British Journal of Earth Sciences Research
Vol.9, No.2, pp.1-15, 2021
Print ISSN: 2397-7728(Print),
Online ISSN: 2397-7736(Online)

RELATIONSHIP BETWEEN VARIATION OF TOTAL OZONE CONCENTRATION AND SEVERE GEOMAGNETIC STORMS OVER LAGOS IN NIGERIA

Eucharia Chidinma Okoro[1], Daniel Izuikedinachi Okoh[2], Francisca Nneka Okeke[1] and Chukwuma Moses Anoruo[3]
[1]Department of Physics and Astronomy, University of Nigeria, Nsukka
[2]Space Environment Research Laboratory, Centre for Atmospheric Research, National Space Research and Development Agency, Abuja
[3]Department of Physics, Imo State University, Owerri

ABSTRACT: *This paper investigates the relationship between total ozone concentration (TOC) and severe geomagnetic storm index (peak DST* ≤ -100 *nT) over Lagos (Geographic:* 6.5^0*N,* 3.4^0*E; dip:* 6.9^0*S), Nigeria, from 1997 to 2005. Analyses show that there is a significant and persistent response of total column ozone to severe geomagnetic storms. Severe geomagnetic storms can cause ozone concentration depletions or enhancements by amounts that could be up to 3 DU in the equatorial region. Positive variations of total column ozone occurred only in wet season, and under high solar activity maximum/East phase Quasi Biennial Oscillation (QBO) conditions. Furthermore, it was observed that the minimal variation of total column ozone response to major geomagnetic storms appears to be caused by changes in QBO, which is an important component of atmospheric dynamics in the equatorial stratospheric region. Invariably, this shows that changes of circulation pattern agree qualitatively with changes in total column ozone. Also, the seasonal variation of ozone* (O_3) *column in the equatorial latitude (Lagos) followed a definite pattern, indicating maximum amplitude between July and September and minimum amplitude between December and February.*

KEYWORDS: Severe geomagnetic storm, solar activity, DST, QBO, column ozone.

INTRODUCTION

Day-to-day total ozone (O_3) variability has been of a considerable interest for some time now. This variability is significantly affected internally by dynamical and photochemical atmospheric processes (Young et al. 2013). Though, there could be some effects on ozone variations from extraterrestrial phenomenon (Dobson et al. 1946; Hathaway 2010; Isikwue and Okeke 2009; Manohar 2007; Okoro and Okeke 2017; Midya et al. 2011; Mlch 1994; Mlch and Lastovicka 1995; Rind et al. 2002). It has been speculated that total ozone content is likely affected by geomagnetic storms, because the later produce large disturbances in the ionosphere and also affect the neutral atmosphere, which includes the middle atmosphere and troposphere (e.g. Mitra 1947; Cravens and Stewart 1978, Lastovicka 1996; Mansilla 2011; Lastovicka and Mlch 1999). Disturbance storm time (DST) index denotes the average change in the horizontal component of the earth's magnetic field due to the geomagnetic storm at four low latitude stations (Gopalswamy 2009). According to Gonzalez et al. 1994 and Sugiura and Chapman 1960, geomagnetic storms can be classified using

ULR: https://doi.org/10.37745/bjesr.2013

DST indices as follows: intense storms (peak DST ≤ -100 nT), moderate storms (-100 nT $<$ peak DST < -50 nT) and weak storms (-30 nT $>$ peak DST > -50 nT). Geomagnetic storms can be distinguished according to three phases in terms of time sequence as presented in Figure 1, thus; the initial, the main and the recovery phase. Geomagnetic storms are probably the most important phenomenon among those related to solar wind and high energy particles (Forbes et al. 1996).

The effects of a geomagnetic storm are generally strongest in the auroral zone (Bucha and Bucha 1998), their amplitude weakens toward middle latitudes (Buonsanto 1995), some of them disappear at low latitudes, but some of them reappear or strengthen near the geomagnetic equator, basically at F region (Codrescu et al. 1997).

Positive and negative ionospheric storm effects are as a result of dissipation of solar wind energy into the upper atmosphere showing a strong dependence on local time (Prolss 1995; Rishbeth 1998). Negative storm effects are attributed to composition changes (Prolss et al. 1988) and are the dominant characteristic in ionospheric response to geomagnetic activity enhancements (Cander and Mihajlovic 1998). It has been suggested that positive ionospheric storm effects are also caused by composition changes (Rishbeth 1991; Field et al. 1998). There is a conflicting aspect that positive storm effects are caused by the transport of ionization (Prolss 1995) either by electric fields (Reddy and Nishida 1992) or by thermospheric winds (Prolss 1991; Sivla et al. 2018). A possible scenario for time sequence ionospheric thermospheric storm effects were suggested by Prolss (1993) based on the assumptions that positive storms are attributed to meridional winds and negative ionospheric storms may be caused by changes in the neutral gas composition. Positive storm effects present a spiky structure and are more often observed at nighttime than during daytime. Negative storm effects are smooth in nature and last up to 24 hours. They follow geomagnetic storms only. They correlate reasonably well with the DST index during the whole development of the geomagnetic storm (e.g Bojkov 1992; Brasseur and Solomon 2005; Lastovicka and Krizan 2005, 2009; Lastovicka 1995; Lastovicka et al. 1992)

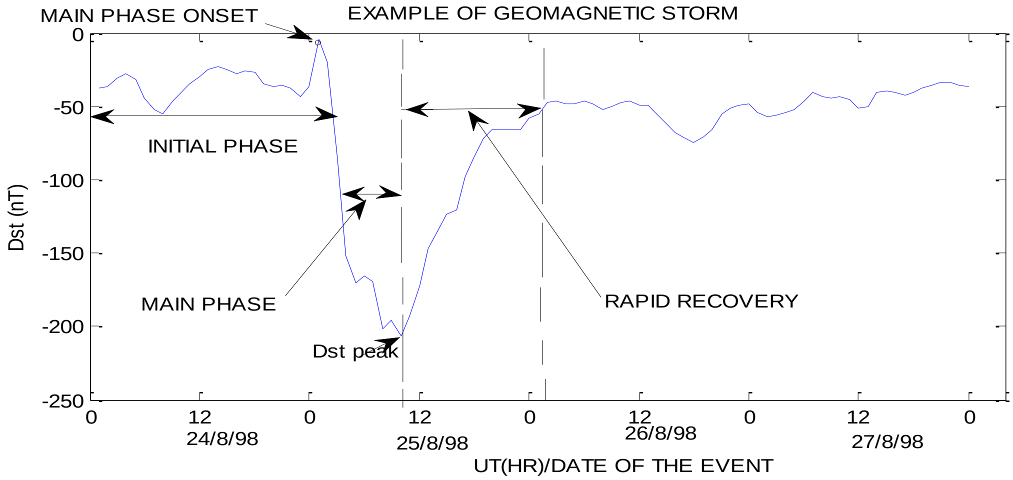


Figure 1. Schematic diagram of a storm-like variation featuring a typical geomagnetic storm

Objectives

The ozone response to geomagnetic storms has not been given adequate attention over equatorial latitude. Therefore, the aim of this study is to:

(i) analyze effects of solar activity represented by severe geomagnetic storms on total column ozone variation over equatorial region.

(ii) verify the influence of quasi biennial oscillation on total column ozone variation for the solar cycle 23 in the tropical latitude Lagos, Nigeria.

Sources of data and method of Analyses

The database used in this study is from the period of 1997 – 2005, and consist zonal averaged daily values of total ozone observations (column ozone amount) in Dobson units for the latitude of Lagos (Geographic: 6.5^0N, 3.4^0E; dip: 6.9^0S), Nigeria obtainable from the website: ftp://toms.gsfc.nasa.gov/pub/eptoms/data/zonal_means/ozone/. The software used for ozone data was TOMS Version 8 Level 3 Data File Format which was written to read the files by changing filename and date entries. The Quasi-Biennial Oscillation (QBO) index was got from http://www.geo.fuberlin.de/en/met/ag/strat/produkte/qbo/. The hourly values of DST were obtained from the world Data Center at the University of Kyoto database (http://swdc.kugi.kyoto-u.ac.jp/dstdir).

We have selected 84 geomagnetic storms occurring during solar cycle 23. We define an intense/severe geomagnetic storm as a minimum in the hourly DST index falling below $\leq$ -100 nT. In order to interpret possible relationships between peak values of DST index, the study was made by dividing cycle 23 into three phases thus; the rising (1997-1999), the maximum (2000-2002) and the decay (2003-2005). This is categorized based on: the onset of solar activity, the peak and declining or decaying stage.

The method of neural networks was used to study the quiet-time (DST > -20) variation of ozone concentration. This is necessary to derive the ozone concentration variation during quiet geomagnetic conditions (which we shall hereafter refer to as the background ozone concentration), and to subsequently use this background to measure deviations observed in the ozone concentration during intense geomagnetic conditions. The methods detailed in Okoh et al. (2015) were used for the neural network training, and the results of the neural network predictions compared to the real observations are as shown in Figure 2. The top panel contains two line plots: the first plot in blue color (for the measured ozone data) and the second in red color (for the neural network prediction). The blue plot is almost invisible because the prediction was so accurate that it seemed to just overlay on the measured data. This necessitated the plot on the bottom panel which is the difference between the observations and the predictions. Again, the plot is almost completely on zero line which shows very insignificant difference between the observations and the predictions. The root mean square error (RMSE) was computed to be as low as 0.3946 DU for the entire observations, and the correlation coefficient between the observations and the predictions was as high as 0.9994. In this way, we demonstrate that the developed neural network model is reliable for quiet-time ozone concentration predictions with errors as low as < 0.4 DU.

RESULTS AND DISCUSSIONS

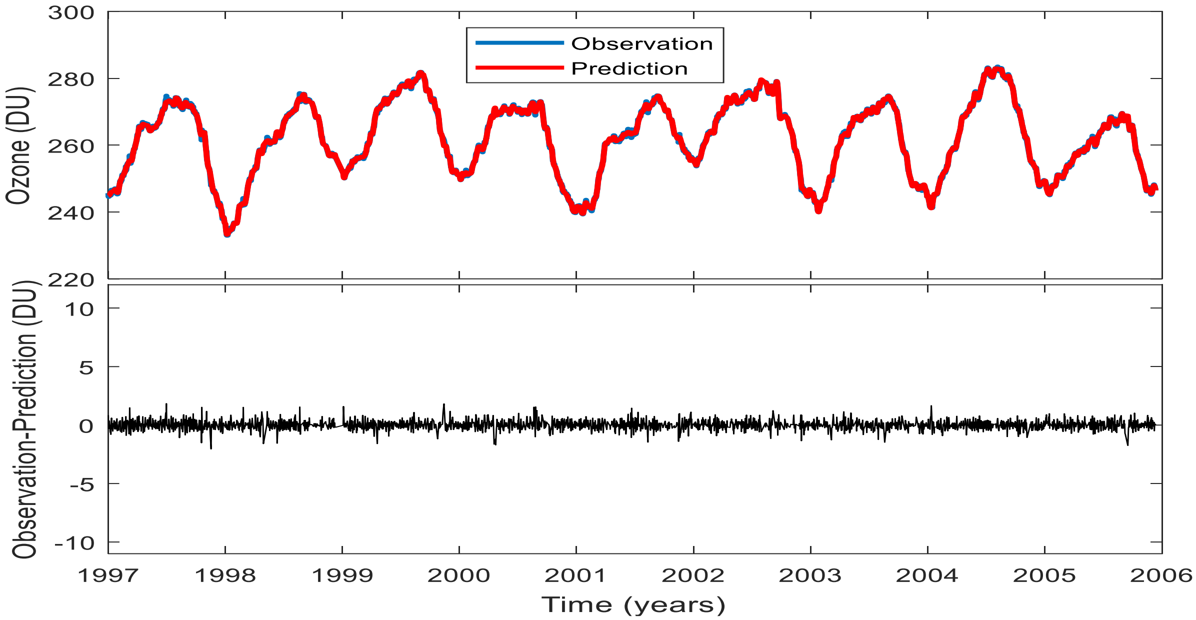
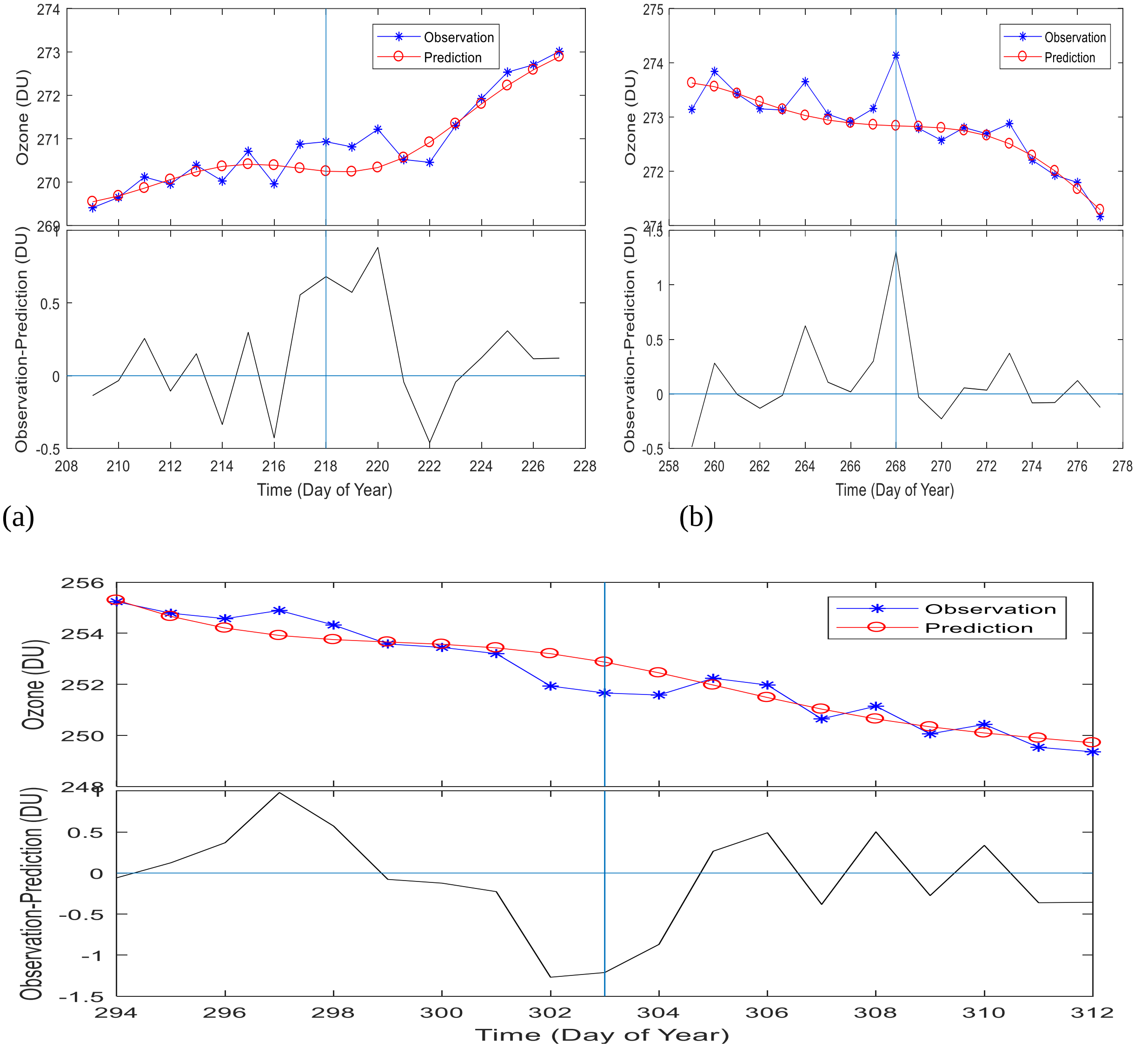


Figure 2. Neural network predictions of the quiet-time ozone concentrations compared to the corresponding observations from 1997 to 2005

For each of the severe storms considered in this work, the neural network was used to predict the background ozone concentrations around the storm day (a span of 9 days before and 9 days after the storm occurrence to make sure that the plots are sufficiently large to see the happenings before and after the storm occurrence). This enabled us to figure-out deviations that are signatures of the geomagnetic storms. A separate figure was generated for each of the 84 severe storms considered. Figures 3(a-c) are representative illustrations for the storms of 6 Aug 1998, 25 Sep 1998, and 29 Nov 2000 respectively.



(a) (b)

(c)

Figure 3. Ozone concentration observations versus neural network predictions of the quiet-time values for severe geomagnetic storm days of (a) 6 Aug 1998, (b) 25 Sep 1998, and (c) 29 Nov 2000

The plots illustrated in Figure 3(a-c) indicate that some of the effects of geomagnetic storms on ozone concentration are seen before the day that the storm peaks. This is expected since the storm commences some hours (or possibly days) before the peak hour. An examination of the plots for all the severe geomagnetic storms considered in this work revealed that the peak effects were witnessed in the period within 2 days before and after the storm peak days.

For each of the 84 storms, we computed the values of the maximum deviations and as can be seen in Figure 3(a-c), the geomagnetic storms can sometimes lead to enhancements in the ozone concentration (that is positive values of the largest ozone deviations in which the observed ozone concentrations are higher than the background predictions, e.g. Figures 3(a) and (b)) and sometimes the geomagnetic storms can lead to depressions in the ozone concentration (that is, negative values of the largest ozone deviations, in which the observed ozone concentrations are lower than the background predictions, e.g. Figure 3(c)). In the 84 storms considered, a total of 48 enhancement cases, and 36 depletion cases were observed.

Figure 4 illustrates how the absolute values of the maximum deviations relate to the minimum DST values for each of the 84 cases.

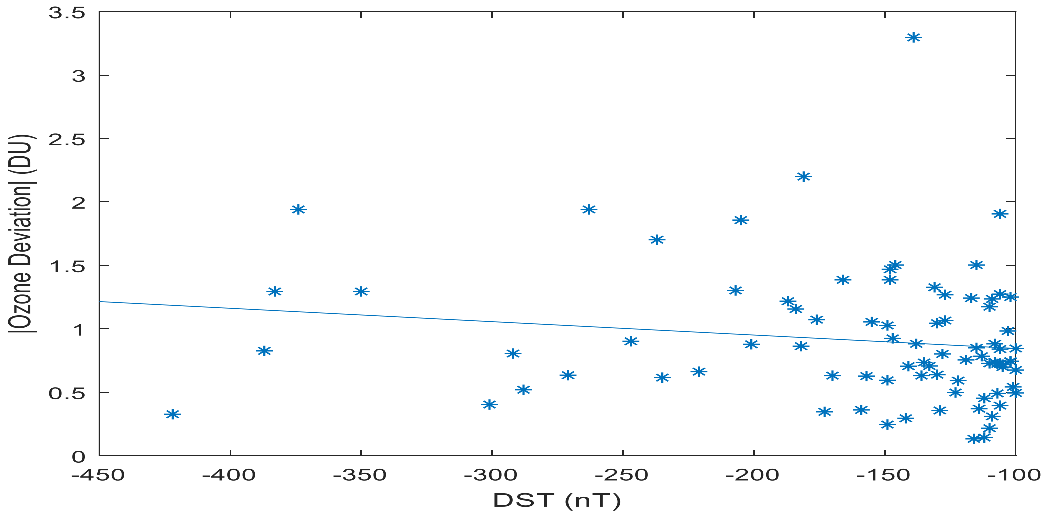


Figure 4. Absolute values of the maximum ozone deviations versus minimum DST values for each of the 84 cases.

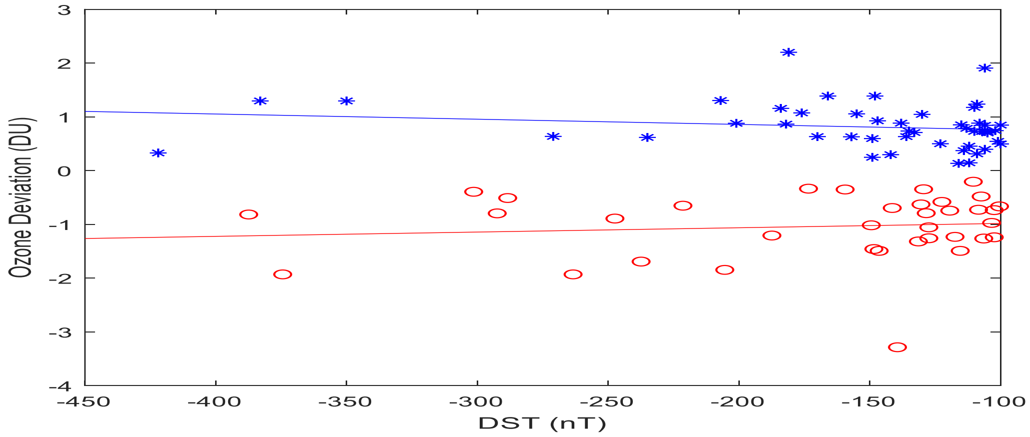


Figure 5. Plot during ozone concentration enhancement and depletion cases

The correlation coefficient between the absolute deviations in ozone concentration and the absolute values of DST is 0.1525. This is a relatively low positive value, suggesting that the most severe storms could lead to more ozone deviations, but with a low correlation.

The best fitted regression line by method of least squares is given by equation (1).

$$|DU| = 0.7409 - 0.0011\, DST \quad (1)$$

Where |DU| is absolute deviation in ozone concentration

Figure 5 illustrates how the DST values relate to the ozone deviations for separated cases of ozone enhancements and depletions. Both cases also showed that there is a positive correlation between the storm severity and the magnitudes of the ozone concentration deviations. The correlation coefficients were: 0.1667 (for cases of ozone concentration enhancements), and 0.1034 (for cases of ozone concentration depletions). The best fitted regression lines are respectively given by equations (2) and (3).

$$DU = 0.6646 - 0.0010\, DST \quad (2)$$

$$DU = 0.0008\, DST – 0.9033 \quad (3)$$

where DU is ozone concentration deviation (that is, observed ozone concentration minus background ozone concentration). The blue points in Figure 5 are therefore cases of the ozone concentration enhancements, while the red points are cases of the ozone concentration depletions. The Figure shows that geomagnetic storms can cause ozone concentration depletions or enhancements by amounts that could be up to 3 DU.

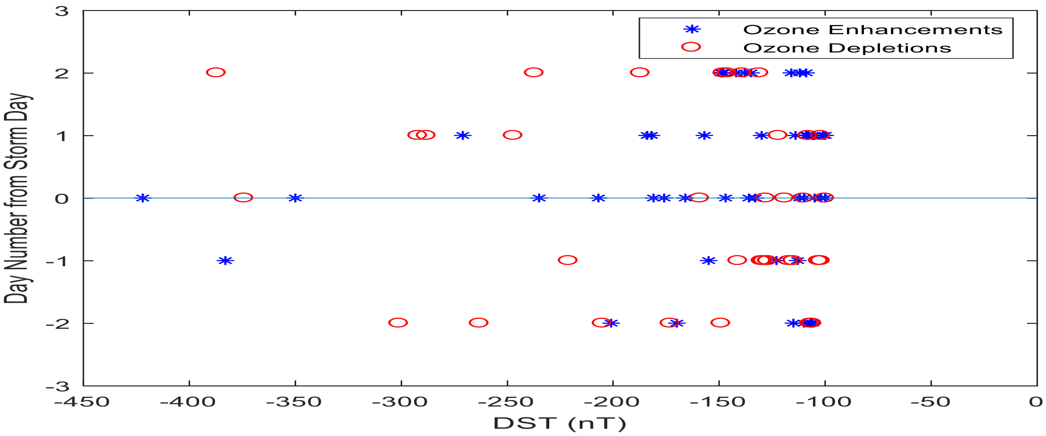


Figure 6(a). Chart indicating the days (relative to the storm peak day) when the greatest ozone deviations are observed

Figures 6(a) and (b) further illustrate the pattern of the deviations. The chats indicate the distributions of the occurrences of the maximum ozone deviations. The day of the peak storm is 0;

days before it are negative, and days after it are positive. The Figure (top panel of Figure 6(b)) shows that more of the enhancement cases usually happen on the peak storm day and on the days after it, while the reverse is the case for the depletion cases; the middle panel shows that more of the depletion cases usually occur before the day of the peak storm. The scenario suggests that conditions prior to the peak of geomagnetic storms promote ozone depletions, while conditions during and after the peak of geomagnetic storms promote ozone enhancements. The bottom panel of the Figure shows that the peak of the ozone concentration deviation is usually observed on the same day as the day the storm peaks, and that the observation of the ozone peak deviation is more towards the days after than for the days before the day of the peak storm.

An interesting observation in Figure 6(a) is that most of the very severe storms (with DST less than -200nT) usually lead to ozone depletions, and the maximum depletions usually occur farther away from the day of the peak storm compared to when there are enhancements.

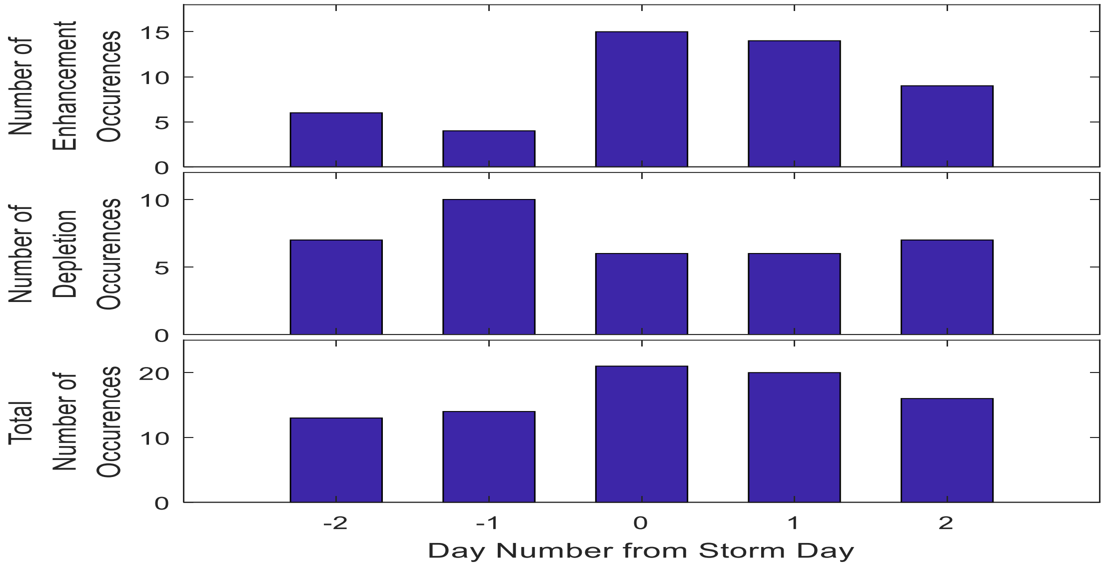


Figure 6(b). Bar charts indicating occurrences of the ozone concentration deviation peaks relative to the day of the peak of geomagnetic storm

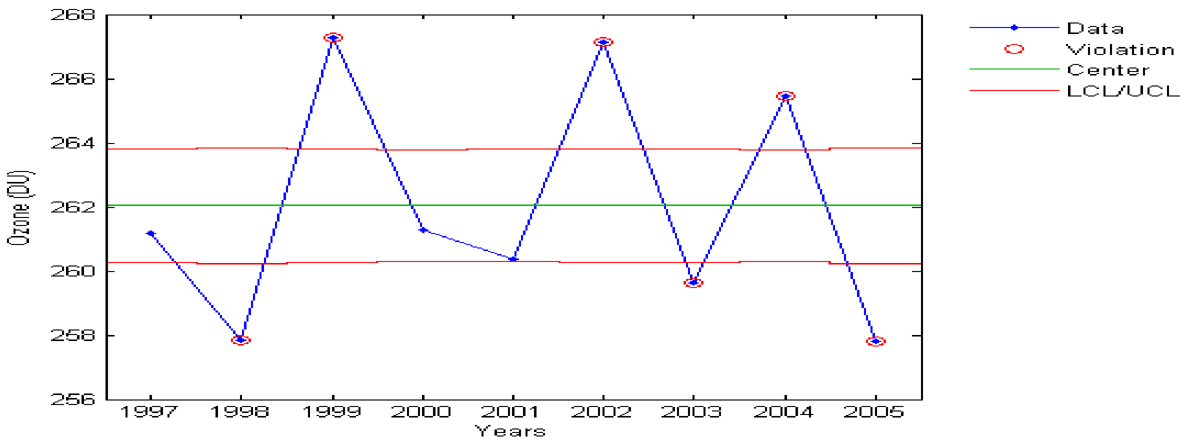


Figure7. Time series variation of ozone from 1997 to 2005

Figure 7 depicts a control chart time series variation of ozone from 1997 to 2005. A peak violation was observed in 1999, 2002 and 2004 which falls on the upper control limit. This could be attributed to QBO modulation represented in Figure 8. The ozone gain rate peaks occurred during the easterly phase of QBO in tropical wind direction at ~30km over 1999, 2002 and 2004 years at low pressure. While ozone loss was observed in 1998, 2003 and 2005 that falls on the lower control limit.

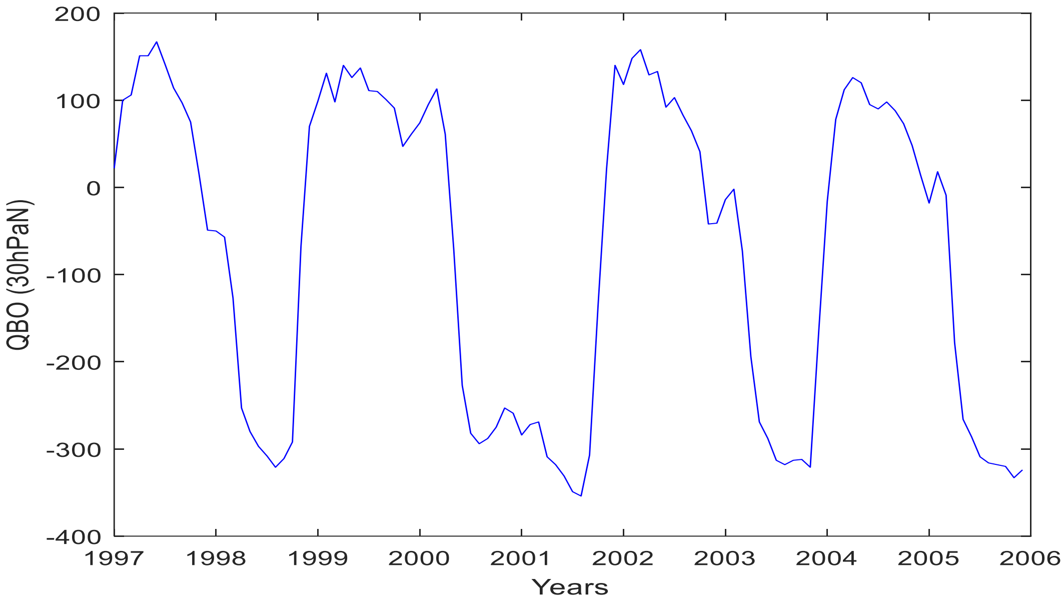
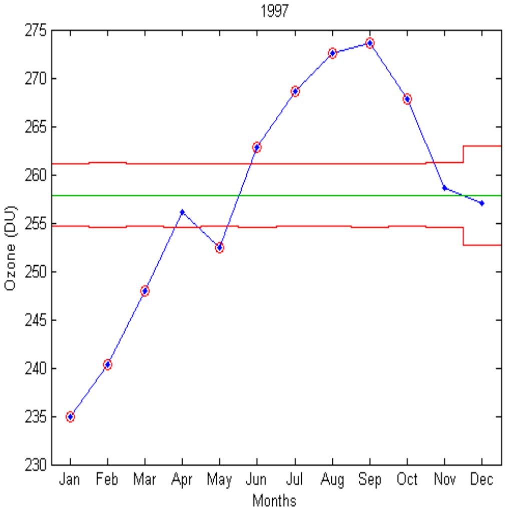
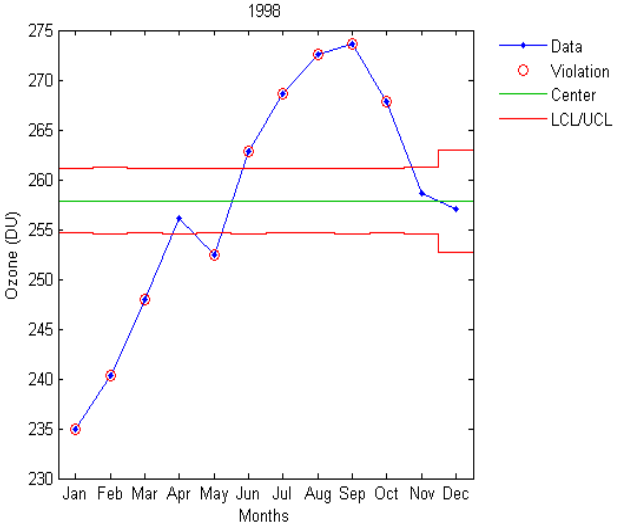


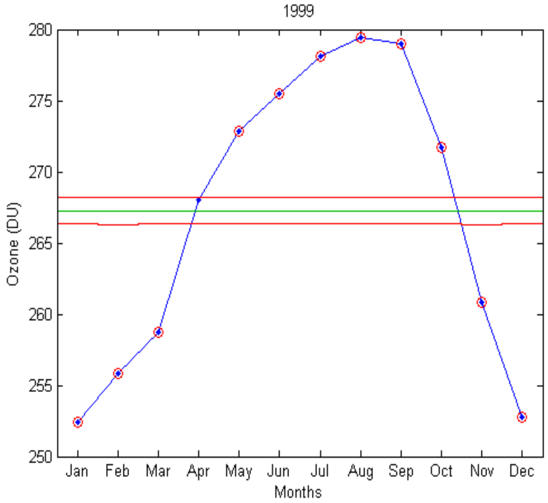
Figure 8. Average monthly/yearly variations of QBO at 30 hPa Northern Hemisphere (1997 -2005)


1997
Ozone (DU)
275
270
265
260
255
250
245
240
235
230
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Months

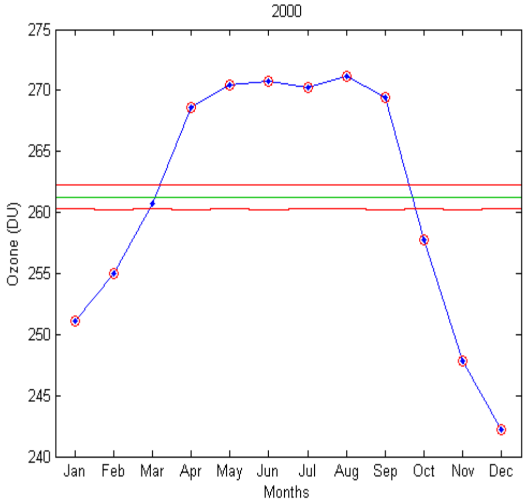
(a)


1998
Ozone (DU)
275
270
265
260
255
250
245
240
235
230
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Months
Data
Violation
Center
LCL/UCL

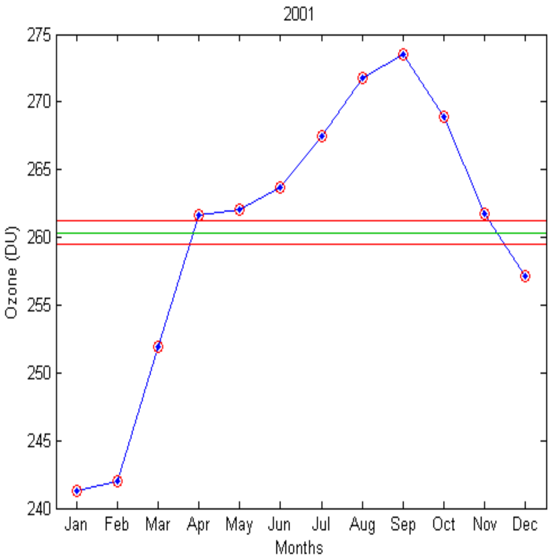
(b)


1999
Ozone (DU)
280
275
270
265
260
255
250
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Months

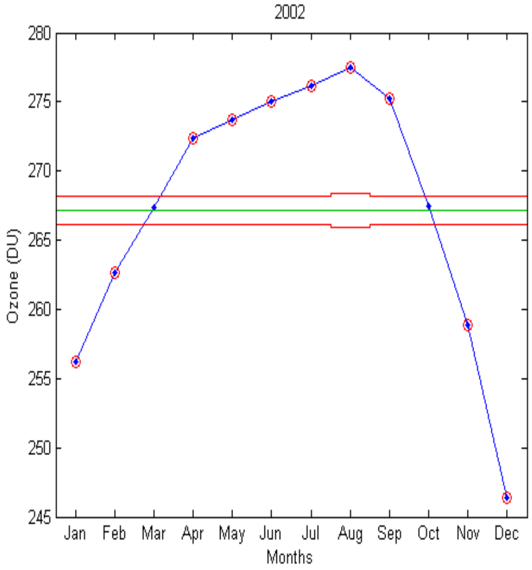
(c)


2000
Ozone (DU)
275
270
265
260
255
250
245
240
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Months

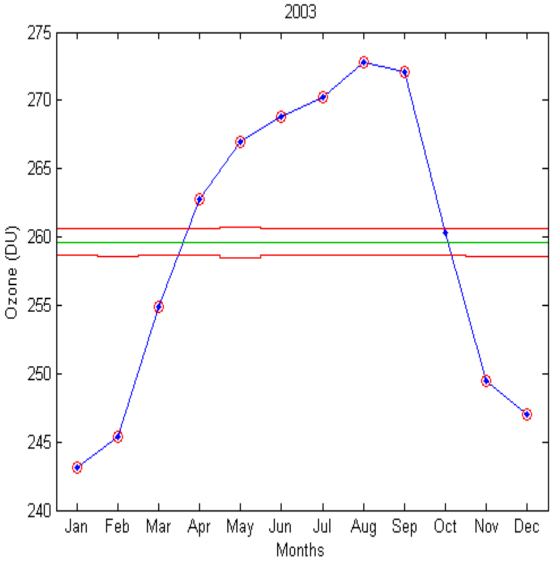
(d)


2001
Ozone (DU)
275
270
265
260
255
250
245
240
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Months

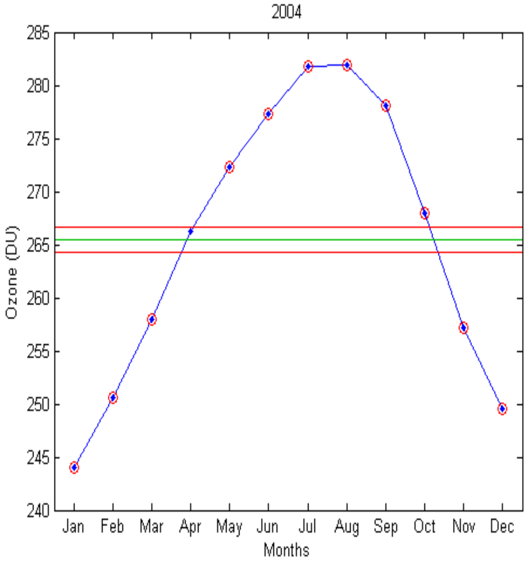
(e)


2002
Ozone (DU)
280
275
270
265
260
255
250
245
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Months

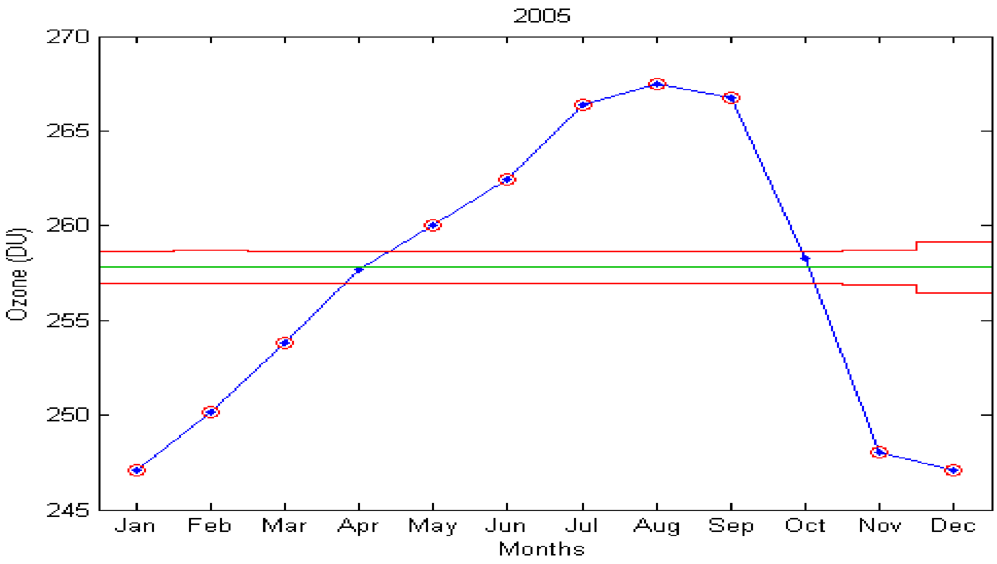
(f)


2003
Ozone (DU)
275
270
265
260
255
250
245
240
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Months

(g)


2004
Ozone (DU)
285
280
275
270
265
260
255
250
245
240
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Months

(h)



(i)

Figures 9. Seasonal variation of ozone column in Lagos from (a) 1997, (b) 1998, (c) 1999, (d) 2000, (e) 2001, (f) 2002, (g) 2003, (h) 2004, and (i)2005.

Interestingly, Figures 9(a-i) depict the seasonal variation of ozone (O_3) column in the equatorial latitude of the zonal averaged of Lagos. It followed a definite pattern, indicating maximum amplitude between July and September and minimum amplitude between December and February which were the wet and dry seasons respectively. Therefore, ozone enhancement occurred in wet season it showed that the observed phenomenon could only be through transportation of ozone content and not production or loss; because this effect prospers under the presence of sunlight.

CONCLUSION

It has been ascertained that severe geomagnetic storm have impact on total column ozone variations in the equatorial region; Lagos throughout the period of study (1997 to 2005); eventhough the contribution was minimal. Using the method of neural networks, the quiet-time variation of the ozone concentration was modeled, and the root-mean-square error for the model predictions wer less than 0.4 DU. The neural network model developed was used to predict the background ozone concentrations around the storm day, and by comparison with observations for the storm day, we found that severe geomagnetic storms can lead to ozone concentration variations up to 3 DU. The study shows that intense geomagnetic storms can lead to ozone enhancements as well as ozone depletions; we observed ~57% cases of ozone enhancements and ~43% cases of ozone depletions.

The results show that more of the enhancement cases usually occur on the peak storm day and on the days after it, while more of the depletion cases occur before the peak storm day, suggesting that conditions prior to the peak of geomagnetic storms promote ozone depletions, while conditions during and after the peak of geomagnetic storms promote ozone enhancements. We also observed that the peak of the ozone concentration deviations are usually observed on the same day as the day the storm peaks, and that there are more ozone peak deviations for days after the peak storm day than there are for the days before the peak storm day. Most of the very severe storms (with DST less than -200nT) usually lead to ozone depletions, and the maximum depletions usually occur farther away from the day of the peak storm compared to when there are enhancements.

Furthermore, it was noted that total ozone column variations which occurred in wet season was at variance with Eastern phase of quasi-bienniel oscillation. This indicates that a different precursor (QBO) could be responsible for the wide enhancement of ozone column around the equator.

Acknowledgment

The authors are thankful to World Data Centre for Geomagnetism, Kyoto, Japan for making available the geomagnetic indices. We are grateful to Goddard Institute for Space Study, USA, the owner of the satellite Earth Probe Total Ozone Mass Spectroscopy (EPTOMS). We are equally grateful to Freie Universitat Berlin for the availability of Quasi-Biennial-Oscillation (QBO) data.

References

Bojkov, R.D. 1992. “Changes in Polar Ozone.” *W.M.O. Bulletin* 41: 171-180.

Brasseur, G., and S. Solomon. 2005. “Aeronomy of the Middle Atmosphere—Chemistry and Physics of the Stratosphere and Mesosphere.” 3rd Edition, Springer, Berlin.

Bucha, V., and V. Bucha Jr. 1998. “Geomagnetic forcing of changes in climate and in the atmospheric circulation.” *J. Atmos. Sol. Terr. Phys.* 60: 145.

Buonsanto, M. 1995. “Millstone Hill incoherent scatter *F* region observation during the disturbances of June 1991.” *J. Geophys. Res.*, 100: 5743.

Cander, L.R., and S.J. Mihajlovic. 1998. “Forecasting ionospheric structure during the great geomagnetic storms.” *J. Geophys. Res.* 103: 391-398.

Codrescu, M. V., T. J. Fuller-Rowell, and I. S. Kutiev. 1997. “Modeling the *F* layer during specific geomagnetic storms.” *J. Geophys. Res.* 102 (14): 315.

Cravens, T. E., and A. I. Stewart. 1978. “Global morphology of nitric oxide in the lower *E* region.” *J. Geophys. Res.*, 83: 2446.

Dobson, G.M.B., A. W. Brewer, and B. M. Cwilong. 1946. “Meteorology of the Lower Stratosphere.” *Proc.Roy.Soc., A.* 185:144.

Field, P.R., H. Rishbeth, R.J. Moffett, D.W. Idenden, T.J. Fuller-Rowell, G.H. Millward, and A.D. Aylward. 1998. “Modelling composition changes in F-layer storms.” *J. Atmos. Solar-Terr. Phys*. 60: 523-543.

Forbes, J. M., R. Gonzalez, F. A. Marcos, D. Revelle, and H. Parish. 1996. “Magnetic storm response of lower thermosphere density.” *J. Geophys. Res.* 101: 2313.

Gonzalez, W.D., J. A. Joselyn, Y. Kamide, H. W. Kroehl, G. Rostoker, B. T. Tsurutani, and V. M. Vasyliunas. 1994. "What is a geomagnetic storm?." *Journal of Geophysical Research* 99: 5771-5792

Gopalswamy, N. 2009. "CME link to the geomagnetic storms." *Proc. IAU Symposium* 264: 119.

Hathaway, D. H. 2010. "The Solar Cycle." *Living Rev. Solar Phys.* 7: 1-65

Isikwue, B.C., and F. N. Okeke. 2009. "Effects of Some Atmospheric Parameters on the Dynamics of Lower Stratospheric Ozone in the Low Latitude." *The Pacific Journal of Science and Technology* 10 (1): 686– 692.

Lastovicka, J. 1996. "Effects of Geomagnetic Storms in the Lower Ionosphere, Middle Atmosphere and Troposphere." *Journal of Atmospheric and Solar Terrestrial Physics* 58 (7): 831-843.

Lastovicka, J., and P. Krizan. 2005. "Geomagnetic Storms, Forbush Decreases of Cosmic Rays and Total Ozone at Northern Higher Middle Latitudes." *Journal of Atmospheric and Solar-Terrestrial Physics* 67 (1-2): 119-124.

Lastovicka, J., and P. Krizan. 2009. "Impact of Strong Geomagnetic Storms on Total Ozone at Southern Higher Middle Latitudes." *Studia Geophysica et Geodaetica* 53 (1): 151-156.

Lastovicka, J., and P. Mlch. 1999. "Is Ozone Affected by Geomagnetic Storms?." *Advances in Space Research* 24 (5): 631-640.

Lastovicka, J. (995. "Effects of geomagnetic storms in the ionosphere, middle atmosphere and troposphere." *Journal of Atmospheric and Solar-Terrestrial Physics* 58 (7): 831-843.

Lastovicka, J., J. Bremer, and M. Gil. 1992. "Ozone response to major geomagnetic storms." *Ann. Geophysicae* 10: 683 – 689.

Manohar, L. 2007. "Study of ozone variability at equatorial latitude during severe geomagnetic storm." *Bulletin of Astronomical Society of India* 35: 569-574.

Mansilla, G. A. 2011. "Response of the Lower Atmosphere to Intense Geomagnetic Storms." *Advances in Space Research* 48 (5): 806-810.

Midya, S.K., U. Saha, P. Panda, A. Kundu, A. Chaudhuri, and H. Sarkar. 2011. "Variation of Total Ozone Concentration and Rainfall over Different Stations of India." *The Pacific Journal of Science and Technology* 12 (1): 580 – 590.

Mitra, S. K. 1947. "The Upper Atmosphere." *A Royal Asiatic Society of Bengal monograph Series* 5: 616.

Mlch, P. 1994. "Total Ozone Response to Major Geomagnetic Storms during Non-Winter Period." *Studia Geophysica et Geodaetica* 38 (4): 423-429.

Mlch, P., and J. Lastovicka. 1995. "Total ozone response to major geomagnetic storms and changes in meteorological situations." *Studia geoph. et geod.* 39: 189 – 207.

Okoh, D., N. Yusuf, O. Adedoja, I. Musa, and B. Rabiu. 2015. "Preliminary results of temperature modelling in Nigeria using neural networks." *Weather* 70: 336–343. doi:10.1002/wea.2559.

Okoro, E., and F. Okeke. 2017. "Effects of zonal wind on stratospheric ozone variations over Nigeria." *International Journal of Remote Sensing* 38 (6): 1665-1681.

Prolss, G.W., M. Roemer, and J.W. Slowey. 1988. "Dissipation of solar wind energy in the earth's upper atmosphere: The geomagnetic activity effect, CIRA 1986." *Adv. Space Res.* 8 (5): 215-261.

Prolss, G.W. 1991. "Thermosphere-ionosphere coupling during disturbed conditions." *J. Geomag. Geoelectr.* 43: 537-549.

Prolss, G.W. 1993. "On explaining the local time variation of ionospheric storm effects." *Ann. Geophys.* 11: 1-9.

Prolss, G.W. 1995. "Ionospheric F-region storms." in *Handbook of Atmospheric Electrodynamics* CRC Press II, 195-248.

Reddy, C.A., and A. Nishida. 1992. "Magnetospheric substorms and nighttime height changes of the F2 region at middle and low latitudes." *J. Geophys. Res*. 97: 3039-3061.

Rind, D., P. Lonergan, N. K. Balachandran, and D. Shindell. 2002. "2 × CO2 and solar variability influences on the troposphere through wave-mean flow interactions." *J. Meteorol. Soc. Jpn*., 80: 863–876. doi:10.2151/jmsj.80.863.

Rishbeth, H. 1998. "How the thermospheric circulation affects the ionospheric F2-layer." *J. Atmos. Solar-Terr. Phys.* 60: 1385-1402.

Rishbeth, H. 1991. "F-region storms and thermospheric dynamics." *J. Geomag. Geoelectr*. 43: 513-524.

Sivla W. T., O. J. Ugonabo,. and E. C. Okoro. 2018. "High-latitude thermospheric zonal winds during low solar activity period." *International Journal of Physical Sciences* 13(2): 8-15.

Sugiura, M., and S. Chapman. 1960. "The Average Morphology of Geomagnetic Storms With Sudden Commencement." *Abhandl. Akad. Wiss. GOttingen, Math.-Phys. KI.*, Sonderheft 4, Gottingen.

Young, P .J., A. T. Archibald, K. W. Bowman, J. F. Lamarque, V. Naik, D. S. Stevenson, S. Tilmes, A. Voulgarakis, O. Wild, D. Bergmann, P. Cameron-Smith, I. Cionni, W. J. Collins, S. B. Dalsøren, R. M. Doherty, V. Eyring, G. Faluvegi, L. W. Horowitz, B. Josse, Y. H. Lee, I. A. MacKenzie, T. Nagashima, D. A. Plummer, M. Righi, S. T. Rumbold, R. B. Skeie, D. T. Shindell, S. A. Strode, K. Sudo, S. Szopa, and G. Zeng. 2013. "Pre-industrial to end 21st century projections of tropospheric ozone from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP)." *Atmos. Chem. Phys.*, 13: 2063–2090. DOI: https://doi. org/10.5194/acp-13-2063-2013.