The effect of the stratospheric QBO on the neutral density of the D region

Selçuk Sağır[1], Ramazan Atıcı[2,*], Osman Özcan[3], Nurullah Yüksel[3]

[1] Mus Alparslan University, Vocational School, Department of Electronics and Otomation, Mus, Turkey

[2] Mus Alparslan University, Faculty of Education, Mus, Turkey

[3] Mus Alparslan University, Faculty of Arts and Sciences, Department of Physics, Mus, Turkey

ABSTRACT

A multiple regression model, which defines relationship between two variables, is used to perform a statistical analysis of the relationship between the stratospheric QBO and the neutral density of the D region (N_nD) at altitudes of 75 km and 90 km for Singapore station. While performing the analysis, the solar maxima and solar minima epochs of the sun for 21st, 22nd and 23rd solar cycles (SCs) are taken into account. Before applying the model for the statistical analysis of the relationship, the stationary of the variables is investigated by using the unit root test. The relationship between the variables is also investigated by using the co-integration test. The relationship between N_nD measured at 75 km altitude and QBO obtained at altitude of 10 hPa is observed that it is positive for solar maximum epoch at 21st and 23rd SCs and for solar minimum epoch at 21st SC and is negative at the other epochs. The relationship between N_nD measured at 90 km altitude and QBO is observed to be negative at both the solar maxima expect for solar maximum of 23rd SC and the solar minima epochs. The relationship between variables is positive for both phases (east and west) of QBO. Thus, QBO leads to a statistical change in the N_nD. It may also give rise to changes on the ion chemistry of the D region.

1. Introduction

The region that includes the lower part of the ionosphere, at an altitude of approximately 50 to 100 kilometers, is referred to as the lower ionosphere. The D-region, that makes up a significant portion of the lower ionosphere, can be considered as a complex transition region from the neutral atmosphere to the ionosphere that are characterized by the plasma properties [Kero 2008]. One of the most important characteristics of this region is the electron density. As the rates of the chemical processes in the D-region of the ionosphere are relatively low, advection and convection significantly affect the distribution of electron density in this region [Kazimirovski and Kokoruov 1995]. Thus, the structure and composition of this region cannot be completely determined, without the clarification of the role of the atmospheric motions on all scales; particularly, its interaction with ionospheric processes, and its role in initiating the vertical transport of gas components, in the case of large scale circulation. This region is especially sensitive to meteorological influences, which may lead to variations in the electron concentration of magnitude's order. It should be noted that the normal system, which is determined by absorption of the solar radiation (both daily and annual cycles), has been perturbed sometimes by large scale waves from the troposphere [Kazimirovski and Kokoruov 1995, Krivolutsky 2009].

The Quasi-Biennial Oscillation(QBO),which is one of the meteorological effects on the D-region, is the quasi-periodic oscillation of the wind between the easterlies and the westerlies in the tropical stratosphere, with a mean period of 28 to 29 months [Heaps et al. 2000]. The QBO generally originates in the equatorial region and moves with a velocity of approximately 30 m/s in the eastward direction and 20 m/s in the westward direction. Even though the maximum amplitude of the QBO is at the level of 10 hPa, it can vary from 100 hPa to 2 hPa. The QBO can extend up to the Mesosphere and Lower Thermosphere (MLT) beyond the stratopause with the help of waves. On reaching the mesosphere, the QBO generates a new oscillation called the Mesospheric Quasi Biennial Oscillation (MQBO) [Baldwin et al. 2001]. From this region, the QBO can extend up to the F-layer of the ionosphere, along the geomagnetic field lines of the Earth [Chen 1992]. The QBO as energy and momentum are carried by inertia-gravity waves, gravity waves, equatorial waves (Kelvin and Rossby gravity waves), and planetary waves

from lower stratosphere to the lower ionosphere. (see Figure 1) [Baldwin et al. 2001].

In this study, the effect of QBO on N_nD, is investigated statistically to determine the structure and the mixture of this region. In this context, a multiple regression is used to explore the structure of the irregularities and the underlying effects caused by QBO in N_nD. The relationship between N_nD and QBO is investigated by using the multiple regression model. Statistical analysis method used in the study, the results and discussion, and the conclusion are presented in Sections 2, 3 and 4.

2. Analysis process

A multiple regression model has three statistical parts in this study. The first one is the unit root test that analyzes the stationarity of the variables. The second one is the co-integration test that proves the relationship between the variables. The third one is the regression model that designates the value of the relationship between the variables.

In the unit root test, stationarity properties of variables are primarily examined. In order to examine the statistical relationship between the variables, the series must be stable. If the series are not stable, with the mean and the variance changing with time, then these series are made stationary by calculating the first order of difference of QBO and N_nD (D(QBO), D(N_nD)). There are three basic tests that are commonly used in the statistical studies for stationarity, namely Augmented-Dickey Fuller Test (ADF), Phillips-Perron Test (PP) and Kwiatkowski-Phillips-Schmidt-Shin Test (KPSS). ADF is widely used for investigation of the presence of the unit root in the time series. The equation including the lagged values of the dependent variable is defined by adding a constant and a time trend as follows [Enders 2008, Sagir et al. 2015]:

$$\Delta y_t = \mu + \beta t + \delta y_{t-1} + \sum_{j=1}^{k} \alpha_j \Delta y_{t-j} + \varepsilon_t , \qquad (1)$$

where y is the dependent variable, μ is the mean value, β is the coefficient of time trend, Δ is the difference processor, t is the time trend, ε is the error term and k is the number of lags. The ADF test is based on the estimation of parameter δ. If the parameter δ is different from zero, it means that the series is not stationary. If the parameter is equal to zero, it means that the series is stationary. The PP Test, which is developed to control the high degree of correlation, is a unit root test that does not include the restrictive assumptions about the error terms. In the PP test, the lagged values of the dependent value are not sufficiently included to elimi-
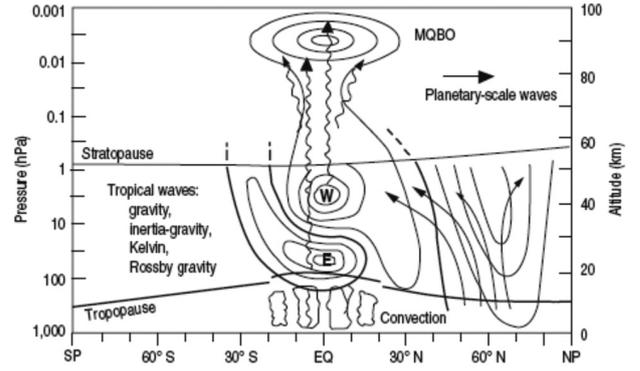

Figure 1. The atmospheric waves affecting to spread of the QBO [Mohanakumar 2008].

nate the auto-correlation in the model. Instead, it is adapted by the Newey-West estimator [Enders 2008]. The KPSS Test expresses that the series are stationary under the null hypothesis. The KPSS statistics depends on the error terms obtained from regression provided by exogenous variables of the time series [Kwiatkowski et al. 1992]. For each test, the series is proved to be stationary when the absolute value of the test values of the variables is greater than MacKinnon critical value [Enders 2008].

When two time series are not stationary and there is a stationary-linear compound in the variables, a co-integration relationship is considered. The co-integration analysis is used to estimate a relationship between the non-stationary time series. The presence of the co-integration indicates a relationship between the variables. The Engle-Granger analysis is widely used in the co-integration analysis [Engle and Granger 1987]. In the first stage of the Engle-Granger method, a relationship between the variables is estimated by the Ordinary Least Square method (OLS). After the variable coefficients are estimated by OLS, the error terms of the regression are investigated to see whether or not the series is stationary [Sagir et al. 2015].

Before performing the analysis, the QBO is considered to be the wind. The effects of the eastern (the negative sign values of QBO indicated by DummyE in Equation 2) and the western (the positive sign values of QBO indicated by DummyW in Equation 2) side of the wind are added to the model through dummy variables. The model is defined as follows:

$$N_nD_t =$$
$$c + \beta_1 D(QBO_t) + \beta_2 DummyW_t + \beta_3 DummyE_t + \varepsilon_t$$
$$\qquad (2)$$

where, c is constant and β_1, β_2, and β_3 denote coefficients of variables.

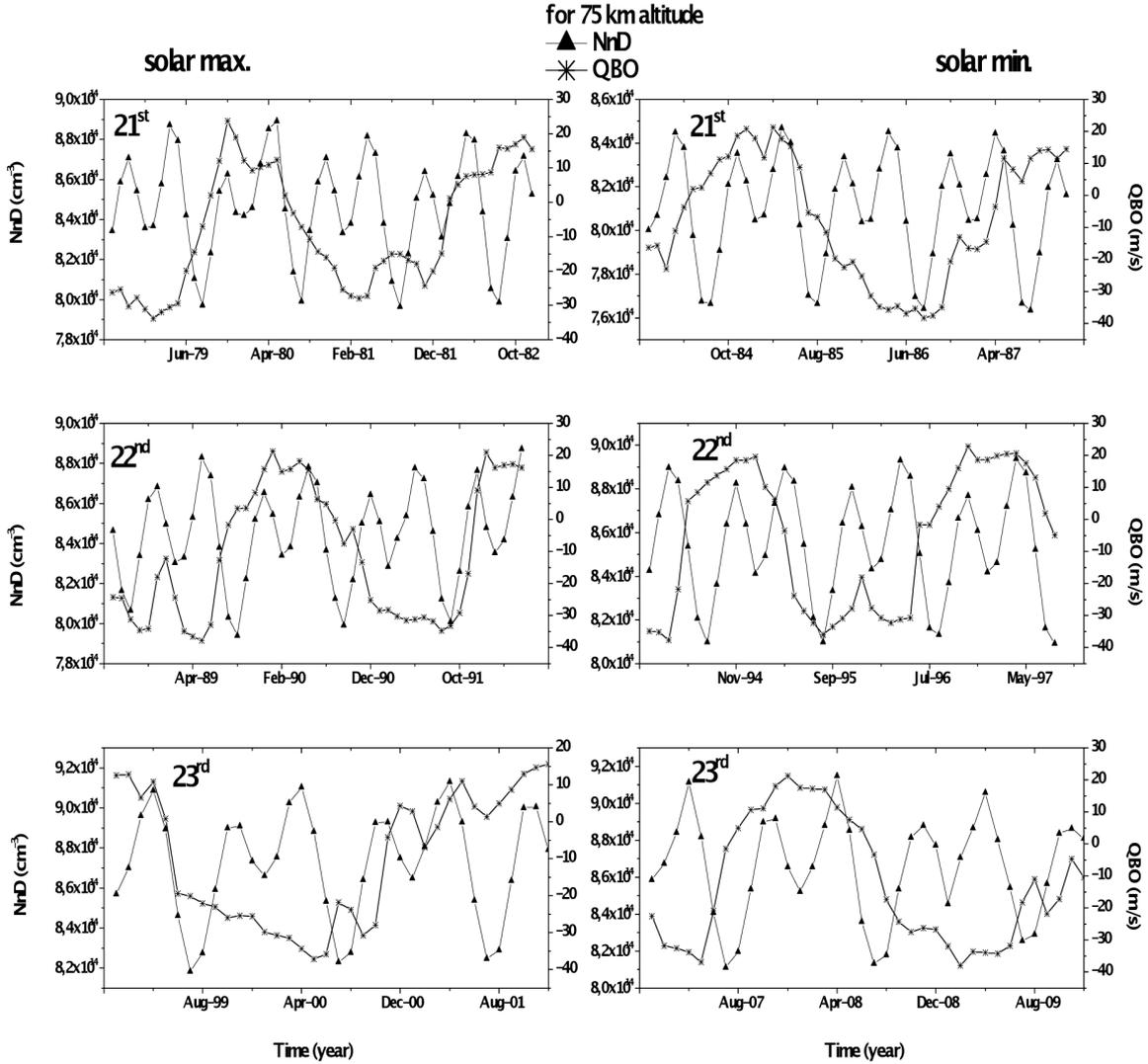In statistical model, a dummy variable is a variable that marks or encodes a particular attribute. It is often

Figure 2. The variation with years of relationship between QBO and N_nD calculated at 75 km altitude in solar maximum (left-side) and solar minimum (right-side) epochs for 21st, 22nd and 23rd SCs.

called binary or dichotomous variable as it takes just two values, usually 1 or 0, to indicate the presence or absence of a characteristic. Using Equation (2), the relationship between QBO and N_nD is computed for solar maxima and solar minima epochs.

3. Results and discussion

The QBO data used in this study are obtained from the website http://strat-www.met.fu-berlin.de, from Singapore station for the geographical coordinates 01.22N and 103.55E. The N_nD values are obtained monthly from the website http://ccmc.gsfc.nasa.gov/modelweb/models/nrlmsise00.php for the NRLM-SISE-00 atmospheric model for the same coordinates as that of the QBO data, at the local time 1200 (LT1200), and at altitudes of 75 km and 90 km, respectively. Here, the N_nD is expressed by the sum of N_2, O_2, and O, which are the primary components of the atmosphere.

The data used (both QBO and N_nD) are determined so as to cover the entire month at the time interval

09/1978-12/1982, 06/1988-04/1992, 01/1999-12/2001 for solar maxima epochs and at time interval 01/1984-12/1987, 02/1994-08/1997, 01/2007-12/2009 for solar minima epochs (21th, 22nd and 23rd SCs). The solar minima and maxima epochs are calculated by taking the previous and next years of the year that sunspots are at lowest and highest values, respectively [Kirov et al. 2014]. The results are obtained by using given equations in Section 2 and taking reference from Enders [2008].

As a result, there is a continuing relationship between QBO and N_nD. However, this relationship changes according to altitude and SCs . The results of unit root test and co-integration test are shown at the tables for 21st, 22nd, and 23rd SCs at both 75 km and 90 km altitudes.

3.1. The analysis results for N_nD measured at an altitude of 75 km

Figure 2 shows the variation of N_nD measured at 75 km altitude with QBO in solar maximum (left-side) and solar minimum (right-side) epochs for 21st, 22nd

and 23rd SCs. In the solar maximum case, there is a positive relationship between N_nD and west-directional QBO for all three SCs.

It is observed that there is a positive relationship between N_nD and east-directional QBO for 21st SC. However, there is a negative relationship between variables for other SCs. In the solar minimum epoch, a positive relationship is observed between both the west-directional and east-directional QBO and N_nD for all the SCs.

Unit root test results

The purpose of the unit root test is to test the stationary nature of the variables. Because of the importance of the unit root test, it is supplemented with three separate tests (ADF, PP, and KPSS). In this test, the QBO and the N_nD values recorded for each of the test types at the top of Table 1 need to be greater than the MacKinnon critical values or the absolute values at the bottom of the table. Table 1 tabulates the results of the unit root test between the QBO measured at 10 hPa altitude and the N_nD obtained for 75 km.

As shown in this table, the N_nD variable is significant at a level of 1% in the ADF and the KPSS tests, while it is significant at a level of 10% in the PP test. This indicates that the N_nD variable is stationary. However, QBO is not stationary, so it has been made stationary by taking its first difference (D(QBO)) [see Sagir et al. 2015]. D(QBO) variable is significant at a level of 5% in ADF , PP and KPSS tests.

Variables	10 hPa		
	ADF	PP	KPSS
QBO	-1.95	-1.65	0.10
N_nD	-5.14	-3.32	0.49
D(QBO)	-4.15	-4.07	0.20
The level of significance	MacKinnon [1996] critical values		
	ADF	PP	KPSS
1%	-4.243	-4.243	0.216
5%	-3.544	-3.544	0.146
10%	-3.204	-3.204	0.119

Table 1. The unit root test results at an altitude of 75 km.

Co-integration test results

The co-integration test results are listed in Table 2 for altitude of 75 km in solar maxima and solar minima epochs. Since the ADF values are greater than MacKinnon critical values as the absolute values, in case of both solar maximum (|−4.69|>|−2.65|) and solar mini-

mum (|−5.94|>|−2.65|) there are a relationship between the QBO and the N_nD. Meanwhile, since the p-values are smaller than 0.05 for both epochs (solar maximum and solar minimum), there are also a relationship at a level of 1% between the QBO and the N_nD. Looking at both comparisons (ADF-MacKinnon and p-values-0.05), a relationship between the QBO and the N_nD have been observed in the 1% level of significance that is the most significant level.

Regression model	Solar maximum		Solar minimum	
	ADF	p-value	ADF	p-value
Model	-4.69	0.000	-5.94	0.000
The level of significance	MacKinnon [1996] critical values			
1%	-2.65			
5%	-1.95			
10%	-1.61			

Table 2. The co-integration test results for 75 km.

Regression analysis results

Table 3 lists the results of the regression analysis for N_nD measured at an altitude of 75 km. Ordinary Least Square (OLS) method estimates are consistent in the presence of heteroskedasticity, but the standard errors are no longer valid. The white heteroskedasticity (White Het.) Test is a test for heteroskedasticity in OLS residuals. The null hypothesis of the White Test is that there is no heteroskedasticity, and the value of this variable must also be larger than 0.05. The Durbin-Watson Test for serial correlation assumes that   is stationary and normally distributed with mean as zero. It tests the null hypothesis that the errors are uncorrelated and the values of variables need to be between 1.5 and 2.5. Probability (F-statistics) (Prob. (F-statistic)) tests the overall significance of the regression model and the value of this parameter must be smaller than 0.05 [Enders 2008, Sagir et al. 2015].

Values for the last three rows located on the bottom of the table show significance of established model and coefficients in this model. The values given in parentheses in the first five rows of the table refer to the significance of the coefficient obtained. The statistical significance of these values are shown by ⋆ sign outside the parentheses.

When the coefficients in Table 3 are investigated, it is observed that there is a negative relationship for 22nd SC in the solar maximum epoch and for 22nd and 23rd SCs in the solar minimum epoch and there is a positive relationship in other epochs. While increase of 1 meter

Coefficents	Solar maximum			Solar minimum		
	21st	**22nd**	**23rd**	**21st**	**22nd**	**23rd**
c (Constant)	8.41×10^{20}	8.25×10^{20}	8.70×10^{20}	8.10×10^{20}	8.45×10^{20}	8.63×10^{20}
	(0.000)***	(0.000)***	(0.000)***	(0.000)***	(0.000)***	(0.000)***
β_1 D(QBO)	6.13×10^{17}	-5.0×10^{17}	5.70×10^{17}	8.68×10^{17}	-3.63×10^{17}	-6.19×10^{17}
	(0.015)**	(0.022)**	(0.009)***	(0.004)***	(0.010)***	(0.040)**
β_2 (DummyW)	8.54×10^{20}	8.52×10^{20}	8.73×10^{20}	8.11×10^{20}	8.44×10^{20}	8.70×10^{20}
	(0.000)***	(0.000)***	(0.000)***	(0.000)***	(0.000)***	(0.000)***
β_3 (DummyE)	8.41×10^{20}	8.25×10^{20}	8.70×10^{20}	8.10×10^{20}	8.45×10^{20}	8.63×10^{20}
	(0.000)***	(0.000)***	(0.000)***	(0.000)***	(0.000)***	(0.000)***
AR (1)	0.113	0.998	1.47	0.385	1.001	1.052
	(0.555)	(0.000)***	(0.000)***	(0.024)**	(0.000)***	(0.000)***
R^2	0.82	0.77	0.86	0.72	0.85	0.84
Adj. R^2	0.79	0.74	0.84	0.68	0.82	0.81
Durbin Watson	1.851	1.991	2.027	1.602	2.011	1.923
Prob. (F-statistics)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
White Het.	(0.611)	(0.116)	(0.945)	(0.305)	(0.688)	(0.094)

Table 3. The regression model results for 75 km altitude. (*),(**),(***) represents the significant level at 1 %, 5%, and 10%, respectively.

per second of QBO in the solar maxima epochs for 21st and 23rd SCs causes an increase of 6.13×10^{17} m^{-3} and 5.7×10^{17} m^{-3}, it causes a decrease of 5.0×10^{17} m^{-3} in 22nd SC. Whereas increase of 1 meter per second of QBO in the solar minima epochs for 22nd and 23rd SCs causes a decrease of 3.63×10^{17} m^{-3} and 6.19×10^{17} m^{-3}, it causes an increase of 8.68×10^{17} m^{-3} in 21st SC. The correlation coefficient (R^2) in the analysis carried out with the whole set of the QBO is higher than those Danilov [1998] who investigates relationship between QBO and electron density.

It is observed that β_2 (DummyW) and β_3 (DummyE) coefficients indicating wind direction are having positive effect on N_nD in both solar maxima and solar minima epochs. This positive relationship can be associated with carrying positive/negative ions and neutral particles upward of QBO through waves abovementioned based on sentence expressed by Lastovicka [2006] "The meteorological influences play an important role in the overall ionospheric variability [e.g., Forbes et al. 2000, Rishbeth and Mendillo 2001]". This results obtained are fully consistent with Danilov [1998] for β_2 coefficient, while β_3 coefficient are partly consistent with Danilov [1998]. The impact rate of these coefficients is close to each other. Although Adj.R^2 value varies with the solar cycle, it is expressed that about 68%- 84% of changes in N_nD according to this model can be explained by QBO. The remaining portion (approximately 32%-16%) can be explained by the other effects which are

not including to model here (such as, lightning, earthquakes, tides) of sub-atmospheric origin. The results obtained are supported that the ion-generation processes that occur in the lower ionosphere are closely related to the chemistry of neutral components and to meteorological processes [Krivolutsky 2009].

3.2. The analysis results for N_nD measured at an altitude of 90 km

Figure 3 shows the variation of N_nD calculated at 90 km altitude with QBO in the solar maximum (left-side) and solar minimum (right-side) epochs for 21st, 22nd and 23rd SCs. In the solar maximum epoch, there is a positive relationship between N_nD and west-directional QBO for all three SCs. While there is a positive relationship between N_nD and east-directional QBO for 21st SC, a negative relationship is observed for 22nd and 23rd SCs. In the solar minimum epoch, there is a positive relationship between N_nD and west-directional QBO for all three SCs. While there is a negative relationship between N_nD and east-directional QBO in 23rd SC, a positive relationship is observed in 21st and 22nd SCs.

Unit root test results

Table 4 lists the results of the unit root test of the QBO and N_nD variables, measured at 10 hPa and at an altitude of 75 km, respectively. It can be seen that the variables are not stationary for all the three
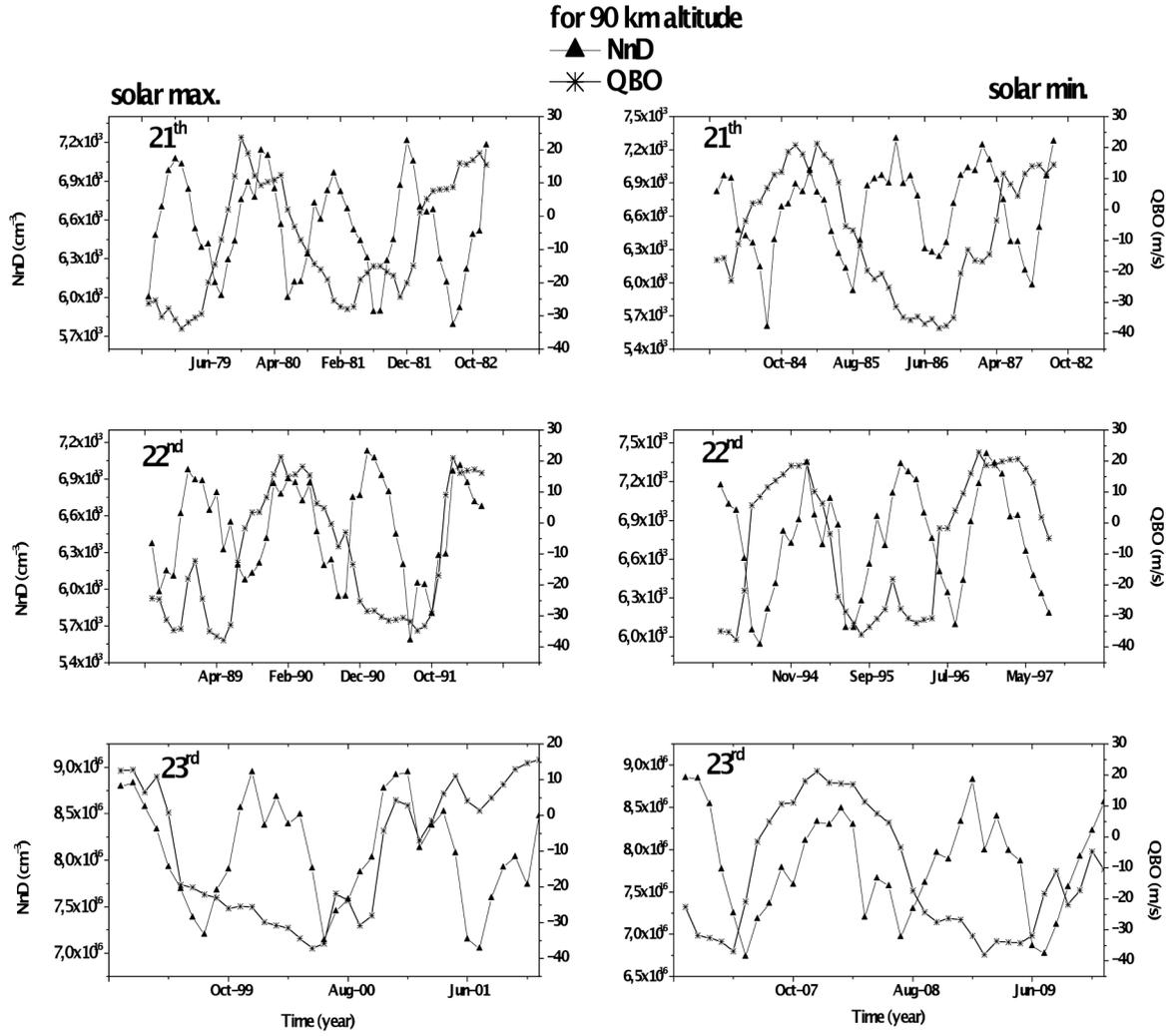
Figure 3. The variation with years of relationship between QBO and N_nD calculated at 90 km altitude in solar maximum (left-side) and solar minimum (right-side) epochs for 21st, 22nd and 23rd SCs.

tests. In order to make the variable stationary, their first differences (D (QBO), D (N_nD)) were considered. As a result, the variable D(QBO) is statistically significant at 1% in the ADF and PP tests, while it is statistically insignificant in the KPSS test. The variable NnD is the same as the variable QBO. Thanks to the variables D(QBO) and D(N_nD) are significant according to two tests (ADF and PP), they are considered to be stationary.

Co-integration test results

In Table 5, the results of the co-integration test for N_nD measured at an altitude of 90 km for solar maximum and the solar minimum epochs are listed. Since the ADF values are greater than MacKinnon critical values as the absolute values, in both solar maximum ($|-4.24|>|-2.65|$) and solar minimum epochs ($|-5.71|>|-2.65|$) there are a relationship between the QBO and the N_nD. Meanwhile, since the p-values are also smaller than 0.05 for both cycles (solar maximum and solar minimum), there is relationship between the QBO and the N_nD. Looking at both comparisons (ADF-MacKinnon and p-values-0.05), a relationship between the QBO and the N_nD has been observed in the 1% level of significance that is the most significant level.

Variables	10 hPa		
	ADF	**PP**	**KPSS**
QBO	-2.63	-2.63	0.078
N_nD	-7.22	-3.65	0.040
D(QBO)	-7.36	-7.36	0.084
D(N_nD)	-5.30	-4.50	0.080
The level of significance	**MacKinnon [1996] critical values**		
	ADF	**PP**	**KPSS**
1%	-4.243	-4.243	0.216
5%	-3.544	-3.544	0.146
10%	-3.204	-3.204	0.119

Table 4. The unit root test results for 90 km.

Regression analysis results

The regression analysis results for N_nD, measured at an altitude of 90 km, are listed in Table 6. If the resultant value is smaller than the Probability (F-statistic) (Prob. (F-statistic)) value of 0.05, it indicates that the developed model is significant. It is observed that β_2 and β_3 coefficients indicating wind direction are having positive effect on N_nD and this effect is very close to each other in 21st and 22nd SCs. Such as β_1 coefficient, it is observed that effect on N_nD of β_2 and β_3 coefficients is also higher in the 23rd SC than 21st and 22nd SCs. Although Adj.R^2 value varies with the SC, changes of about 50% - 75% in N_nD can be explained by QBO. This result shows that QBO can disturb to lower ionosphere via troposphere based waves as expressed to introduction [Kazimirovski and Kokoruov 1995, Krivolutsky 2009]. According to the coefficients in Table 6, it is observed that there is only a positive relationship in the solar maximum epoch for 23rd SC and there is a negative relationship for all remaining cases. Change of 1 meter per second in QBO (β_1 coefficient in the Table 6) in both solar maximum and solar minimum epochs for 21st and 22nd SCs gives rise to a decrease of about 1.36×10^{16} m^{-3} -13×10^{16} m^{-3}. However, this change in the 23rd SC causes an increase of 2.32×10^{20} m^{-3} in solar maximum epoch and brings about a decrease of 1.98×10^{16} m^{-3} for solar minimum epoch.

Values for the last three lines located on the bottom of the table show significance of established model

Regression model	Solar maximum		Solar minimum	
	ADF	p-value	ADF	p-value
Model	-4.24	0.0001	-5.71	0.000
The level of significance	MacKinnon [1996] critical values			
1%	-2.65			
5%	-1.95			
10%	-1.61			

Table 5. The co-integration test results for 90 km.

and coefficients in this model. The values given in parentheses in the first five lines of the table refer to the significance of the coefficient obtained. The statistical significance of these values are shown by $\star$ sign outside the parentheses.

When results obtained for both altitudes (75 km and 90 km) are compared, as expected, it is found that occurring change in N_nD by QBO is higher about 10 times at 75 km altitude than 90 km altitude in 21st and 22nd SCs. But, this change is higher about 1000 times at 90 km altitude than 75 km altitude in 23rd SC.

4. Conclusion

In this study, the underlying effects and the changes in the N_nD caused by the stratospheric QBO are investigated using a multiple regression model. Also, both the solar maxima and the solar minima epochs are taken into

Coefficents	Solar maximum			Solar minimum		
	21st	22nd	23rd	21st	22nd	23rd
c (Constant)	6.54×10^{19}	6.49×10^{19}	8.22×10^{22}	6.80×10^{19}	6.62×10^{19}	7.67×10^{22}
	(0.000)***	(0.000)***	(0.000)***	(0.000)***	(0.002)***	(0.000)***
β_1 D(QBO)	-9.75×10^{16}	-1.36×10^{16}	2.32×10^{20}	-1.30×10^{17}	-8.58×10^{16}	-1.98×10^{16}
	(0.075)*	(0.031)**	(0.011)**	(0.065)*	(0.055)*	(0.018)**
β_2 (DummyW)	6.56×10^{19}	6.74×10^{19}	8.36×10^{22}	6.67×10^{19}	6.62×10^{19}	7.89×10^{22}
	(0.000)***	(0.000)***	(0.000)***	(0.000)***	(0.000)***	(0.000)***
β_3 (DummyE)	6.54×10^{19}	6.49×10^{19}	8.22×10^{22}	6.80×10^{19}	6.62×10^{19}	7.67×10^{22}
	(0.000)***	(0.000)***	(0.000)***	(0.000)***	(0.000)***	(0.000)***
AR (1)	1.635	0.523	0.495	0.815	0.557	0.543
	(0.000)***	(0.003)***	(0.032)**	(0.003)***	(0.003)***	(0.000)***
R^2	0.78	0.67	0.58	0.59	0.63	0.67
Adj. R^2	0.75	0.56	0.50	0.51	0.58	0.61
Durbin Watson	2.143	2.059	1.823	1.997	1.970	2.030
Prob. (F-statistics)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
White Het.	(0.243)	(0.670)	(0.356)	(0.919)	(0.568)	(0.509)

Table 6. The regression model results for 90 km. (*),(**),(***) represents the significant level at 1 %, 5%, and 10%, respectively.

consideration at the evaluating of the relationship between variables. The results are as follows:

- The explainable rate is higher at 75 km altitude than at 90 km altitude.

- The explainable rate of the effect on the N_nD of QBO is 79%, 74% and 84% and 68%, 82% and 81% in the solar maxima and the solar minima epochs for 21st, 22nd and 23rd SCs at 75 km altitude, respectively.

- The explainable rate of the effect on the N_nD of QBO is 75%, 56% and 50% and 51%, 58% and 61% in the solar maxima and the solar minima epochs for 21st, 22nd and 23rd SCs at 90 km altitude, respectively.

- The relationship between variables is positive for both direction of QBO at both altitudes.

- The relationship between QBO and N_nD is positive for 21st and 23rd SCs in solar minimum epoch and for 21st SC in solar maximum epoch at 75 km altitude. In the remaining cases, relationship between variables is negative.

- While the relationship between QBO and N_nD is positive for 23rd SC in solar minimum epoch, it is negative in the remaining cases at 90 km altitude.

It is noted that, none of these statistical studies provides any physical mechanism to determine the apparent relationships, but the QBO through the atmospheric waves [Pancheva et al. 1991] may have a greater effect on the N_nD in the D-region, which is considered as weakly ionized plasma. Apart from causing a statistical decrease in the N_nD due to the QBO, it is also may give rise to changes in the ion chemistry of this region [Krivolutsky 2009]. This change would become physically and chemically by interacting with the carrying momentum by QBO of neutral components in D-region. Thus, neutrals turn into ions by means of collisions and various chemical reactions or *vice versa*, and N_nD number may be changed. Thus, QBO, that is one of the meteorological influences, can play an important role in the lower ionospheric N_nD.

References

Baldwin, M., L. Gray, T. Dunkerton, K. Hamilton, P. Haynes, W. Randel, J. Holton, M. Alexander, I. Hirota and T. Horinouchi (2001). The quasi-biennial oscillation, Rev. Geophys., 39 (2), 179-229.

Chen, P.R. (1992). Evidence of the ionospheric response to the QBO, Geophys. Res. Lett., 19 (11), 1089-1092.

Danilov, A.D. (1998). Solar activity effects in the ionospheric D region, Ann. Geophysicae, 1527-1533.

Enders, W. (2008). Applied Econometric Time Series, John Wiley & Sons.

Engle, R.F., and C.W.J. Granger (1987). Co-integration and error correction: Representation, estimation and testing, Econometrica, 55, 251-276.

Forbes, J.M., S.E. Palo and X. Zhang (2000). Variability of the ionosphere, J. Atmos. Terr. Phys., 62 (8), 685-693.

Heaps, A., W. Lahoz and A. O'Neill (2000).The Quasi-Biennial zonal wind Oscillation (QBO), Centre for Global Atmospheric Modelling, Department of Meteorology, University of Reading, UK.

Kazimirovsky, E.S., and V.D. Kokourov (1995). Meteorological effects in the ionosphere: A review, Geomagn. Aeron., 35 (3), 303-320.

Kirov, B., S. Asenovski, K. Georgieva and V.N. Obridko (2014). What causes geomagnetic activity during sunspot minimum?, Solar and Solar-Terrestrial Physics, Saint Petersburg, Pulkovo, October 20-24, 219-222.

Kero, A. (2008). Ionospheric D-region Studies by Means of Active Heating Experiments and Modelling, Sodankylä Geophysical Observatory Publications No. 102, Oulu University Press, Finland.

Krivolutsky, A.A. (2009). Russian studies of the middle atmosphere in 2003-2006, Izvestiya, Atmos-Oceanic Phys., 45 (4), 528-539.

Kwiatkowski, D., P.C.B. Phillips, P. Schmidt and Y. Shin (1992). Testing the null hypothesis of stationary against the alternative of a unit root: How sure are we that economic time series have a unit root?, J. Econometrics, 54 (1), 159-178.

Lastovicka, J. (2006). Forcing of the ionosphere by waves from below, J. Atmos. Terr. Phys., 68 (3-5), 479-497.

MacKinnon, J.G. (1996). Numerical distribution functions for unit root and cointegration tests, J. App. Econometrics, 11, 601-618.

Mohanakumar, K. (2008). Stratosphere Troposphere Interaction, Springer Doc. Goghin.

Pancheva, D., J. Lastovicka, B.A. de la Morena (1991). Quasi-periodic fluctuations in ionospheric absorption in relation to planetary activity in the stratosphere, J. Atmos. Terr. Phys., 53, 1151-1156.

Rishbeth, H., and M. Mendillo (2001). Patterns of F2-layer variability, J. Atmos. Terr. Phys., 63 (15), 1661-1680.

Sagir, S., S. Karatay, R. Atici, A. Yesil and O. Ozcan (2015). The relationship between the Quasi Biennial Oscillation and Sunspot Number, Adv. Space Res., 55 (1), 106-112.

Corresponding author: Ramazan Atıcı,
Mus Alparslan University, Faculty of Education, Mus, Turkey;
email: r.atici@alparslan.edu.tr.