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Long-term trend of f_oF_2 at a West African equatorial station linked to greenhouse gas increase and dip equator secular displacement

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[1] Long-term variability of f_oF_2 at Ouagadougou station (12.4°N, 358.5°E; dip, 1.45°), a West African equatorial station, is studied, analyzing an annual mean data series at 12 LT for the period 1966–1998. After filtering the solar activity effect using *Rz* as a solar activity proxy, a downward trend of −0.015 MHz/yr is obtained, that is a ~5% decrease during the period of 33 years here considered, equivalent to a ~0.2%/yr. The downward trend is qualitatively consistent with a decreasing trend expected from increasing greenhouse gas concentration but greater than the ~0.003%/yr that would result from the 20% increase in CO_2 that actually took place during the period of analysis. The f_oF_2 decreasing trend is not in agreement with the trend expected from the secular variation of the dip angle at the location of Ouagadougou, but here an additional mechanism is considered, that is the secular movement of the dip equator toward Ouagadougou. This implies an approaching of the trough of the equatorial ionization anomaly and thus an f_oF_2 decrease at Ouagadougou that is qualitatively in agreement with the observed trend.

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1. Introduction

[2] Trends in the upper atmosphere have become a main subject since the beginning of the 1990s as a consequence of the increasing interest in global changes and the effects of increasing greenhouse gas concentration [*Aikin et al.*, 1991; *Roble*, 1995; *Ulich and Turunen*, 1997; *Jarvis et al.*, 1998; *Lastovicka*, 2005, 2009; *Bremer et al.*, 2012]. For complete reviews on upper atmosphere trends, see *Qian et al.* [2011] and *Lastovicka et al.* [2012].

[3] In the case of the ionosphere, long-term trends of different parameters have been linked mainly to four possible causes: increasing greenhouse gas concentration [*Roble and Dickinson*, 1989; *Rishbeth*, 1990; *Hall and Cannon*, 2002; *Qian et al.*, 2008], long-term solar variability [*Torta et al.*, 2009], geomagnetic activity long-term variation [*Danilov and Mikhailov*, 1999; *Mikhailov and Marin* 2000], and Earth's magnetic field secular variation [*Foppiano et al.*, 1999; *Elias and Ortiz de Adler*, 2006; *Cnossen and Richmond*, 2008; *Yue et al.*, 2008; *Elias*, 2009; *Cnossen et al.*, 2012].

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[4] In this work, we analyze the f_oF_2 long-term variation at Ouagadougou, a West African equatorial station, located near the trough of the equatorial ionization anomaly (EIA). The observed trend is evaluated considering the greenhouse gas increase and Earth's main magnetic field secular variation, together with the consequent dip equator displacement, as possible causes.

[5] There are several studies on the variability of f_oF_2 measured at Ouagadougou [*Ouattara et al.*, 2009; *Akala et al.*, 2011; *Ouattara et al.*, 2012; *Ouattara and Amory-Mazaudier*, 2012]. Long-term trends in f_oF_2, at different times of day and seasons measured at this ionospheric station have also been studied by *Ouattara* [2012]. He arrived at the following conclusions: negative trends are observed during daytime and positive trends from about midnight to 10 LT; trend absolute values are greater at night than during daytime; trend absolute values are higher in summer than in winter; at 4 LT (when the greatest positive trend is observed), the trend is positive from 1966 to 1981 and negative from 1981 to 1996, and at 19 LT (when the greatest negative trend is observed), the trend is negative for the entire period of analysis, that is 1966 to 1996. Based on a qualitative analysis of Earth's main magnetic field secular variation, *Ouattara* [2012] concluded that this may be a mechanism capable of producing some of the observed trends together with the geomagnetic activity since he observed that for some hours, f_oF_2 long-term behavior is well correlated to that of *Ap*.

[6] The goal of the present paper is to analyze the f_oF_2 long-term trend at a station in the African EIA sector, Ouagadougou, considering an ionospheric possible trend-inducing mechanism not considered by *Ouattara* [2012]. This mechanism consists of the displacement of the EIA

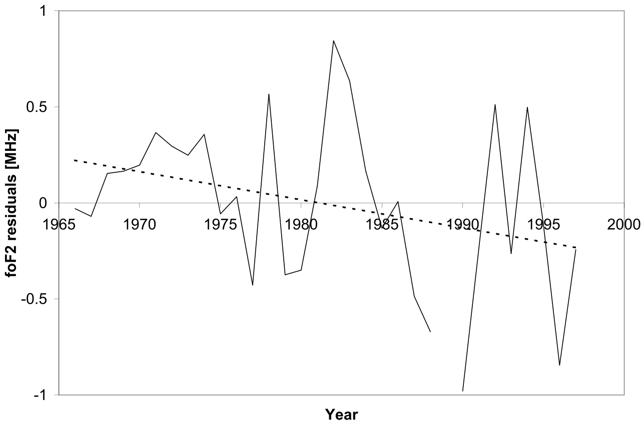

Figure 1. The f_oF_2 residuals (MHz) obtained after filtering the solar activity effect from f_oF_2 considering a linear dependence with *Rz* (solid line). Linear trend of f_oF_2 residuals (dashed line). Slope, -0.015 ± 0.008 MHz/yr.

f_oF_2 latitudinal pattern that accompanies the secular movement of the dip equator. Although it is not an additional mechanism, since it results from the secular variation of Earth's main magnetic field, it needs some special considerations.

[7] Since ionization for Ouagadougou is higher between 11 and 15 LT and the geomagnetic effect on trends is smaller at 12 LT according to *Ouattara* [2012, Figure 2], we chose to analyze f_oF_2 at 12 LT even though *Ouattara* [2012] showed that at other local times, the long-term trend can be stronger. The negative trend observed is linked to increasing greenhouse gas concentration and the displacement of the EIA latitudinal profile that follows from the dip equator movement.

2. Data Analysis

[8] Annual f_oF_2 data, for 12 LT, measured at Ouagadougou (12.4°N, 358.5°E; dip, 1.45°), a West African equatorial station, are analyzed for the period 1966–1998, with one missing year, 1989, due to data gaps.

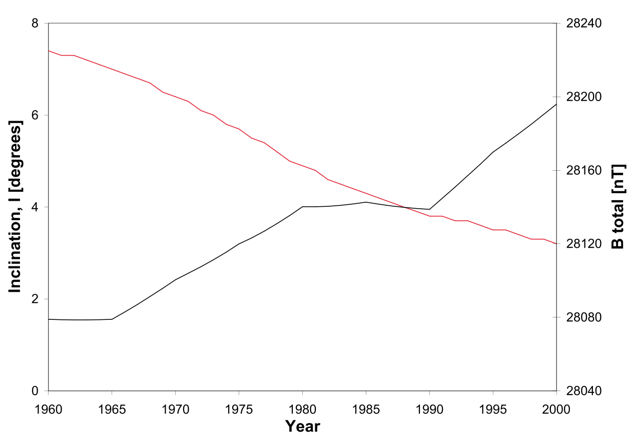

Figure 2. Inclination *I* (red line) at 300 km height and Earth's magnetic field magnitude *B* (black line), obtained from the International Geomagnetic Reference Field (IGRF), at Ouagadougou location (12.4°N, 358.5°E).

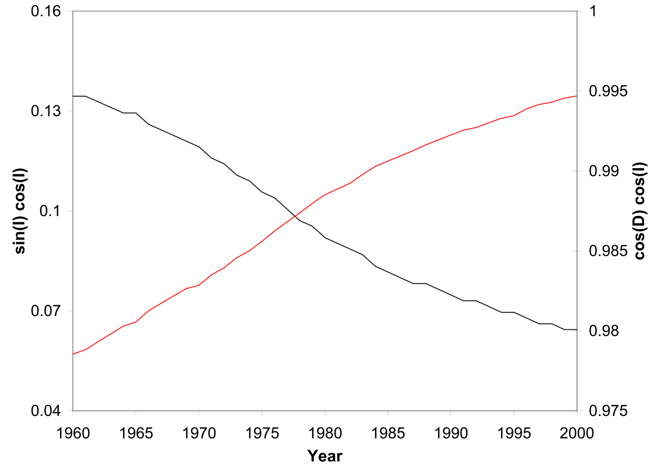

Figure 3. The sin(*I*)cos(*I*) factor (black line) and cos(*D*)cos(*I*) factor (red line). Inclination *I* and declination *D*, obtained from the International Geomagnetic Reference Field (IGRF), at Ouagadougou location (12.4°N, 358.5°E).

[9] To filter out the solar activity effect, we used a linear dependence of f_oF_2 on *Rz* although *Ouattara* [2012] used a third-degree polynomial for the same Ouagadougou data. Since the correlation and determination coefficients between f_oF_2 and *Rz* are 0.94 and 0.97, respectively, in the case of a third-degree polynomial and 0.96 and 0.92 in the case of a first-degree polynomial, we consider that it is reasonable to use the first-degree one. The standard deviation of the residuals in this case is 0.4 MHz. Another difference with the *Ouattara*'s [2012] study is that we used absolute f_oF_2 data instead of relative ones.

[10] The resulting trend of f_oF_2 residuals (shown in Figure 1) is -0.015 ± 0.008 MHz/yr, which is a ~0.2%/yr f_oF_2 decrease. The decreasing trend observed is qualitatively consistent with the expected decrease in f_oF_2 due to increasing greenhouse gas concentration but much greater. For an actual mean value of ~0.5%/yr increase in CO_2, a 0.003%/yr decrease in f_oF_2 should be expected if we linearly extrapolate the results of *Rishbeth* [1990] and *Rishbeth and Roble* [1992] for a doubling in CO_2 concentration.

[11] Considering the secular variation of Earth's magnetic field at the location of Ouagadougou station, Earth's magnetic field magnitude, *B*, presents an almost monotonic increase during the period of analysis, while the magnetic inclination, *I*, decreases. Both parameters, obtained from the International Geomagnetic Reference Field (IGRF), available from the National Space Science Data Center, are shown in Figure 2. The sin(*I*)cos(*I*) factor, associated with the effects of neutral winds on h_mF_2 [*Rishbeth*, 1998], decreases during the whole period considered as *I* does (see Figure 3). The mechanism through which this factor affects h_mF_2, and consequently f_oF_2, is the following. The horizontal thermospheric wind *U* drives ions and electrons up during the night and down during the day along the geomagnetic field lines at speed *U* cos(*I*). Then, the vertical component, *U* sin(*I*)cos(*I*), raises the F_2 peak during nighttime and lowers it during daytime, resulting in an f_oF_2 increase at night or an f_oF_2 decrease during the day. So an increase in the sin(*I*)cos(*I*) factor due to changes in *I* would produce an additional lowering of the *F* region with a

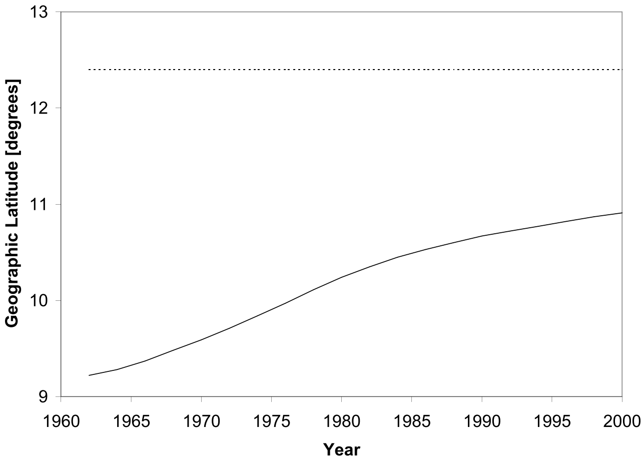

Figure 4. Variation of the geographic latitude of the dip equator (solid line) at the geographic longitude of Ouagadougou station (358.5°E). Also shown the latitude of Ouagadougou (dashed line).

decrease in f_oF_2 during daytime (when U blows from equator to pole) and an additional rise of the region with an increase in f_oF_2 during the night (when U blows from pole to equator). A decrease in the sin(I)cos(I) factor would produce the opposite effect. In the case of Ouagadougou, the decrease observed in the sin(I)cos(I) factor should induce then an f_oF_2 increase during the day instead of the observed decrease.

[12] In addition to this reasoning, we can consider the results of *Yue et al*. [2008] who concluded that at equatorial stations, f_oF_2 follows the trend of cos(D)cos(I) that is depicted in Figure 3, D being the magnetic declination. Again, a positive trend should be expected, in accordance with the positive trend which should be induced by the decrease in the sin(I)cos(I) factor.

[13] Considering variations in $E \times B$ induced by secular trends in B and the displacement of the dip equator, the expected f_oF_2 trend is different. *Cnossen and Richmond* [2008] and *Cnossen et al*. [2012] obtained a negative trend for the vertical component of $E \times B$ drift at West Africa, which results in slight but decreasing f_oF_2 trends. Regarding the displacement of the dip equator, its latitudinal movement is depicted in Figure 4 at the geographic longitude of Ouagadougou station. It can be clearly noticed that the dip equator is approaching Ouagadougou during the period here analyzed. Due to the closeness of Ouagadougou to the trough of the equatorial ionization anomaly, EIA, its movement accompanying the dip equator displacement should induce f_oF_2 variations. Since the EIA pattern is centered at the magnetic dip equator, then we expect the EIA trough and crests to follow its migration. This implies that trends in h_mF_2 and f_oF_2 should be linked to the secular variation of the magnetic dip equator. To qualitatively assess these trends, we calculated f_oF_2 for different latitudes at the geographic longitude of Ouagadougou with the IRI2007 model available at http://omniweb.gsfc.nasa.gov/vitmo/iri_vitmo.html [*Bilitza and Reinisch*, 2008]. As an example, the latitudinal f_oF_2 profile estimated for an initial condition (January, at 12 LT, and solar activity level corresponding to $F10.7 = 150$) was moved in latitude according to the displacement of the magnetic dip equator at the given longitude, as shown in Figure 5. The

Table 1. f_oF_2 Trend[a]

Local Time	Using Annual Mean f_oF_2 Versus Rz Residuals	Using *Ouattara* [2012] Values	Using IRI2007 f_oF_2 Latitudinal Profiles
	f_oF_2 Trend (MHz/yr)		
4	0.004	0.007	0.005
12	−0.015	−0.007	−0.001
19	−0.028	−0.023	−0.007

[a]Calculated using the residuals of the linear regression between f_oF_2 annual mean and Rz (first column), using *Ouattara* [2012] values multiplied by the mean f_oF_2 for the corresponding hour (second column), and displacing the latitudinal f_oF_2 profile obtained with IRI2007 by the same latitude range as the dip equator has shifted at the longitude of Ouagadougou (third column).

dotted vertical line indicates the latitude of Ouagadougou. It can be clearly noticed that from the north of the trough until the northern crest, f_oF_2 should decrease as a consequence of the northward EIA displacement at this longitude.

[14] In order to check if this mechanism can also explain trends obtained at other local times, we calculated the f_oF_2 latitudinal profiles with IRI2007 as in the case of 12 LT, considering now 4 LT and 19 LT, times of day for which extreme positive and negative trends, respectively, are found by *Ouattara* [2012]. This profile was shifted in latitude according to the displacement of the dip equator at this longitude, and the difference between f_oF_2 after and before the shift was taken as the f_oF_2 trend. These trend values together with that already obtained in the present work for 12 LT and values obtained by *Ouattara* [2012] are shown for comparison in Table 1. A positive trend is obtained at 4 LT and a negative trend at 19 LT, which are stronger than that at 12 LT, in qualitative agreement with *Ouattara* [2012] results. However, the 4 LT case should be considered with caution; since due to the absence of the EIA pattern at this particular time, the trend obtained displacing the f_oF_2 latitudinal profile may result "artificially" from displacing a pattern with maximum at the geographic

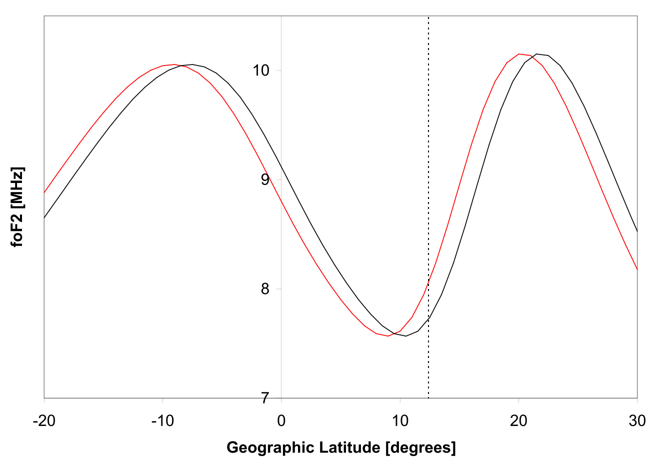

Figure 5. Latitudinal profile of f_oF_2 at the geographic longitude of Ouagadougou (358.5°E) obtained with International Reference Ionosphere model, IRI2007, as an example for January, at 12 LT, and solar activity level corresponding to $F10.7 = 150$ (red line). f_oF_2 profile displaced according to the displacement of the magnetic dip equator at the Ouagadougou longitude (black line). The dotted vertical line indicates the latitude of Ouagadougou.

equator (which is expected in the absence of the EIA effect) toward the Ouagadougou position.

[15] We included in Table 1 the f_oF_2 trend at 4 LT and 19 LT estimated in the same way as that for 12 LT f_oF_2 data. *Ouattara* [2012] assessed the "annual" trend by calculating first the monthly mean relative residual of the regression between f_oF_2 and *Rz* for a given month during the period 1966–1996, for each month. Then, he calculated the average of these 12 monthly mean values for each year and finally assessed the annual trend for a given hour.

3. Discussion and Conclusions

[16] In the present work, we obtain a decreasing f_oF_2 trend at Ouagadougou station which, although is in qualitative agreement with the effect of increasing greenhouse gas concentration, is much larger than expected. In fact, the f_oF_2 trend obtained is around 50 times greater than that expected from the ~0.5%/yr increase in CO_2 which takes place during the period here analyzed.

[17] Another factor which can explain the negative trend observed in Ouagadougou, and which would add its effect to that of the greenhouse gas increase, is the displacement of the EIA trough, which follows the dip equator secular movement.

[18] This last argument can also explain results for two other stations under the EIA, Huancayo (12.0°S, 284.7°E) and Phu Thuy (21.3°N, 106.0°E), obtained by *Upadhyay and Mahajan* [1998] and *Pham Thi Thu et al*. [2011], respectively.

[19] Huancayo is in a similar geographic situation as Ouagadougou. It is an equatorial ionospheric station located north of the dip equator but in the Southern Hemisphere. In this case, the dip equator is moving away from the station, so an increase in f_oF_2 should be expected. The f_oF_2 trend for this station was assessed by *Upadhyay and Mahajan* [1998] who obtained a positive value of 0.017 MHz/yr, qualitatively in agreement with the displacement of the EIA trough. In this case, the positive trend is in qualitative agreement also with the decrease of the sin(*I*)cos(*I*) factor at the corresponding location.

[20] Phu Thuy is located close to the EIA northern crest, toward the EIA trough. At the Phu Thuy longitude position, the EIA crest is approaching the station, so an f_oF_2 increase should be expected. In fact, *Pham Thi Thu et al*. [2011] obtained a positive 0.025 MHz/yr trend which is qualitatively in agreement with the expected trend due to the EIA pattern secular displacement.

[21] f_oF_2 trends at Ouagadougou obtained by *Ouattara* [2012] at different local times can also be explained by the displacement of the EIA latitudinal pattern which accompanies the dip equator movement. At this location, the EIA pattern is more pronounced at 19 LT resulting in a stronger f_oF_2 variation when the EIA latitudinal profile is displaced as a whole. This would be in agreement with the stronger negative trend obtained by *Ouattara* [2012] at 19 LT with respect to 12 LT. At 4 LT, a positive trend is obtained, again in accordance with *Ouattara* [2012] results. However, as already mentioned, this result should be considered with caution since due to the absence of the EIA pattern at this local time, the trend obtained displacing the f_oF_2 latitudinal profile may artificially result from approaching a pattern with maximum at the geographic equator.

[22] Further work is needed to quantify the effect of the secular displacement of the dip equator over ionospheric stations under the EIA in order to determine whether, at least in the case of Ouagadougou, it is responsible for the entire negative trend observed in f_oF_2 when added to the effect of increasing greenhouse gases and also its relative importance in comparison with the secular variation of the sin(*I*)cos(*I*) factor that, in this case, seems to be exceeded by the negative trend inducers.

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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*(3), 416–419.

Akala, A. O., E. O. Somoye, A. B. Adeloye, and A. B. Rabiu (2011), Ionospheric foF2 variability at equatorial and low latitudes during high, moderate and low solar activity, *Indian J. Radio Space Phys.*, *40*, 124–129.

Bilitza, D., and B. Reinisch (2008), International reference ionosphere 2007: Improvements and new parameters, *J. Adv. Space Res.*, *42*, 599–609, doi:10.1016/j.asr.2007.07.048.

Bremer, J., T. Damboldt, J. Mielich, and P. Suessmann (2012), Comparing long-term trends in the ionospheric F2-region with two different methods, *J. Atmos. Sol. Terr. Phys.*, *77*, 174–185.

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, doi:10.1016/j.jastp.2008.05.003.

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.

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, doi:10.1016/j.jastp.2009.05.014.

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, doi:10.1016/j.jastp.2006.02.008.

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.

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.

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.

Lastovicka, L., S. C. Solomon, and L. Qian (2012), Trends in the neutral and ionized upper atmosphere, *Space Sci. Rev.*, *168*, 113–145, doi:10.1007/s11214-011-9799-3.

Mikhailov, A. V., and D. Marin (2000), Geomagnetic control of the foF2 long-term trends, *Ann. Geophys.*, *18*, 653–665.

Ouattara, F. (2012), foF2 long term trends at Ouagadougou station, *Br. J. Appl. Sci. Tech.*, *2*(3), 240–253.

Ouattara, F., and C. Amory-Mazaudier (2012), Statistical study of the equatorial F2 layer critical frequency at Ouagadougou during solar cycles 20, 21 and 22, using Legrand and Simon's classification of geomagnetic activity, *J. Space Weather Space Clim.*, *2*(A19), 10 pp., doi:10.1051/swsc/2012019.

Ouattara, F., C. Amory-Mazaudier, R. Fleury, P. Lassudrie Duchesne, P. Vila, and M. Petitdidier (2009), West African equatorial ionospheric parameters climatology based on Ouagadougou ionosonde station data from June 1966 to February 1998, *Ann. Geophys.*, *27*, 2503–2514.

Ouattara, F., A. Gnabahou, and C. Amory-Mazaudier (2012), Seasonal, diurnal and solar-cycle variations of electron density at two West Africa equatorial ionization anomaly stations, *Int. J. Geophys.*, *2012*, 640463, doi:10.1155/2012/640463.

Pham Thi Thu, H., C. Amory-Mazaudier, and M. Le Huy (2011), Time variations of the ionosphere at the northern tropical crest of ionization at Phu Thuy, Vietnam, *Ann. Geophys.*, *29*, 197–207.

Qian, L., S. C. Solomon, R. G. Roble, and T. J. Kane (2008), Model simulations of global change in the ionosphere, *Geophys. Res. Lett.*, *35*, L07811, doi:10.1029/2007GL033156.

Qian, L., J. Lastovicka, R. G. Roble, and S. C. Solomon (2011), Progress in observations and simulations of global change in the upper atmosphere, *J. Geophys. Res.*, *116*, A00H03, doi:10.1029/2010JA016317.

Rishbeth, H. (1990), A greenhouse effect in the ionosphere?, *Planet. Space Sci.*, *38*, 945–948.

Rishbeth, H. (1998), How the thermospheric circulation affects the ionospheric F2-layer, *J. Atmos. Sol. Terr. Phys.*, *60*, 1385–1402.

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*(12), 1441–1444, doi:10.1029/GL016i012p01441.

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.

Upadhyay, H. O., and K. K. Mahajan (1998), Atmospheric greenhouse effect and ionospheric trends, *Geophys. Res. Lett.*, *25*(17), 3375–3378, doi:10.1029/98GL02503.

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:10.1029/2007JAO12995.