of H was calculated as the difference between the maximum and minimum value of the magnetic perturbations of each day, and then averaged over the five quietest days for each month. The solar activity effect was filtered out by calculating the residuals of the Sq amplitude from the linear regression between the 12 month running mean of the Sq amplitude, Sq_{12}, and the 12 month running mean of the sunspot number, Rz_{12}. That is:

$$\text{residual of } Sq = Sq_{12} - (a\ Rz_{12} + b)$$

where a and b are calculated using ordinary least squares applied to the linear regression of Sq_{12} with Rz_{12}. The residuals of the Sq amplitude were used to calculate linear trends. Their statistical significance was assessed using a t test, where the reduction in the degrees of freedom by 12 due to the 12 month smoothing was taken into account.

2.2. Model Simulation Analysis

[12] The CMIT model [*Wiltberger et al.*, 2004; *Wang et al.*, 2004; *Wang et al.*, 2008] is a combination of the Lyon-Fedder-Mobarry global magnetospheric code [*Lyon et al.*, 2004] and the Thermosphere-Ionosphere-Electrodynamics General

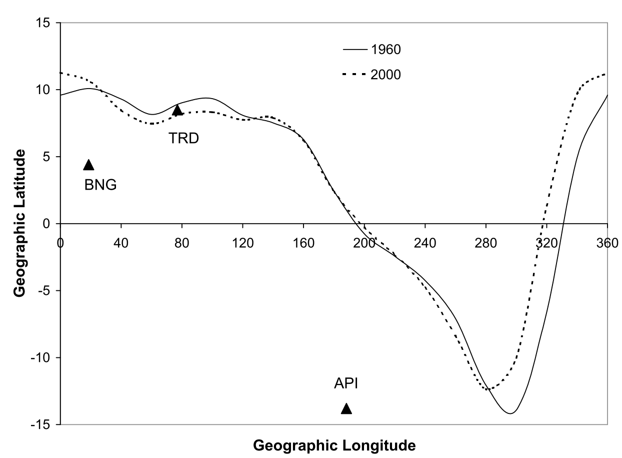

Figure 4. Geographic position of the magnetic dip equator for 1960 and 2000, and the locations of Apia, Bangui, and Trivandrum.

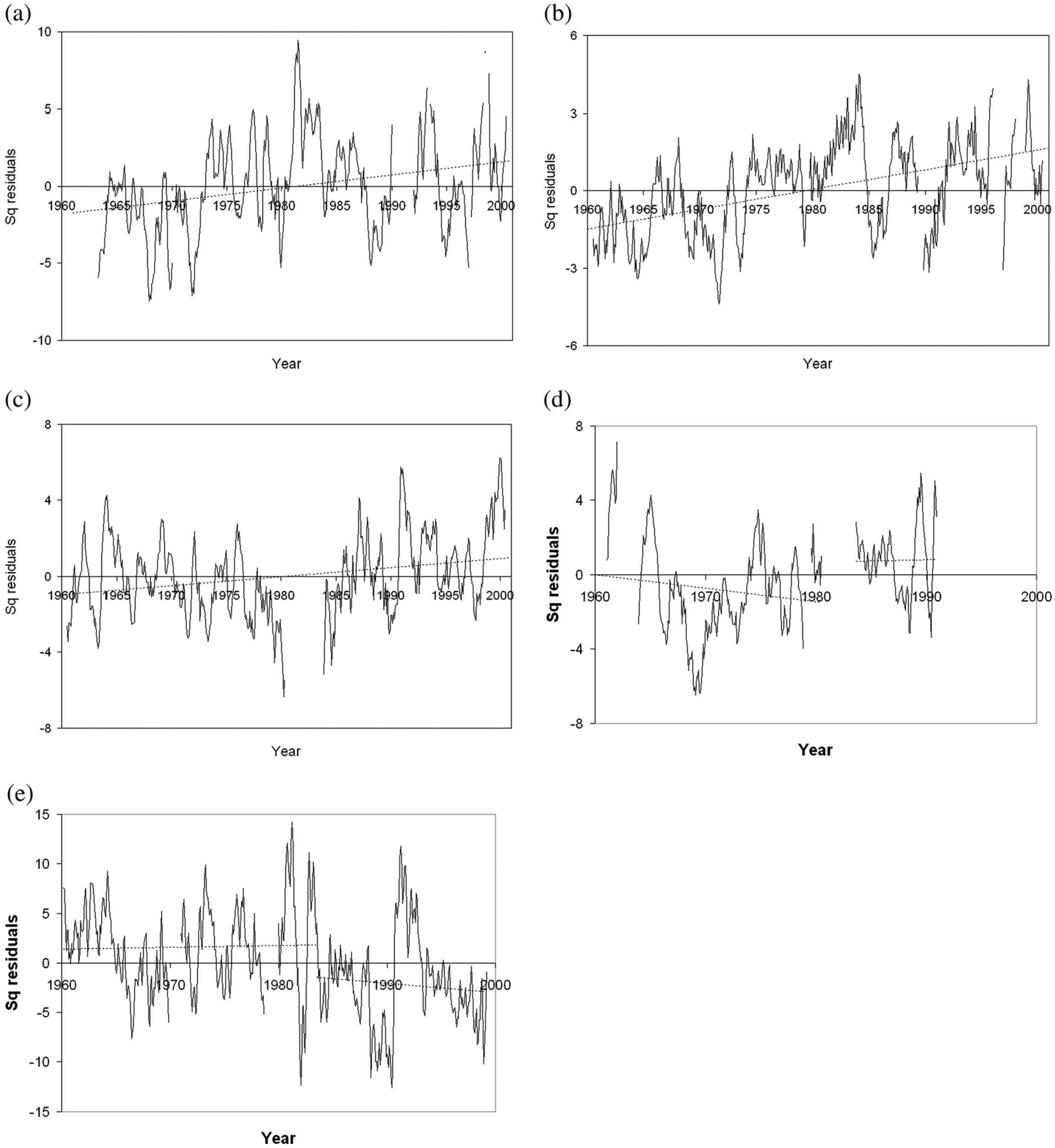

Figure 5. Sq residuals in nT (solid line) and linear trend (dashed line) for the period 1960–2000 for (a) Apia, (b) Hermanus (c) Fredericksburg, (d) Bangui, and (e) Trivandrum.

Circulation Model [*Roble et al*., 1988; *Richmond et al*., 1992]. *Cnossen and Richmond* [2013] performed simulations with CMIT to assess the global effects of long-term changes in the Earth's magnetic field on the ionosphere-thermosphere system and the daily Sq amplitude. Their study relied on three simulations with the main magnetic fields of 1908, 1958, and 2008, respectively, specified through the International Geomagnetic Reference Field (IGRF) [*Finlay et al*., 2010]. We will use the latter two simulations here again. We also performed an additional simulation with the magnetic field of the year 1983 which was set up in the same way as the previous ones. *Cnossen and Richmond* [2013] describe the simulation setup and analysis in detail, so here we just repeat the key points relevant to this study.

[13] Each simulation ran for 15 days, from 0 UT on 21 March to 0 UT on 5 April, and each used the measured solar activity level and solar wind conditions from 2008 during that interval, so that the only difference between the simulations was the main magnetic field. We chose the solar activity and solar wind conditions of 2008, because on average the solar activity was very low (F10.7 $\approx$ 70 solar flux units), and geomagnetic conditions were relatively quiet, and therefore ideal to study Sq variation. Magnetic perturbations were calculated with a postprocessing code described by *Doumbia et al*. [2007] and *Richmond and Maute* [2013]. We note that the model tends to underestimate the perturbations somewhat.

[14] The amplitude of the daily Sq variation was calculated by taking the difference between the maximum and minimum value of the magnetic perturbations each day. The average amplitude of the five quietest days for March–April 2008 and the standard deviations over those five days for both simulations were used to interpolate linear trends from the

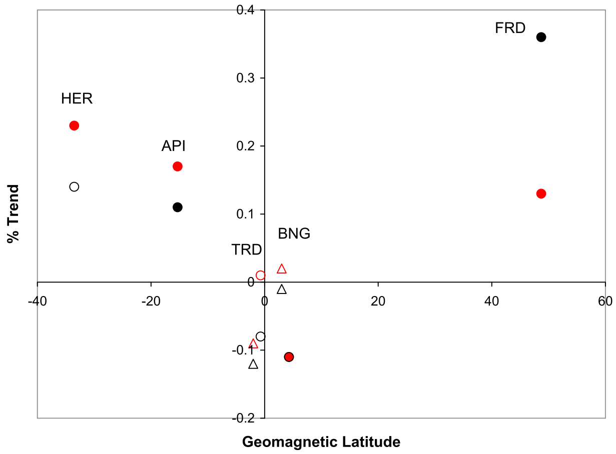

Figure 6. Trend values in %/year (also listed in Table 1) of the Sq amplitudes obtained with experimental data (red symbols) and with the CMIT model (black symbols). Filled and empty symbols correspond to significant and nonsignificant values, respectively. Circles correspond to trends for the complete period of analysis (1960–2000) which applies to Hermanus, Apia, and Fredericksburg. In the cases of Bangui and Trivandrum, circles correspond to the 1960–1983 period, and triangles (displaced some degrees to the left to make the figure clearer) correspond to 1983–2000.

differences between the simulations and to determine their significance. This makes the analysis as similar as possible to the analysis done on the experimental data. The trend values in %/year and their significance are listed in Table 1.

3. Results

[15] To ensure that the CMIT model produces a reasonable Sq variation for the stations considered here, we first compare the mean Sq amplitudes that were observed and simulated for the five quietest days in March–April, using years with low solar activity level in the case of observed data and the results for 2008 in the case of the modeled data. This is shown in Figure 2, with the black dots indicating the simulated values and the red dots indicating the observed values. As expected, the simulated Sq amplitude is smaller than observed for all five stations, with considerable differences for the three stations located closest to the magnetic equator (Apia, Trivandrum, and Bangui). This makes sense, as this is the more complex region of the ionosphere. It does mean that the model could potentially also underestimate the trends in Sq amplitude associated with magnetic field changes for these stations. Further away from the magnetic equator (Fredericksburg and Hermanus), the observed and simulated Sq amplitudes agree much better, so we would expect the model to describe the effects of magnetic field changes on Sq amplitude also quite well.

[16] Figure 3 shows the secular variation of *B* at each observatory estimated from the IGRF, available from the National Space Science Data Center. The values of *B* were normalized to show all observatories in one figure. At the location of Apia, Fredericksburg, and Hermanus, *B* presents a monotonic decreasing trend, so an increasing trend in Sq amplitude is expected for the whole period analyzed. At Bangui, *B* presents an increasing trend until ~1980 and then a much less steep decreasing trend. A decreasing trend in Sq then is expected for the first period followed by a weaker increasing trend. The full 1960–2000 interval was therefore split into two sections which were analyzed separately. At Trivandrum, there is a clear increasing trend in *B* since ~1985. That is, a decreasing trend in Sq amplitude should be expected after that year. For the period previous to 1986, a not very clear or small trend should be expected. Also, for Trivandrum, we therefore divided the full interval into two sections for separate analysis.

[17] Each of the stations analyzed, except Trivandrum, experienced a change in their position with respect to the magnetic equator between 0.5° and 0.2°. Only for Trivandrum, which is located just under the magnetic equator, this was slightly more, at ~0.8°. Still, the locations of all the stations considered here at geographic longitudes where the magnetic equator has had relatively little displacement, as can be seen in Figure 4. Hermanus and Fredericksburg are not shown in this figure since they are more than 20° distant from the magnetic equator.

[18] The time series of the experimental Sq residuals are shown in Figure 5 together with the linear trends calculated from these residuals. The trend values in %/year are listed in Table 1 together with their significance level calculated with a *t* test. The reduction in the degrees of freedom by a factor of 12 due to the 12 month running mean that was applied to the Sq amplitude was considered. The trends obtained with experimental data and with the CMIT simulation (all listed in Table 1) are also shown in Figure 6 for easy comparison.

4. Discussion and Conclusions

[19] Significant trends in the daily amplitude of the Sq variation of *H* are obtained using experimental data for Apia, Fredericksburg, Hermanus, and Bangui. For this last station, the significant trend corresponds to the period of increasing *B*, that is, 1960–1983. For Bangui for the period 1983–2000, and for Trivandrum for both 1960–1983 and 1983–2000, the trends obtained are not statistically significant.

[20] Based on the theoretical considerations of the effects of *B* on the E-layer conductivity, there is qualitative agreement between the observed and expected trends for all the cases analyzed. There is also a reasonably good quantitative agreement with the trend values estimated from the CMIT simulations, especially for Apia, Bangui, and Hermanus. To quantify how well the observed and simulated trends agree, Table 2 shows the difference between these two trends, together with the significance of the difference. This was estimated by applying the *t* test to the difference between

Table 2. Difference Between Linear Trends of the Sq Amplitude Residuals in % per Year Calculated From the Experimental Data and From the CMIT Simulations[a]

Station	Period	Difference Between % Trend	Significance
Apia	1960–2000	−0.06	95%
Hermanus	1960–2000	−0.09	NS
Fredericksburg	1960–2000	0.23	95%
Bangui	1960–1983	0.00	NS
	1983–2000	−0.03	NS
Trivandrum	1960–1983	−0.09	NS
	1983–2000	−0.03	NS

[a]The period considered for the linear trends involved in the difference is indicated in the Period column. The statistical significance of the difference is indicated in the Significance column. NS: not statistically significant

the observed and simulated trends, divided by the standard error of the trend difference.

[21] Table 2 shows that for Apia, the difference between the observed and simulated trends is statistically significant, indicating that the model cannot (fully) explain the observed trend. This might be because the model also underestimates the Sq amplitude itself for Apia (see Figure 2), which could lead to an underestimation of the trend. Indeed, the simulated trend for Apia is smaller than observed. For Hermanus, where the model provides a much better estimate of the Sq amplitude (see Figure 2), the difference between the simulated and observed trends is not statistically significant, although the simulated trend itself was not significant. The good agreement between observed and simulated trends for Bangui may be somewhat surprising, as the model considerably underestimated the Sq amplitude itself for this station. It appears that either the model does still provide a good estimate of the trend in Sq amplitude here, or, if it is underestimating the trend associated with magnetic field changes, there might be a different process acting in the opposite direction, bringing the observed trends more in line with the simulations.

[22] The modeled trend at Fredericksburg is considerably stronger than observed. However, *Cnossen and Richmond* [2013] showed that the change in Sq amplitude at that location associated with magnetic field changes between 1958 and 2008 is not statistically significant. This could indicate that the observed Sq trend at Fredericksburg cannot be explained through magnetic field changes, in which case one would not necessarily expect the experimental and modeled trends to match. However, it is also possible that a significant trend might be obtained if longer simulations were done, so we cannot completely rule out the possibility that secular changes in the magnetic field have contributed to the trend observed at Fredericksburg. At Trivandrum, the modeled trend for 1983–2000 is also larger than observed, but in this case, both the experimental trend and the trend derived from the model simulations are not significant, so in that sense they agree.

[23] A possible source of some of the differences between the model results and the observations at the geomagnetic observatories is the electric current induced in the Earth's interior by the external currents flowing in the ionosphere. Also, induction in the oceans strongly affects the Sq variation in stations close to the coast [*Macmillan and Droujinina*, 2007; *Kuvshinov et al*., 2007], which applies to most of the stations analyzed here (see Figure 1). At the Earth's surface, magnetometers measure the composite of external and internal field components from the currents, so that the observed Sq variation is also a composite of these two current systems. The CMIT model, on the other hand, only simulates the external currents. The contribution of the internal currents can be as much as 30% of the total Sq variation [e.g., *Schlapp et al*., 1990], but varies with location due to the heterogeneous conductivity of the Earth's interior and oceans. This could explain some of the discrepancies between the model simulations and observations, and perhaps also why a better match is found for some stations than others.

[24] Still, from our model-observation comparisons, we can conclude that changes in the magnetic field have played an important role in causing trends in Sq amplitude at some stations, but are not important everywhere. Nevertheless, it is important to consider this factor when analyzing long-term trends in Sq variation.

[25] The qualitative agreement between experimental trends in Sq amplitude and the trends in B suggests that the change in B, through its influence on the ionospheric conductivity, is the main cause of the trends in Sq amplitude. A larger role for changes in field intensity rather than changes in orientation is consistent with the relatively good quantitative agreement found by *Cnossen et al*. [2012] between observed trends reported in the literature and trends derived from model simulations that only considered a decrease in dipole moment. However, the simulations by *Cnossen et al*. [2012] demonstrated a global mean effect, as they considered the overall decrease in dipole moment, while the current results suggest that the local change in B is perhaps at least as important, as stations with different local trends in B show more or less correspondingly different trends in Sq amplitude. We do note that none of the stations analyzed here experienced large changes in magnetic field orientation or in their position with respect to the magnetic equator. Any effects of such type of changes in the magnetic field were therefore likely to be small for these stations in any case. In future work, it would be interesting to consider also stations that have experienced a larger shift in their position with respect to the magnetic equator if possible.

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References

Aikin, A. C., M. L. Chanin, J. Nash, and D. J. Kendig (1991), Temperature trends in the lower mesosphere, *Geophys. Res. Lett.*, *18*, 416–419.

Bloxham, J., and D. Gubbins (1985), The secular variation of the Earth's magnetic field, *Nature*, *317*, 777–781.

Bremer, J. (2004), Investigations of long-term trends in the ionosphere with world-wide ionosonde observations, *Adv. Radio Sci.*, *2*, 253–258.

Bremer, J. (2008), Long-term trends in the ionospheric E and F1 regions, *Ann. Geophys.*, *26*, 1189–1197.

Cnossen, I., and A. D. Richmond (2008), Modelling the effects of changes in the Earth's magnetic field from 1957 to 1997 on the ionospheric hmF2 and foF2 parameters, *J. Atmos. Sol. Terr. Phys.*, *70*, 1512–1524.

Cnossen, I., and A. D. Richmond (2013), Changes in the Earth's magnetic field over the past century: Effects on the ionosphere-thermosphere system and solar quiet (Sq) magnetic variation, *J. Geophys. Res.*, *118*, 849–858, doi:10.1029/2012JA018447.

Cnossen, I., A. D. Richmond, and M. Wiltberger (2012), The dependence of the coupled magnetosphere-ionosphere-thermosphere system on the Earth's magnetic dipole moment, *J. Geophys. Res.*, *117*, A05302, doi:10.1029/2012JA017555.

Danilov, A. D., and A. V. Mikhailov (1999), Long-term trends in the parameters of the F2-region: A new approach, *Geomagn. Aeron.*, *39*, 473–479.

Doumbia, V., A. Maute, and A. D. Richmond (2007), Simulation of equatorial electrojet magnetic effects with the thermosphere-ionosphere-electrodynamics general circulation model, *J. Geophys. Res.*, *112*, A09309, doi:10.1029/2007JA012308.

Elias, A. G. (2009), Trends in the F2 ionospheric layer due to long-term variations in the Earth's magnetic field, *J. Atmos. Sol. Terr. Phys.*, *71*, 1602–1609.

Elias, A. G., and N. Ortiz de Adler (2006), Earth magnetic field and geomagnetic activity effects on long-term trends in the F2 layer at mid-high latitudes, *J. Atmos. Sol. Terr. Phys.*, *68*, 1871–1878.

Elias, A. G., M. Zossi de Artigas, and B. F. de Haro Barbas (2010), Trends in the solar quiet geomagnetic field variation linked to the Earth's magnetic field secular variation and increasing concentrations of greenhouse gases, *J. Geophys. Res.*, *115*, A08316, doi:10.1029/2009JA015136.

Finlay, C. C., et al. (2010), International Geomagnetic Reference Field: the eleventh generation, *Geophys. J. Int.*, *183*, 1216–1230.
Foppiano, A. J., L. Cid, and V. Jara (1999), Ionospheric long-term trends for South American mid-latitudes, *J. Atmos. Sol. Terr. Phys.*, *61*, 717–723.
Hall, C. M., and P. S. Cannon (2002), Trends in fof2 above Tromso, *Geophys. Res. Lett.*, *29*(23), 2128, doi:10.1029/2002GL016259.
Hongre, L., G. Hulot, and G. Khokhlov (1998), An analysis of the geomagnetic field over the past 2000 years, *Phys. Earth Planet. Inter.*, *106*, 311–335.
Jarvis, M. J., B. Jenkins, and G. A. Rodgers (1998), Southern hemisphere observations of a long-term decrease in F region altitude and thermospheric wind providing possible evidence for global thermospheric cooling, *J. Geophys. Res.*, *103*, 20,775–20,778.
Korte, M., and C. Constable (2011), Improving geomagnetic field reconstructions for 0–3 ka, *Phys. Earth Planet. Inter.*, *188*, 247–259.
Korte, M., C. Constable, F. Donadini, and R. Holme (2011), Reconstructing the Holocene geomagnetic field, *Earth Planet. Sci. Lett.*, *312*, 497–505.
Kuvshinov, A., C. Manoj, N. Olsen, and T. Sabaka (2007), On induction effects of geomagnetic daily variations from equatorial electrojet and solar quiet sources at low and middle latitudes, *J. Geophys. Res.*, *112*, B10102, doi:10.1029/2007JB004955.
Lastovicka, J. (2005), On the role of solar and geomagnetic activity in long-term trends in the atmosphere–ionosphere system, *J. Atmos. Sol. Terr. Phys.*, *67*, 83–92.
Lastovicka, J. (2009), Global pattern of trends in the upper atmosphere and ionosphere: Recent progress, *J. Atmos. Sol. Terr. Phys.*, *71*, 1514–1528.
Lyon, J. G., J. A. Fedder, and C. M. Mobarry (2004), The Lyon-Fedder-Mobarry (LFM) global MHD magnetospheric simulation code, *J. Atmos. Sol. Terr. Phys.*, *66*(15-16), 1333–1350.
Macmillan, S., and A. Droujinina (2007), Long-term trends in geomagnetic daily variation, *Earth Planets Space*, *59*, 391–395.
Mikhailov, A. V., and D. Marin (2000), Geomagnetic control of the foF2 long-term trends, *Ann. Geophys.*, *18*, 653–665.
Richmond, A. D., and A. Maute (2013), Ionospheric electrodynamics modeling, in *Modeling the Ionosphere/Thermosphere System*, *Geophys. Monogr. Ser.*, edited by J. Huba, R. Schunk, and G. Khazanov, AGU, Washington, D. C., doi:10.1029/2012BK001331, in press.
Richmond, A. D., E. C. Ridley, and R. G. Roble (1992), A thermosphere/ionosphere general circulation model with coupled electrodynamics, *Geophys. Res. Lett.*, *19*, 601–604.
Rishbeth, H. (1985), The quadrupole ionosphere, *Ann. Geophys.*, *3*, 293–298.
Rishbeth, H. (1990), A greenhouse effect in the ionosphere?, *Planet. Space Sci.*, *38*, 945–948.
Rishbeth, H., and R. G. Roble (1992), Cooling of the upper atmosphere by enhanced greenhouse gases. Modeling of the thermospheric and ionospheric effects, *Planet. Space Sci.*, *40*, 1011–1026.
Roble, R. G. (1995), Major greenhouse cooling (yes, cooling): The upper atmosphere response to increased CO_2, *Rev. Geophys.*, *33*, 539–546.
Roble, R. G., and R. E. Dickinson (1989), How will changes in carbon dioxide and methane modify the mean structure of the mesosphere and thermosphere?, *Geophys. Res. Lett.*, *16*, 1441–1444.
Roble, R. G., E. C. Ridley, A. D. Richmond, and R. E. Dickinson (1988), A coupled thermosphere/ionosphere general circulation model, *Geophys. Res. Lett.*, *15*, 1325–1328.
Schlapp, D. M., R. Sellek, and E. C. Butcher (1990), Studies of worldwide secular trends in the solar daily geomagnetic variation, *Geophys. J. Int.*, *100*, 469–475.
Sellek, R. (1980), Secular trends in daily geomagnetic variations, *J. Atmos. Sol. Terr. Phys.*, *42*, 689–695.
Takeda, M. (1996), Effects of the strength of the geomagnetic main field on the dynamo action in the ionosphere, *J. Geophys. Res.*, *101*, 7875–7880.
Torta, J. M., L. R. Gaya-Pique, J. J. Curto, and D. Altadill (2009), An inspection of the long-term behaviour of the range of the daily geomagnetic field variation from comprehensive modelling, *J. Atmos. Terr. Phys.*, *71*, 1497–1510.
Ulich, T., and E. Turunen (1997), Evidence for long-term cooling of the upper atmosphere in ionosonde data, *Geophys. Res. Lett.*, *24*, 1103–1106.
Wang, W., M. Wiltberger, A. G. Burns, S. C. Solomon, T. L. Killeen, N. Maruyama, and J. G. Lyon (2004), Initial results from the coupled magnetosphere-ionosphere-thermosphere model: Thermosphere-ionosphere responses, *J. Atmos. Sol. Terr. Phys.*, *66*(15–16), 1425–1441, doi:10.1016/j.jastp.2004.04.008.
Wang, W. B., J. H. Lei, A. G. Burns, M. Wiltberger, A. D. Richmond, S. C. Solomon, T. L. Killeen, E. R. Talaat, and D. N. Anderson (2008), Ionospheric electric field variations during a geomagnetic storm simulated by a coupled magnetosphere ionosphere thermosphere (CMIT) model, *Geophys. Res. Lett.*, *35*, L18105, doi:10.1029/2008GL035155.
Wiltberger, M., W. Wang, A. G. Burns, S. C. Solomon, J. G. Lyon, and C. C. Goodrich (2004), Initial results from the coupled magnetosphere ionosphere thermosphere model: Magnetospheric and ionospheric responses, *J. Atmos. Sol. Terr. Phys.*, *66*(15–16), 1411–1423, doi:10.1016/j.jastp.2004.03.026.
Yue, X., L. Liu, W. Wan, Y. Wei, and Z. Ren (2008), Modeling the effects of secular variation of geomagnetic filed orientation on the ionospheric long term trend over the past century, *J. Geophys. Res.*, *113*, A10301, doi:10.1029/2007JA012995.