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Changes in the Earth's magnetic field over the past century: Effects on the ionosphere-thermosphere system and solar quiet (Sq) magnetic variation

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[1] We investigated the contribution of changes in the Earth's magnetic field to long-term trends in the ionosphere, thermosphere, and solar quiet (Sq) magnetic variation using the Coupled Magnetosphere-Ionosphere-Thermosphere (CMIT) model. Simulations with the magnetic fields of 1908, 1958, and 2008 were done. The strongest differences occurred between ~40°S–40°N and ~100°W–50°E, which we refer to as the Atlantic region. The height and critical frequency of the F_2 layer peak, h_mF_2 and f_oF_2, changed due to changes in the vertical $E \times B$ drift and the vertical components of diffusion and transport by neutral winds along the magnetic field. Changes in electron density resulted in changes in electron temperature of the opposite sign, which in turn produced small corresponding changes in ion temperature. Changes in neutral temperature were not statistically significant. Strong changes in the daily amplitude of the Sq variation occurred at low magnetic latitudes due to the northward movement of the magnetic equator and the westward drift of the magnetic field. The simulated changes in h_mF_2, f_oF_2, and Sq amplitude translate into typical trends of ± 1 km/decade (night) to ± 3 km/decade (day), -0.1 to $+0.05$ MHz/decade, and ± 5 to ± 10 nT/century, respectively. These are mostly comparable in magnitude to observed trends in the Atlantic region. The simulated Atlantic region trends in h_mF_2 and f_oF_2 are ~2.5 times larger than the estimated effect of enhanced greenhouse gases on h_mF_2 and f_oF_2. The secular variation of the Earth's magnetic field may therefore be the dominant cause of trends in the Atlantic region ionosphere.

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1. Introduction

[2] Numerous studies have observed long-term trends in the thermosphere and ionosphere over the past ~50–100 years [for reviews see, e.g., *Qian et al.*, 2011 and *Cnossen* 2012]. In general, the temperature in the thermosphere has been decreasing, leading to lower densities at fixed heights due to thermal contraction. The cooling and contraction of the upper atmosphere is qualitatively consistent with the increase in greenhouse gas concentrations that has taken place since the industrial revolution. However, the effects of enhanced greenhouse gases simulated by models [e.g., *Akmaev et al.*, 2006; *Qian and Solomon*, 2011] tend to be too weak to explain observed trends in temperature and density in the upper thermosphere (>300 km) completely [*Cnossen*, 2012]. Trends in the F_2 layer ionosphere pose another problem: some stations have shown a decrease in the height of the peak of the F_2 layer, h_mF_2, again qualitatively consistent with thermal contraction [e.g., *Ulich and Turunen*, 1997], but other stations have shown in fact an increase in h_mF_2 [e.g., *Bremer*, 1998; *Upadhyay and Mahajan*, 1998]. The increase in greenhouse gas concentrations may therefore not be the only driver of long-term trends in the thermosphere-ionosphere system. Other drivers that have been suggested include the secular variation of the Earth's magnetic field, long-term trends in solar and/or geomagnetic activity, and changes in forcing from the lower atmosphere.

[3] Here we focus on the role of the secular variation of the Earth's magnetic field. Figures 1 and 2 show how the Earth's magnetic field intensity and the magnetic field inclination angle have changed from 1908 to 2008. Clearly, the magnetic field has not changed in a geographically uniform manner. The strongest changes have taken place roughly in the region of the South Atlantic Anomaly (SAA), a region of relatively weak magnetic field over South America and the southern Atlantic Ocean. Over the past century, this anomaly has intensified and expanded, and the magnetic equator (0° inclination contour) in the region has moved northward. Many magnetic field structures also exhibit a westward drift over time, as can be seen, for instance, in the positions of the magnetic poles (Figure 2).

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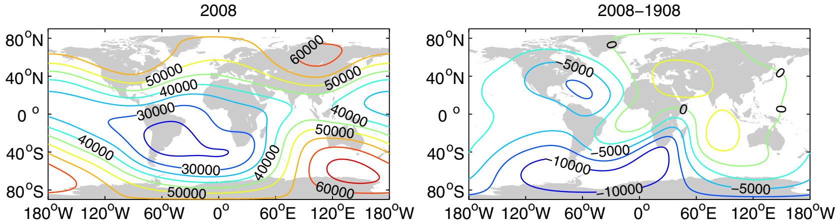

Figure 1. The magnetic field strength in 2008 (left) and the difference with 1908 (2008–1908; right) in nanotesla. The relatively weak magnetic field over South America and the southern Atlantic Ocean is referred to as the South Atlantic anomaly.

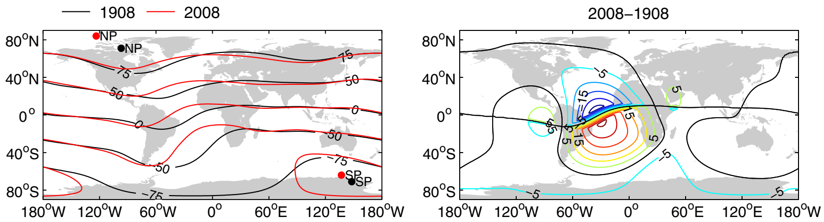

Figure 2. The inclination of the magnetic field in 1908 and 2008 (left) and the difference in the absolute inclination (2008–1908; right), in degrees. In the left panel, contours of 0° (magnetic equator), ±50°, and ±75° are shown, as well as the positions of the magnetic poles.

[4] To our knowledge, *Eyfrig* [1963] was the first to realize that changes in the Earth's magnetic field could lead to gradual changes in the ionospheric F_2 layer. He noted specifically that changes in the magnetic field declination would affect the critical frequency of the F_2 layer, f_oF_2. However, at the time there seemed to be little attention for his suggestion. More recently, with growing interest in long-term trends in the upper atmosphere, *Foppiano et al.* [1999] and *Elias and Ortiz de Adler* [2006] reintroduced the idea that the secular variation of the Earth's magnetic field might contribute to such long-term trends. By then it was also clear that not only changes in declination might be important but changes in inclination and magnetic field strength as well.

[5] *Cnossen and Richmond* [2008], hereafter CR08, performed a global study of the effects of changes in the Earth's magnetic field between 1957 and 1997 using the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM). They showed that magnetic field changes can contribute substantially to long-term trends in h_mF_2 and f_oF_2, in particular in the region of the SAA. Most of these changes were related to changes in the vertical component of plasma transport along magnetic field lines, due mostly to changes in magnetic field inclination. However, since the TIE-GCM does not include the magnetosphere, CR08 could not account for the potential effects of changes in the high-latitude coupling between the magnetosphere and ionosphere-thermosphere system.

[6] This issue was addressed in more recent work by *Cnossen et al.* [2011, 2012] and *Cnossen and Richmond* [2012] using the Coupled Magnetosphere-Ionosphere-Thermosphere (CMIT) model. They performed a number of idealized simulations in which the magnetic field was approximated by a pure dipole, of which the moment and tilt angle were systematically varied. Results indicated that both changes in magnetic field strength and in orientation influence solar wind-magnetosphere-ionosphere coupling processes, which affect the amount and geographic distribution of Joule heating. This can subsequently alter h_mF_2 and f_oF_2 via thermal contraction or expansion and changes in the O/N_2 ratio, although this is mainly important when Joule heating is strong, as during geomagnetically disturbed conditions.

[7] Changes in the Earth's magnetic field also have consequences for the currents flowing through the ionosphere and for the perturbations to the main magnetic field they produce. The solar quiet (Sq) current system is a low-latitude to midlatitude current system on the dayside ionosphere, driven by solar radiation and thermospheric winds. It 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. *Macmillan and Droujinina* [2007] and *Elias et al.* [2010] found long-term trends in the amplitude of the daily Sq magnetic variation, and the latter study argued that these could be at least partially explained by changes in the main magnetic field. *Cnossen et al.* [2012] showed that the increase in ionospheric conductivity, expected from a reduction in dipole moment comparable to that over the past century, could indeed generate trends in Sq amplitude of a similar order of magnitude to observed trends. However, they noted that the local changes in the magnetic field could also be important for the trends observed at a particular station.

[8] To make direct comparisons between simulated and observed trends possible, realistic model experiments need to be done. In this study, we therefore perform CMIT simulations with the magnetic fields of 1908, 1958, and 2008, specified by the International Geomagnetic Reference Field (IGRF) [*Finlay et al.*, 2010]. First, we use these to provide estimates of the effects of changes in the Earth's magnetic field on h_mF_2 and f_oF_2, improved with respect to the original

TIE-GCM-based estimates of CR08. Second, we provide estimates for the effects on several other variables for which long-term trends have been reported in the literature, such as electron and ion temperature, and the Sq daily amplitude. We also analyze how these effects are formed. To facilitate further comparisons between simulated and observed trends, we will make our results available to the long-term trend community on request (contact the corresponding author if interested).

2. Methods

2.1. Model Description

[9] We investigate the effects of changes in the Earth's magnetic field using the CMIT model [*Wiltberger et al.*, 2004; *Wang et al.*, 2004; *Wang et al.*, 2008]. CMIT couples the Lyon-Fedder-Mobarry (LFM) global magnetospheric code [*Lyon et al.*, 2004] with the Thermosphere-Ionosphere-Electrodynamics General Circulation Model [TIE-GCM; *Roble et al.*, 1988; *Richmond et al.*, 1992] through the Magnetosphere-Ionosphere Coupler/Solver (MIX) module [*Merkin and Lyon*, 2010].

[10] The LFM component of the model solves the ideal magnetohydrodynamic (MHD) equations to simulate the interaction between the solar wind and the magnetosphere and calculates the full MHD state vector (plasma density, pressure, velocity, and magnetic field). It requires the solar wind MHD state vector on its outer boundary as input and the ionospheric conductance on its inner boundary. The latter is passed in from the TIE-GCM part of the code through the MIX coupler module. An empirical parameterization described by *Wiltberger et al.* [2009] is used to calculate the energy flux of precipitating electrons into the upper atmosphere.

[11] The TIE-GCM is a time dependent, three-dimensional model that solves the fully coupled, nonlinear, hydrodynamic, thermodynamic, and continuity equations of the thermospheric neutral gas self-consistently with the ion continuity equations. At high latitudes, it requires the auroral particle precipitation and electric field imposed from the magnetosphere, which it receives from the LFM component of the code via the MIX coupler module. The solar activity level is specified through an F10.7 value [*Solomon and Qian*, 2005]. At the lower boundary (~97 km altitude), tidal forcing can be provided by the Global Scale Wave Model (GSWM). In our simulations, we used the GSWM migrating diurnal and semidiurnal tides of *Hagan and Forbes* [2002, 2003].

2.2. Simulation Setup and Analysis

[12] We performed three simulations with the magnetic fields of 1908, 1958, and 2008, respectively, specified through the IGRF. Before each CMIT simulation, the stand-alone TIE-GCM was run for 20 days with the magnetic field of the year in question. The final state of that 20 day run was used as the start condition for the ionosphere-thermosphere system in the CMIT simulation. Each CMIT simulation ran from 0:00 UT on 21 March to 0:00 UT on 5 April (15 days), and each used the measured solar activity level and solar wind conditions from 2008 in order to have a realistic magnitude of solar wind variability. On average, the solar activity was very low ($F10.7 \approx 70$ solar flux units), and geomagnetic conditions were relatively quiet. The Kp index was never higher than 5 and mostly around 2.

[13] Magnetic perturbations were calculated through a postprocessing code described by *Doumbia et al.* [2007] and *Richmond and Maute* [2013]. This includes only perturbations associated with currents flowing in the ionosphere and geomagnetic-field-aligned currents above the ionosphere; any effects of currents flowing perpendicular to the geomagnetic field in the magnetosphere are not considered, apart from fictitious radial currents flowing to or from infinity at each field line apex, needed to balance any net field-aligned current flowing into or out of the ionosphere on a field line. However, given that we are studying just the Sq current system, which is associated with the low-latitude to midlatitude ionospheric wind dynamo, this limitation is not important here. We do note that the TIE-GCM tends to underestimate *E*-region electron densities and conductivities and therefore also tends to underestimate magnetic perturbations. Any differences in magnetic perturbations between simulations may therefore also be underestimated. The amplitude of the daily Sq variation was calculated by taking the difference between the maximum and minimum values of the magnetic perturbations for a given field component at each location for each day.

[14] Most of the thermosphere-ionosphere results are presented in the form of 15 day means at 14:00 UT, with some results shown also at 2:00 UT. These times were chosen so that the region in which the strongest effects occur is captured both in the middle of the day and the middle of the night. The 15 day standard deviations were used to calculate *p*-values with a Student's *t* test to determine the significance level of differences between the simulations.

3. Results

3.1. h_mF_2 and f_oF_2

[15] Figure 3 shows maps of h_mF_2 and f_oF_2 for 2008 and the differences with 1958 and 1908 at 14:00 UT. Statistically significant differences (shaded) are found mostly within the region bounded by ~100°W–50°E and ~40°S–40°N, which we will refer to as the Atlantic region. The Atlantic region corresponds closely to the region in which the strongest changes in magnetic field inclination have occurred (Figure 2). For the longer time span, 1908–2008, Figure 3 shows that differences in h_mF_2 and f_oF_2 are larger and significant over a larger area than for 1958–2008, as might be expected. Significant differences in f_oF_2 for 1908–2008 are also found outside the Atlantic region, over Japan and Indonesia, and in both h_mF_2 and f_oF_2 over part of the southern Ocean.

[16] In previous work, we have shown that changes in the magnetic field affect h_mF_2 and f_oF_2 via changes in the O/N_2 ratio, changes in the vertical $E \times B$ drift, and changes in the vertical component of plasma transport along magnetic field lines [*Cnossen et al.*, 2011; 2012; *Cnossen and Richmond*, 2012]. The latter can consist of plasma diffusion as well as plasma transport by neutral horizontal winds along the magnetic field. We will refer to these terms as $v_{diff,v}$ and $v_{n,par,v}$, respectively. Plasma diffusion along the magnetic field is mainly driven by gravity, so that its vertical component, $v_{diff,v}$, is usually downward, acting to lower h_mF_2. The sign of $v_{n,par,v}$ on the other hand depends on the direction of the horizontal neutral winds: when the winds are equatorward (usual at night), plasma is forced up magnetic field

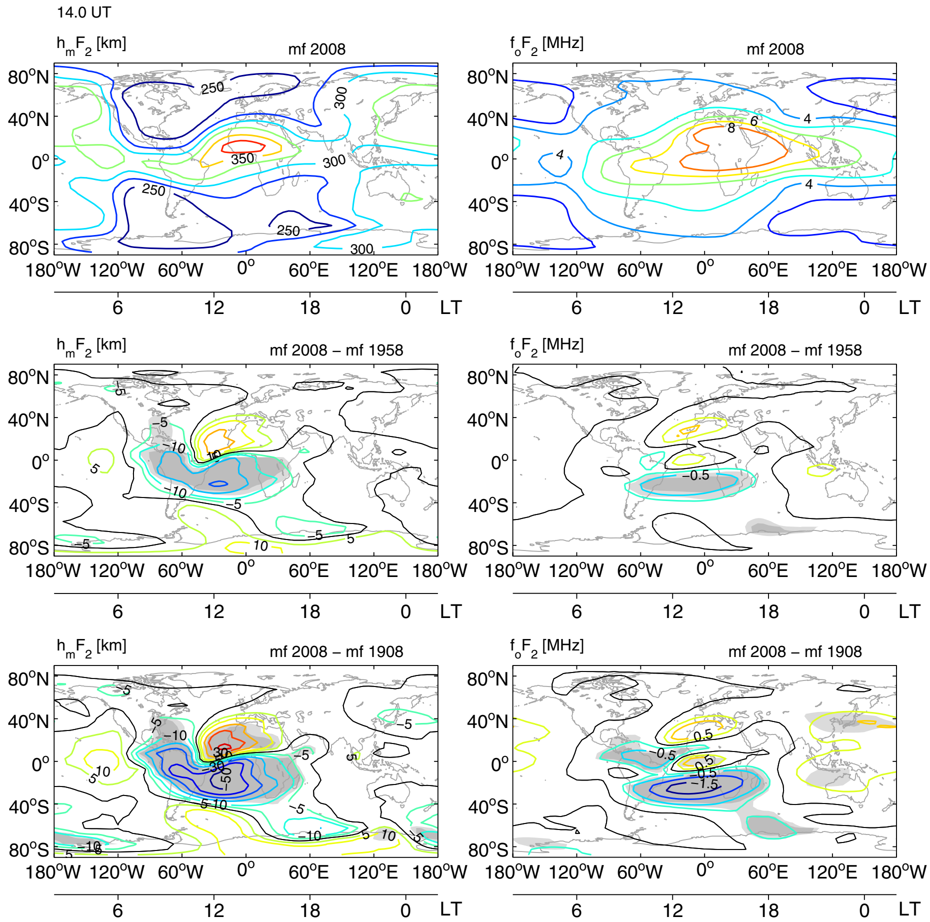

Figure 3. Maps of the 15 day mean h_mF_2 (left) and f_oF_2 (right) in 2008 (top) and the difference with 1958 (middle) and 1908 (bottom) at 14:00 UT. Light (dark) shading indicates 95% (99%) statistical significance.

lines, so that $v_{n,par,v}$ is positive, and vice versa when the winds are poleward (usual during the day).

[17] In our current simulations, changes in the O/N_2 ratio were very small and mostly not statistically significant, even when comparing 2008 and 1908 (not shown), so that we can eliminate this factor. The three transport terms are shown in Figure 4 and do show significant differences. Comparing the difference patterns in these terms to the differences in h_mF_2, we can relate the large decrease in h_mF_2 over mid- and South America and the southern Atlantic Ocean to a combination of changes in the vertical $E \times B$ drift, $v_{n,par,v}$ and $v_{diff,v}$. The increase in h_mF_2 centered at ~10°N, 20°W is associated primarily with changes in vertical $E \times B$ drift and $v_{diff,v}$ only. There is some significant change in the horizontal neutral winds in the Atlantic region (not shown), which contributes to the changes in $v_{n,par,v}$, but changes in inclination and declination contribute as well. Changes in $v_{diff,v}$ are mainly due to changes in inclination, as can be inferred from the similarity in the differences in $v_{diff,v}$ (Figure 4) and the differences in the inclination angle (Figure 2).

[18] The changes in f_oF_2 more or less follow the pattern of the changes in h_mF_2 and are probably caused by changes in the recombination rate as the F_2 peak moves up or down. When the F_2 peak is lower, the ambient neutral density is higher, so that more recombination takes place. This leads to a lower electron density and therefore lower f_oF_2. The opposite happens when the F_2 peak is higher.

[19] At 14:00 UT, it is daytime in the region where the largest changes in h_mF_2 and f_oF_2 occur. In Figure 5, we show the effects of magnetic field changes at 2:00 UT, when it is nighttime in that same region. Only the differences in h_mF_2 and f_oF_2 between 1908 and 2008 are shown here for conciseness. The 2008–1908 differences in h_mF_2 are much smaller and more finely structured at 2:00 UT than at 14:00 UT. In contrast, the differences in f_oF_2 have only become somewhat smaller and are similar in structure.

[20] The similarity in the f_oF_2 differences at 2:00 and 14:00 UT is probably due to the nighttime plasma densities being strongly dependent on the daytime plasma densities. During the day, not only the F_2 peak density is mostly smaller for 2008 than for 1908 in the region where the f_oF_2 differences are strongest, but the entire topside ionosphere in that area is reduced, as shown in Figure 6. The nighttime difference in f_oF_2 is probably a remnant of this large daytime difference in the plasma density from the F_2 peak upward. Figure 6 also demonstrates that only the ionosphere above ~250 km is affected by magnetic field changes. Changes in the magnetic field can therefore not be responsible for observed trends in the E region and F_1 region.

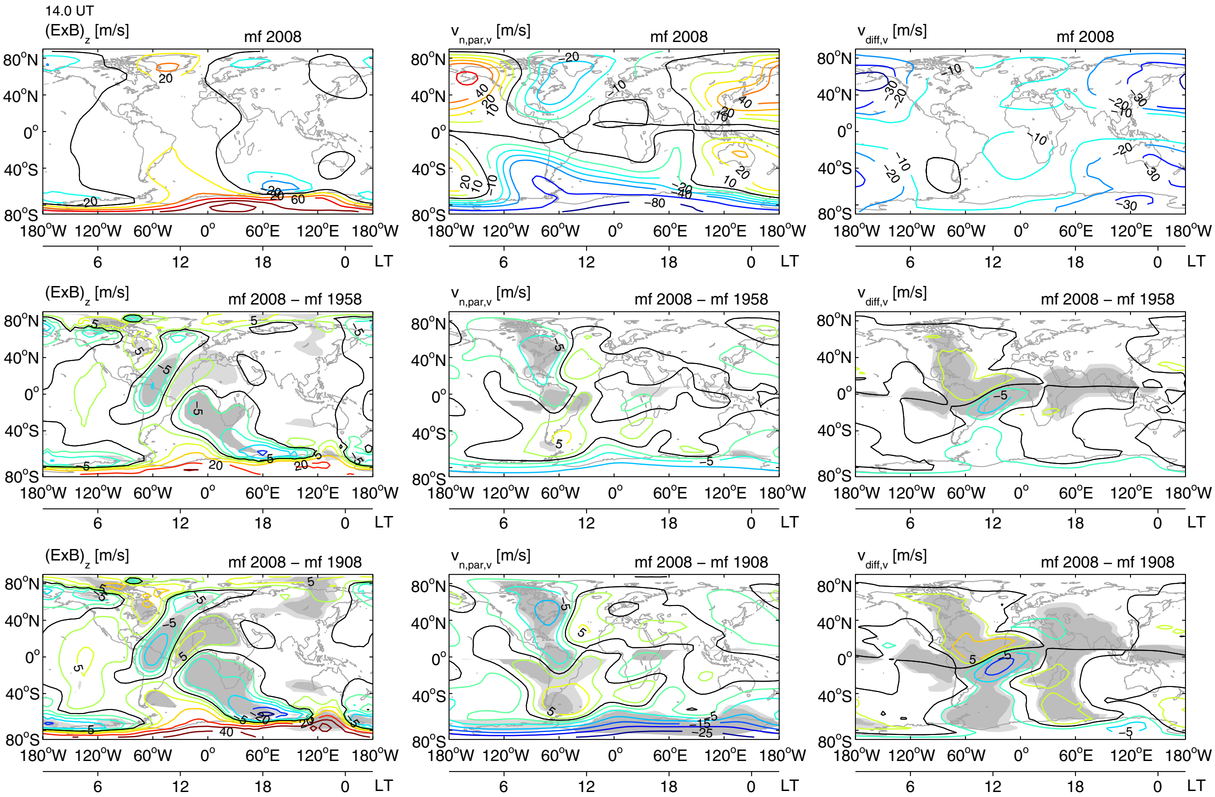

Figure 4. Maps of the 15 day mean vertical E × B drift (left), $v_{n,par,v}$ (middle), and $v_{diff,v}$ (right) in 2008 (top) and the difference with 1958 (middle) and 1908 (bottom) at a constant pressure level of $3.2 \cdot 10^{-8}$ hPa, corresponding roughly to the level of the F_2 peak height, at 14:00 UT. Light (dark) shading indicates 95% (99%) statistical significance.

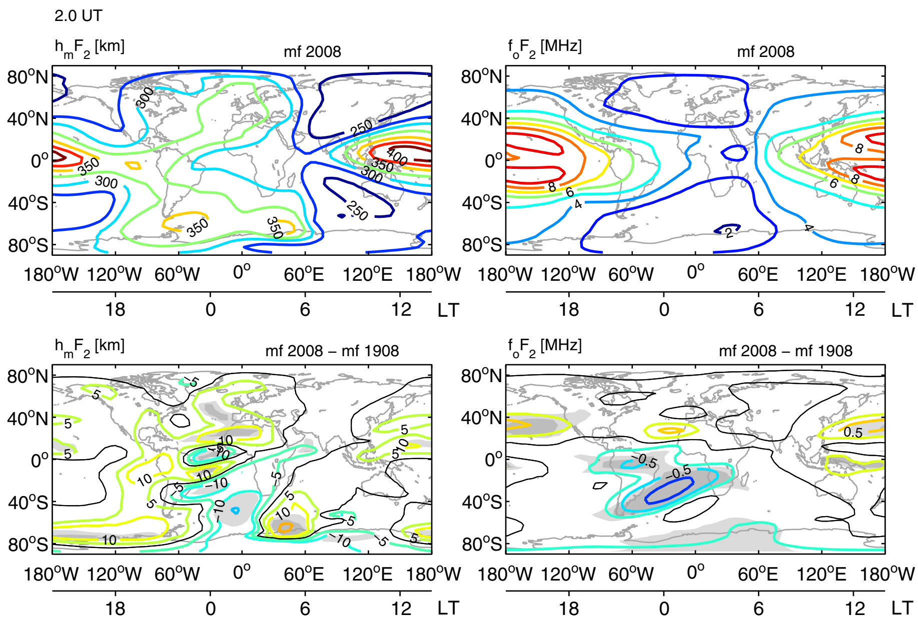

Figure 5. Maps of the 15 day mean h_mF_2 (left) and f_oF_2 (right) in 2008 (top) and the difference with 1908 (bottom) at 2:00 UT. Light (dark) shading indicates 95% (99%) statistical significance.

[21] The small alternating positive and negative responses in h_mF_2 at 2:00 UT can again be related to changes in the vertical E × B drift, $v_{n,par,v}$ and $v_{diff,v}$, shown in Figure 7. The differences in $v_{n,par,v}$ and $v_{diff,v}$ are very similar in structure, but opposite in sign at nighttime. This arises from the change in the neutral wind direction from day to night,

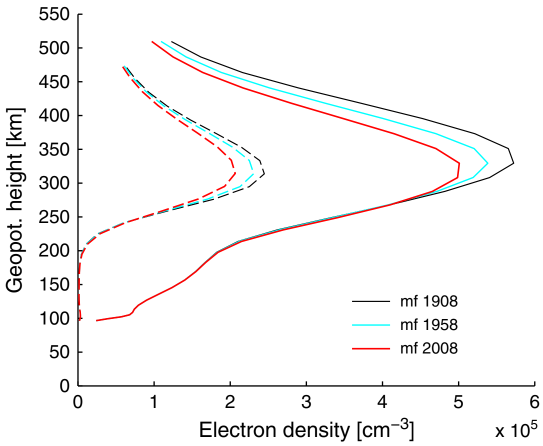

Figure 6. The 15 day mean electron density profiles averaged over 42.5°S–12.5°N and 80°W–50°E at 2:00 and 14:00 UT for 1908, 1958, and 2008. Solid lines are for 14:00 UT (day) and dashed lines for 2:00 UT (night).

changing the structure, and in some regions the sign of $v_{n,par,v}$ but not the structure or sign of $v_{diff,v}$. Both terms tend to add up during the day but partly cancel each other out at night, leading to much smaller changes in h_mF_2 at 2:00 UT than at 14:00 UT.

3.2. Neutral, Ion, and Electron Temperatures

[22] Figure 8 shows maps of the neutral, ion, and electron temperatures in 2008 and the difference with 1958 and 1908 at 14:00 UT. Statistically significant changes in electron temperature can be seen, which follow the changes in f_oF_2 (representing changes in electron density) but with the opposite sign. This arises because the energy transferred from solar photoelectrons to the electron gas is divided over the electrons present. When fewer electrons are present (lower f_oF_2), the average electron temperature is higher. The electrons can heat up the ions and neutrals as well, but the differences in ion temperature are clearly smaller and less significant, and the changes in neutral temperature are not significant at all.

[23] At 2:00 UT, the differences in electron temperature appear to follow the differences in electron density in a similar way (not shown). However, this result may be less reliable because at night the electron temperature is influenced by the downward electron heat flux specified at the TIE-GCM upper boundary. This downward heat flux is specified as a simple function of magnetic latitude and magnetic local time, so we are not sure how realistic the simulated changes in electron temperature, and hence ion temperature, are at 2:00 UT. Differences in neutral temperature are again not significant.

3.3. Sq Variation

[24] Figure 9 shows maps of the (geographic) northward, eastward, and downward daily Sq amplitude in 2008, and the difference with 1958 and 1908. Statistically significant differences occur mostly at low magnetic latitudes, in particular over the eastern/southeastern Pacific Ocean, South America, the southern Atlantic Ocean, and parts of Africa. These low-latitude differences are largely caused by the displacement of the equatorial electrojet, which follows the displacement of the magnetic equator. Since the strongest currents occur during the day, close to local noon, most of the changes in Sq amplitude are associated with a change in the daytime magnetic perturbation.

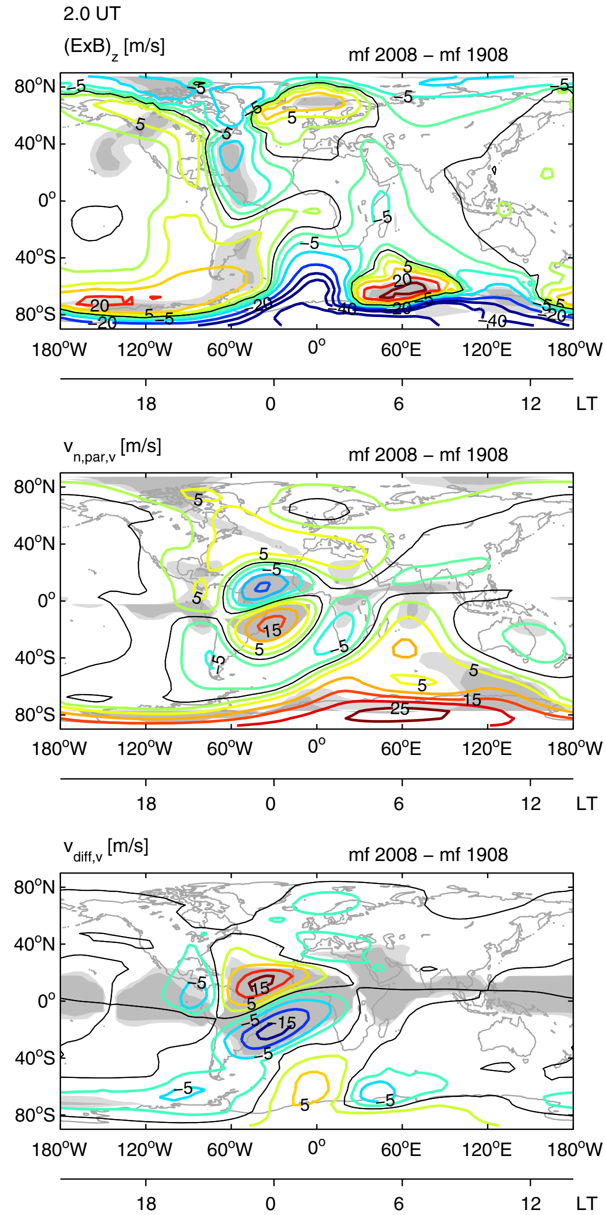

Figure 7. Maps of the 15 day mean difference between 2008 and 1908 in the vertical E × B drift (top), $v_{n,par,v}$ (middle), and $v_{diff,v}$ (bottom) at a constant pressure level of $3.2 \cdot 10^{-8}$ hPa, corresponding roughly to the level of the F_2 peak height, at 2:00 UT. Light (dark) shading indicates 95% (99%) statistical significance.

[25] At low latitudes, the daytime magnetic perturbation in the northward component is strongest right at the magnetic equator, where the equatorial electrojet is the strongest, and gets weaker away from the magnetic equator in either direction. A northward movement of the magnetic equator, as has occurred in most of the Atlantic region, therefore produces a decrease in the daytime northward magnetic perturbation south of the original magnetic equator position and an increase north of it. This corresponds to the changes in amplitude seen in Figure 9. In the westernmost part of the Atlantic region and beyond (~120°W–70°W), the magnetic equator has moved

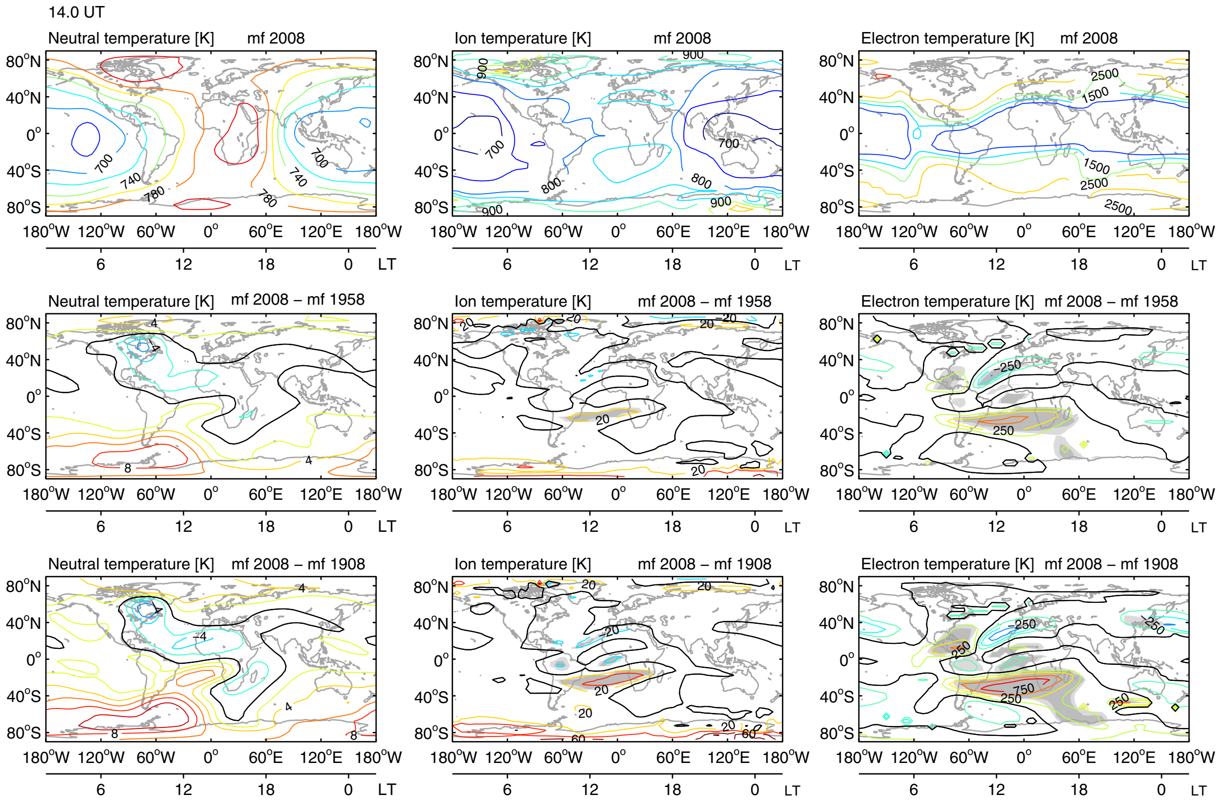

Figure 8. Maps of the 15 day mean neutral temperature (left), ion temperature (middle), and electron temperature (right) in 2008 (top) and the difference with 1958 (middle) and 1908 (bottom) at a constant pressure level of $3.2 \cdot 10^{-8}$ hPa, corresponding roughly to the level of the F_2 peak height, at 14:00 UT. Light (dark) shading indicates 95% (99%) statistical significance.

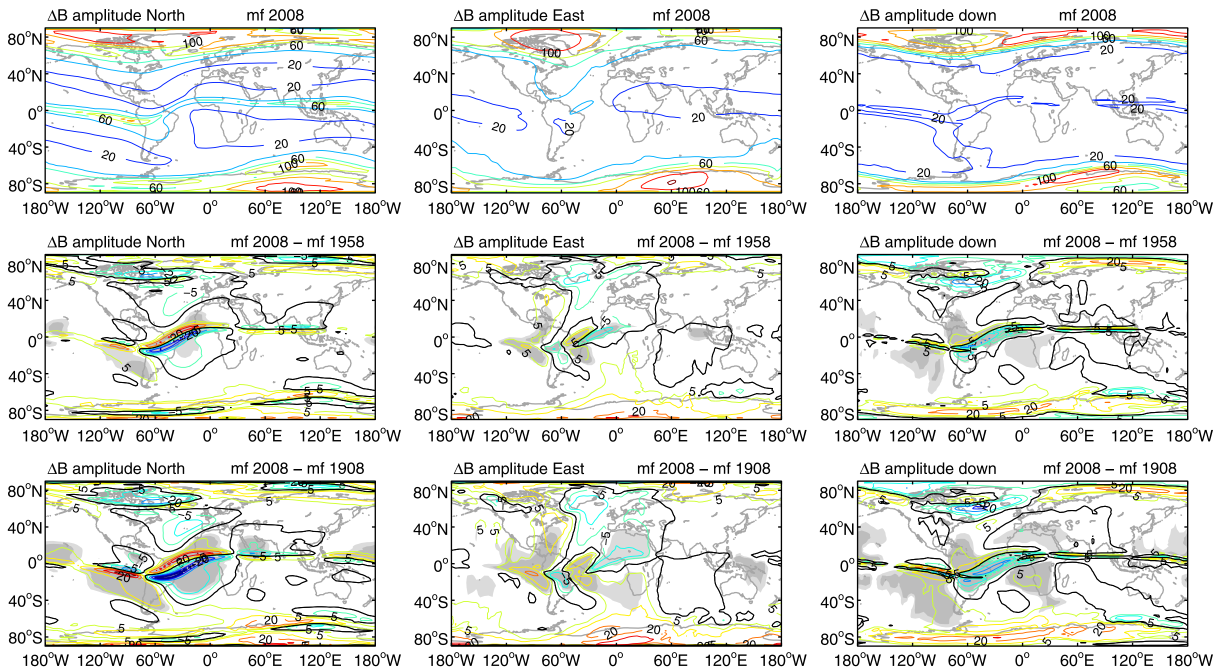

Figure 9. Maps of the 15 day mean northward (left), eastward (middle), and downward (right) component of the daily Sq amplitude in 2008 (top) and the difference with 1958 (middle) and 1908 (bottom). Light (dark) shading indicates 95% (99%) statistical significance.

slightly southward (see Figure 2), and the opposite pattern forms. The downward magnetic perturbation component is affected in a similar way by north–south movements of the magnetic equator, but here it also matters whether a location is situated north of the magnetic equator or south of it because the daytime magnetic perturbation is upward (negative) in the northern hemisphere and downward (positive) in the southern hemisphere. This produces a slightly more complex difference pattern in the Sq amplitude of the downward component.

[26] There are also signs that the Sq system has moved in the zonal direction. This can be seen most easily in the equivalent current function, shown in Figure 10. The equivalent current function is a representation of the ground-level magnetic perturbations in terms of a (fictitious) two-dimensional current sheet at 110 km altitude that produces the same magnetic perturbations as the actual three-dimensional currents in the ionosphere and above. An equivalent current flows along contours of the function. The equivalent current function shown here was evaluated at 15:00 UT, when it is close to local noon in the region where the strongest changes occur. The northern hemisphere anticlockwise current vortex, centered on the minimum in the equivalent current function located at ~15°N, 60°W in 2008, has moved noticeably westward over time, while there seems to have been an eastward movement in the southern hemisphere. The westward movement in the northern hemisphere may be linked to the westward drift of the magnetic field, but changes in the neutral winds may have contributed as well. The latter may also be responsible for the eastward movement in the southern hemisphere. Zonal movements in the Sq current system mostly affect the eastward magnetic perturbations, which are associated with the meridional branches of the current system. Northward currents produce westward perturbations and southward currents eastward perturbations. The westward or eastward movement of the north- and southward branches of the current system then gives a zonally alternating pattern of positive and negative differences in the eastward Sq perturbations, which is also seen in the daily Sq amplitude.

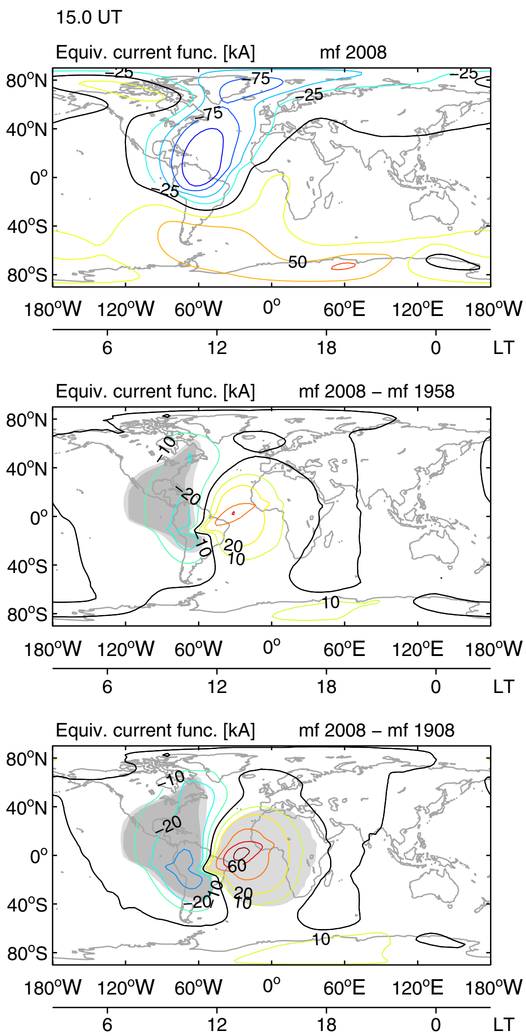

Figure 10. Maps of the 15 day mean equivalent current function in 2008 (top) and the difference with 1958 (middle) and 1908 (bottom) at 15:00 UT. Light (dark) shading indicates 95% (99%) statistical significance.

[27] Changes in the Sq amplitude at midlatitudes to high latitudes may be (partly) related to changes in magnetic field strength. For instance, the increase in the Sq amplitude in the northward and downward components over the southern tip of South America and west of it coincides with a strong local reduction in field strength (see Figure 1). Previous work has indicated that a reduction in field strength would indeed lead to an increase in Sq amplitude due to an increase in ionospheric conductivity [*Cnossen et al.*, 2012]. The fact that the eastward component does not show a similar amplitude increase may be due to changes in the pattern of the current system that happen to offset the effects of intensification on the eastward component.

4. Discussion

[28] Our simulations with the CMIT model indicate that changes in the Earth's magnetic field have produced statistically significant changes in the ionosphere mostly between 40°S–40°N and 100°W–50°E, which we refer to as the Atlantic region. The changes in h_mF_2 and f_oF_2 are similar in character to those found by CR08 using the stand-alone TIE-GCM, but there are also some differences. Their simulations did not show a weaker response in h_mF_2 during nighttime, as we found here, and their response in f_oF_2 was in fact stronger at night, while it was similar for day and night here. In addition, the changes in both f_oF_2 and h_mF_2 simulated by CR08 were confined to a narrower longitudinal range (~90°W–10°E) than we found here, even when we consider the 2008–1958 interval, which is the closest match to the interval studied by CR08.

[29] The reason for these differences is not entirely clear. Most of the responses to magnetic field changes occurred at low latitudes to midlatitudes and should not be greatly affected by the two-way coupling with the magnetosphere that is added in by using CMIT rather than the TIE-GCM, except perhaps during strong magnetic storms. However, in the 15 days simulated here, geomagnetic activity is mostly quite low. In our CMIT simulations, the cross-polar cap potential was on average ~55 kV, compared to a fixed value of 45 kV in the TIE-GCM simulations of CR08. There is a considerable difference in the solar activity level used though: CR08 used F10.7 = 150 solar flux units compared

to F10.7 ≈ 70 solar flux units used here. Possibly, these different solar activity levels could lead to different ionospheric responses to a change in the magnetic field. This should be investigated in future work.

[30] The simulated changes in h_mF_2 in the Atlantic region translate into typical trends of around ±1 km/decade at night and around ±3 km/decade during the day, with even stronger daytime trends (+4 to −5 km/decade) possible in some locations. These are comparable or somewhat smaller in magnitude to trends that have been observed in this region. For instance, *Foppiano et al*. [1999] reported a daytime trend of −2 to −5 km/decade and a nighttime trend of +5 to +10 km/decade at Concepción (36.8°S, 73°W), and *Upadhyay and Mahajan* [1998] reported a daytime trend of −3.6 km/decade at Huancayo (12°S, 75.3°W). The simulated changes in f_oF_2 in the Atlantic region translate into trends of −0.1 to +0.05 MHz/decade, the magnitude of which again compares reasonably well to observed trends at Concepción (−0.15 to −0.3 MHz/decade) [*Foppiano et al*., 1999] and Huancayo (+0.17 MHz/decade) [*Upadhyay and Mahajan*, 1998]. From this we can conclude that changes in the Earth's magnetic field have probably contributed substantially to observed trends in the Atlantic region.

[31] Moreover, changes in the magnetic field appear to be more important than changes in the CO_2 concentration in the Atlantic region. Simulations by *Qian et al*. [2009] of a doubling of the CO_2 concentration suggest typical trends in h_mF_2 of around −1 km/decade, with a maximum trend of about −2 km/decade, and trends in f_oF_2 of 0 to −0.04 MHz/decade, both obtained through linear interpolation. These trends are ~2.5 times smaller than the typical trends we find for the Atlantic region due to magnetic field changes. In other parts of the world, where changes in the magnetic field have been much smaller, their effects are also much smaller. Outside the Atlantic region, it appears that magnetic field changes have mostly not contributed significantly to long-term trends in h_mF_2 or f_oF_2 and do not offer a solution to reconcile the discrepancies between observed trends and those predicted for the change in CO_2 concentration as outlined in the introduction. Trends observed in the *E* or F_1 regions in any part of the world cannot be explained by changes in the magnetic field either, as these only affect the ionosphere above ~250 km.

[32] Changes in the Earth's magnetic field can contribute to long-term trends in electron temperature and, to a lesser degree, in ion temperature, again primarily in the Atlantic region. Trends in these parameters for the Atlantic region have not yet been reported in the literature. S.-R. Zhang and colleagues (personal communication, 2012) do report on ion and electron temperature trends at Millstone Hill (42.5°N, 71.5°E) and noted that the changes simulated here are of the same sign as their trends. However, our simulated changes at this location are not significant against the day-to-day variability produced by the model. Changes in neutral temperature are in reasonable agreement in terms of magnitude with the changes in temperature estimated from idealized CMIT simulations by *Cnossen et al*. [2011, 2012] but are not statistically significant at any location.

[33] *Cnossen et al*. [2012] estimated trends in the daily Sq amplitude due to the decrease in the dipole moment that has taken place over the past century. They found increases of 2.0–2.4, 3.0–4.7, and 1.3–2.0 nT/century for the northward, eastward, and downward components, respectively. However, our current results indicate only significant regional changes in Sq amplitude, which are associated mostly with the movement of the magnetic equator and the westward drift of the magnetic field, rather than changes in field strength. This leads to very strong trends close to the magnetic equator of up to ±40 nT/century in the northward component and ±15 nT/century in the eastward and downward components. More typical trends are on the order of ±5 to ±10 nT/century. The latter are similar in order of magnitude to trends in the daily amplitude of the *H* component observed by *Elias et al*. [2010] for Apia (13.8°S, 171.8°W; 8 ± 1 nT/century), Fredericksburg (38.2°N, 77.4°W; 4.8 ± 0.8 nT/century), and Hermanus (34.4°S, 19.2°E; 7.6 ± 0.6 nT/century) but larger than the average 1.3 nT/century trend reported by *Macmillan and Droujinina* [2007] for 14 observatories, even though the simulated trends may be considered a conservative estimate, given that the TIE-GCM tends to underestimate magnetic perturbations.

[34] In addition to the Sq system, current systems in the midlatitude and high-latitude ionosphere and in the magnetosphere could be affected by magnetic field changes as well. These changes might lead to a different response, and hence different magnetic perturbations at the ground, for a given disturbance in the solar wind. This implies that long-term trends in geomagnetic activity, as observed for instance in the aa index [e.g., *Clilverd et al*., 1998], could potentially be related to the secular variation of the Earth's magnetic field, instead of, or in addition to, changes in the Sun. It also means that long-term trends in geomagnetic activity are not necessarily an independent, external driver of long-term change in the upper atmosphere, as has been proposed by some [e.g., *Danilov and Mikhailov*, 2001]. The possibility of the secular variation of the Earth's magnetic field as a cause of long-term change in measures of geomagnetic activity could have important implications for both solar physics and upper atmospheric long-term change and should be investigated further in future work. We have not addressed this here because CMIT does not yet represent the ring current very well, which plays an important role in the response of the magnetosphere-ionosphere-thermosphere system to magnetic (sub)storms and the associated magnetic perturbations. Work is currently underway to improve this situation.

5. Conclusions

[35] The secular variation of the Earth's magnetic field between 1908 and 2008 has caused statistically significant changes in h_mF_2, f_oF_2, electron temperature, and ion temperature between ~40°S–40°N and ~100°W–50°E, which we refer to as the Atlantic region. The changes in h_mF_2 and f_oF_2 are produced by a combination of changes in the vertical E × B drift and the vertical components of plasma diffusion ($v_{diff,v}$) and transport by neutral winds along the magnetic field ($v_{n,par,v}$). Changes in h_mF_2 are considerably stronger during the day than at night, while changes in f_oF_2 are only somewhat smaller at night. Changes in electron density produce changes in electron temperature with the opposite sign. The changes in electron temperature are partly transferred to the ion temperature, while changes in neutral temperature are not significant on a 100 year timescale.

[36] Changes in the Earth's magnetic field also affect the amplitude of the Sq magnetic variation. The strongest changes occur near the magnetic equator and are mainly associated with the northward movement of the magnetic equator in the Atlantic region and the westward drift of the magnetic field. Changes in magnetic field strength seem to be relatively less important at low magnetic latitudes but may have some influence at midlatitudes to high latitudes.

[37] In the Atlantic region, simulated trends in h_mF_2 and f_oF_2 are comparable in magnitude to observed trends and are ~2.5 times larger than trends predicted from the increase in greenhouse gas concentrations. Also simulated trends in Sq amplitude are comparable to, or even somewhat larger than, typical observed trends in the Atlantic region. The secular variation of the Earth's magnetic field may therefore be the dominant cause of trends in the Atlantic region ionosphere, while it is clearly less important in most other parts of the world. In those parts of the world, our results indicate that changes in the magnetic field have probably not contributed significantly to observed long-term trends. More detailed, quantitative comparisons between simulated and observed trends are needed to determine more precisely the relative contribution of magnetic field changes to observed trends compared to other drivers (e.g., increase in greenhouse gas concentrations), taking into account seasonal, local time, and solar activity influences. The simulation results presented in this study will be made available to the long-term trend community to facilitate such comparisons (contact the corresponding author if interested).

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