Pramana – J. Phys. (2018) 91:54
https://doi.org/10.1007/s12043-018-1627-9

The possible effect of stratospheric quasi-biennial oscillation on the critical frequency of the ionospheric F2-layer

S SAĞIR[1,*], R ATICI[2] and O ÖZCAN[3]

[1]Department of Electronics and Automation, Mus Alparslan University, Mus, Turkey
[2]Faculty of Education, Mus Alparslan University, Mus 49250, Turkey
[3]Department of Physics, Faculty of Sciences, Firat University, Elazig, Turkey
*Corresponding author. E-mail: s.sagir@alparslan.edu.tr

MS received 13 November 2017; revised 2 March 2018; accepted 19 March 2018; published online 20 August 2018

Abstract. In this study, the coupling between the stratospheric quasi-biennial oscillation (QBO) and the critical frequency of the ionospheric F2-layer (foF2) was analysed statistically. The multiple regression model was used as a statistical tool. The model was developed by adding the sunspot number (SSN), which affects the foF2 (measured for Madras, Kodaikanal, Bogota, Manila and Tahiti) in the ionosphere at a significant level. Four different 'Dummy' sets of data were used in the model in order to observe the effect of the direction (east–west) and the magnitude (for both directions, between 0 and 15 m/s and between 0 and 16 m/s and the largest value) of QBO. It was observed that the variations of foF2 in the range of 60–78% in the model could be explained by SSN and SSN^2. The change of 2–13% that occurred in foF2 could be explained by the whole set of QBO. It was also observed that the effect of the direction and magnitude of QBO on foF2 differed between the stations.

Keywords. Ionospheric critical frequency; quasi-biennial oscillation; sunspot number; multiple regression model.

PACS Nos 94.20.Cf; 94.20.dj; 94.20.dt; 94.20.wg

1. Introduction

The ionosphere, which affects the propagation of radio waves, lies between ∼50 and 1000 km altitude [1]. An important parameter that gives information about the state of the ionosphere is the critical frequency. The critical frequency of the F2-layer changes with time, location and also with solar flares, sunspot number (SSN), solar wind, etc. and geomagnetic activities and with the state of the neutral atmosphere [2–8]. Atmospheric disturbances play an important role in the formation of meteorological events, especially in tropical regions [9]. The critical frequency is also affected by these meteorological processes that occur at lower altitudes [10,11]. The meteorological phenomena in the ionosphere can occur due to upward propagating gravity waves, tidal and planetary waves. The meteorological phenomena have an essential effect on the dynamics of the ionosphere [12–18]. Quasi-biennial oscillation (QBO), one of these effects, is a wind blowing in the east–west direction in a period of ∼28–29 months over equatorial stratosphere [19–22]. QBO is transferred as energy and momentum by means of atmospheric waves and (gravity, inertia gravity, Rossby gravity and Kelvin) from the lower stratosphere to the mesosphere (see [11,19,22]).

Some gravity waves propagate vertically through the entire stratosphere and produce a QBO near the mesopause known as the mesospheric QBO or MQBO [19]. MQBO could affect the charge distribution of the ionospheric E-region, and thus the electric field of the E-region. From the mesosphere to lower thermosphere layer, it can be extended by the F-region altitudes throughout the Earth's magnetic field lines [23]. There are many studies which examine the possible effect of QBO on ionospheric parameters (e.g. [22–26]). If there is such an effect, the vertical coupling with the ionosphere of QBO might be very complex because the dynamic processes of short-term effects may mediate a QBO effect in the ionosphere.

This study was derived from the thesis study of 'The effect of QBO on the ionosphere', which ended in 2013 at the Institute of Science and Technology of the University of Firat.

The main purpose of this study is to show the possible effect of QBO on critical frequency of the ionospheric F2-layer (foF2) by referring to the paper by Yadav *et al* [27]. In this context, the relationship between foF2 and QBO measured at 10 and 70 hPa altitude was investigated by using the multiple regression analysis method. The multiple regression analysis model including SSN used by Yadav *et al* [27] was developed to investigate the relationship between foF2 and QBO. In §2, the multiple regression analysis and in §3, the results and discussions are given. The conclusion is given in §4.

2. The multiple regression analysis

The multiple regression model is a statistical tool to detect a possible association between the variables [21,27–30]. In the present study, the multiple regression model was used to examine the relationship between foF2 and QBO measured at 70 and 10 hPa. The analysis model has three statistical parts, namely, the unit root test, the cointegration test and the regression model. The stationarity of the variables is analysed by means of the unit root test. The cointegration test is used to determine whether there is a long-term relationship between the variables or not. The regression model defines the value of the relationship between the variables.

As stationarity was an important step in our model, the stability of the variables was investigated by three separate tests, i.e. the augmented Dickey–Fuller test (ADF), Phillips–Perron test (PP) and Kwiatkowski–Phillips–Schmidt–Shin test (KPSS) [31,32]. If the variables are not stationary, i.e. if the variance and the mean value change over time, then by taking the first-order difference of foF2, QBO and SSN, (D(foF2), D(QBO), D(SSN)), these variables are made stationary. The first-order difference is meant to extract the first data from the second data, and the second data from the third data and so on.

The equation in which the lagged values of the dependent variable are included in the model can be formulated as follows [28]:

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

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, α is the coefficient of the dependent variable and k is the number of lags. After the variables are provided with stationarity, the existence of a long-term relationship between the variables is investigated by ADF cointegration test (this test is based on the fact that the ADF values are greater than the MacKinnon [33] critical values as absolute values). In the last step, the regression equation is set up depending on the stationarity of the variables.

Following the results of Yadav *et al* [27], which were obtained at low latitude with a quadratic relationship between SSN and foF2, we defined eq. (2) as Model 1 in this study. This quadratic relationship allows the partial reproduction of the ionosphere saturation effect with the increasing solar activity at low latitudes:

$$\mathrm{foF2}_t = \beta_0 + \beta_1 \mathrm{SSN}_t + \beta_2 \mathrm{SSN}_t^2 + \varepsilon_t, \qquad (2)$$

where β_0 is a constant, β_1 and β_2 indicate the coefficients of the variables and ε_t is the error term.

The regression coefficients are estimated by using eq. (3). The SSN is also included in the model. Before performing this process, since QBO is a wind, the effect of the eastern (negative sign) and western phases (positive sign) of QBO on foF2 is put in the model by means of the dummy variables. In a statistical model, the dummy variable is a variable that marks or encodes a particular attribute. It is often called binary or dichotomous variable as it takes just two values, usually 1 or 0, to indicate the presence or absence of a characteristic [28]. Thus, the new model obtained, i.e. Model II, is defined as follows:

$$\begin{aligned} \mathrm{foF2}_t = {} & \beta_0 + \beta_1 \mathrm{SSN}_t + \beta_2 \mathrm{SSN}_t^2 + \beta_3 \mathrm{QBO}_t \\ & + \beta_4 \mathrm{Dummy1}_t + \beta_5 \mathrm{Dummy2}_t \\ & + \beta_6 \mathrm{Dummy3}_t + \beta_7 \mathrm{Dummy4}_t + \varepsilon_t. \end{aligned} \qquad (3)$$

Here, β_0 is a constant and β_s are coefficients of the variables. The dummy values vary in the range given in table 1.

3. Results and discussion

In the present work, Model I (eq. (2)) and Model II (eq. (3)) given in §2 were applied to the datasets to examine the effect of QBO on foF2. The foF2 (data available at http://spidr.ionosonde.net/spidr/) and QBO (data available at http://strat-www.met.fu-berlin.de) values were obtained from the stations given in table 2 for the specific time intervals. The data periods used for this study are given in table 2 for all stations, and these stations are shown in figure 1. Since QBO data were obtained monthly, the foF2 data were converted into monthly data by taking their median. A period of at least 10 years was considered for each station. The SSN values (data available at http://www.wdcb.ru/stp/data/solar.act-R12) were obtained for the period between 1957 and 1992.

Table 1. The variation of dummies according to the direction and the magnitude of QBO.

QBO values (m/s)	Dummy 1	Dummy 2	Dummy 3	Dummy 4
<–15	1	0	0	0
≤–15 and <0	0	1	0	0
0< and ≤15	0	0	1	0
15<	0	0	0	1

Table 2. The time intervals and stations used for obtaining foF2 and QBO data.

Station name	Latitude	Longitude	Data available periods
foF2 (data available at http://spidr.ionosonde.net/spidr)			
Kodaikanal	10.2°N	77.5°E	06/1957–10/1987
Bogota	4.5°N	74.2°W	07/1957–06/1967
Madras	13.1°N	80.3°E	06/1957–10/1966
Manila	14.7°N	121.1°E	01/1964–08/1992
Tahiti	17.7°S	149.3°W	01/1971–12/1989
QBO (data available at http://strat-www.met.fu-berlin.de)			
Canton Island	02.46°S	171.33°W	01/1953–07/1967
Gan Maldives	00.41°S	73.09°E	08/1967–12/1975
Singapore	01.22°N	103.55°E	01/1976–08/1992

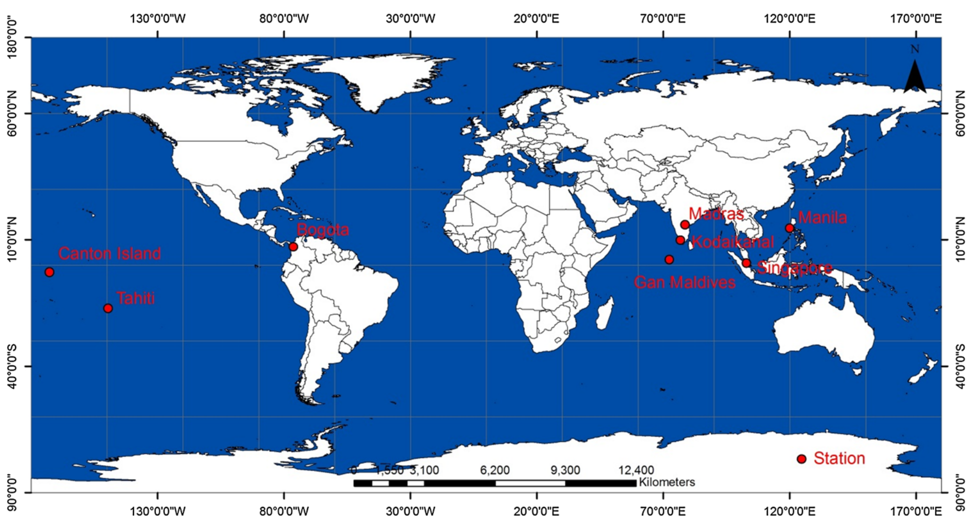

Figure 1. Geographical location of data receiving stations.

Figure 2 shows the variation of QBO, foF2 and SSN in time. It is seen from this figure that foF2 varied with a period of 11 years, while QBO changed with a period of 29 months. In some time periods (June 1962–March 1964; August 1965–August 1966; August 1972–May 1974), the variations in time of QBO measured at 10 hPa and foF2 had opposite trends to each other. Similarly, it is seen that the variations of QBO measured at 70 hPa and foF2 in some time periods (September 1962–September 1963; May 1977–February 1981; November 1985–February 1987) had opposite trends to each other, while their changes in some time periods (November 1985–February 1987) had similar trends. More detailed information about the relationship between QBO and foF2 is given in the results of the multiple regression analysis model (Models I and II).

3.1 *Multiple regression analysis results*

Table 3 gives the unit root test results for the Kodaikanal station. It shows that the variables foF2 and SSN contain the unit root with respect to their levels, and therefore, they are not stationary. In the first difference (D(foF2), D(SSN)) of the series (foF2 and SSN), they become stationary.

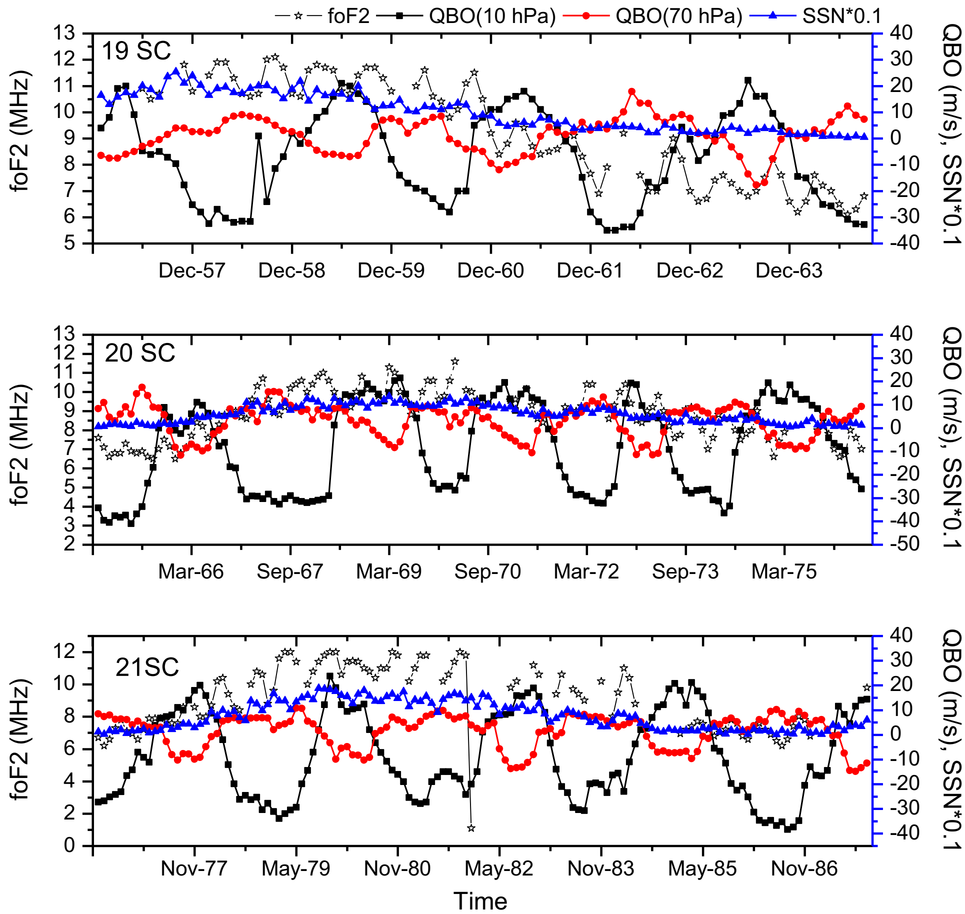

Figure 2. The variation depending on the time of QBO measured at 10 and 70 hPa, and foF2 measured at the Kodaikanal station and sunspot number (SSN*01). Data cover the 19th, 20th and 21st solar cycles. Upper, middle and bottom panels indicate 19th, 20th and 21st solar cycles, respectively.

Table 3. The unit root test results for Kodaikanal station.

Variables	For 10 hPa			For 70 hPa		
	ADF	PP	KPSS	ADF	PP	KPSS
foF2	−1.62	−2.59	0.13	−1.62	−2.59	0.13
SSN	−1.98	−2.70	0.15	−1.98	−2.70	0.15
QBO	−6.57	−6.48	0.04	−10.26	−7.18	0.09
D(foF2)	−8.69	−4.21	0.07	−8.69	−4.21	0.07
D(SSN)	−15.0	−29.5	0.10	−15.0	−29.5	0.10

The level of significance	MacKinnon [33] critical values		
(%)	ADF	PP	KPSS
1	−4.03	−3.99	0.22
5	−3.44	−3.42	0.15
10	−3.14	−3.13	0.12

This process aims to achieve smooth regression results. As the QBO is stationary for its original values, there is no need to take its first difference.

After the unit root test of the variables was analysed, eq. (3) was updated as in eq. (4) based on the results of the unit root test:

$$D(\text{foF2}_t) = \beta_0 + \beta_1 D(\text{SSN}_t) + \beta_2 D(\text{SSN}_t^2) + \beta_3\text{QBO}_t + \beta_4\text{Dummy1}_t + \beta_5\text{Dummy2}_t + \beta_6\text{Dummy3}_t + \beta_7\text{Dummy4}_t + \varepsilon_t. \quad (4)$$

Table 4 shows the cointegration test results obtained for the models established by eqs (1) and (2). As

Table 4. The cointegration test results for Kodaikanal station.

Regression model	For 10 hPa		For 70 hPa	
	ADF	*p*-value	ADF	*p*-value
Model I	−2.83	0.004	−2.83	0.004
Model II	−11.92	0.004	−9.41	0.000

The level of significance (%)	MacKinnon [33] critical values ADF
1	−2.58
5	−1.94
10	−1.61

Table 5. The regression model results for Kodaikanal station.

Coefficient	For 10 hPa		For 70 hPa	
	Model I	Model II	Model I	Model II
β_0 (constant)	6.605	6.192	6.605	6.226
	(0.000)	(0.000)	(0.000)	(0.000)
β_1 D(SSN)	0.045	0.046	0.045	0.053
	(0.000)[a]	(0.000)[a]	(0.000)[a]	(0.000)[a]
β_2 $D(\mathrm{SSN}^2)$	−0.0001	−0.0001	−0.0001	−0.0001
	(0.000)[a]	(0.000)[a]	(0.000)[a]	(0.000)[a]
β_3 (QBO)	–	0.0026	–	0.0025
		(0.017)[b]		(0.044)[b]
β_4 (Dummy 1)	–	−0.592	–	−1.138
		(0.034)[b]		(0.007)[a]
β_5 (Dummy 2)	–	−0.440	–	0.067
		(0.102)[c]		(0.813)
β_6 (Dummy 3)	–	−0.277	–	0.200
		(0.265)		(0.489)
β_7 (Dummy 4)	–	–	–	–
AR (1)	0.620	0.756	0.619	0.341
	(0.000)	(0.000)	(0.000)	(0.017)
R^2	0.775	0.854	0.775	0.913
Adj. R^2	0.771	0.844	0.771	0.902
Durbin–Watson	1.562	2.078	1.562	1.910
Prob. (F-statistic)	(0.000)	(0.000)	(0.000)	(0.000)
Normality	(0.336)	(0.052)	(0.633)	(0.059)
Serial Cor. LM	(0.217)	(0.797)	(0.004)	(0.058)
White Het.	(0.518)	(0.308)	(0.684)	(0.908)

a, b and c represent the significance level at 1%, 5% and 10%, respectively.

the p-values are smaller than 0.05 in the model, and the ADF value is greater – in absolute values – than the MacKinnon [33] critical values at the bottom section of the table ($|-2.83|>|-2.58|$ for Model I and $|-11.92|>|-2.58|$ for Model II) for 10 hPa and ($|-2.83|>|-2.58|$ for Model I and $|-9.41|>|-2.58|$ for Model II) for 70 hPa, it is possible to claim that there is a long-term relationship between the variables. Furthermore, the level of the statistical significance of this relationship is at the rate of 1%.

Table 5 represents the multiple regression analysis results estimated by Models I and II giving the relationship between QBO values at 10 and 70 hPa altitudes, SSN, SSN^2 and foF2 for Kodaikanal station. Serial correlation LM (Serial Cor. LM), White heteroskedasticity (White Het.), Durbin–Watson, Prob. (F-statistic) tests given at the bottom of table 5 are other tests which indicate the accuracy of our model. The reference values of these tests are as follows: Serial Cor. LM and White Het. test values must be >0.05. Durbin–Watson test values must be between 1.5 and 2.5. Prob.

Table 6. Distance from the station measured for QBO to the station measured for foF2 and the values of the relationship coefficients (Adj. R^2) between the variables.

Station name	Distance from the station measured for QBO (km): Canton Island	Gan Maldives	Singapore	The altitude measured for QBO (hPa)	Adj. R^2 (%)	The contribution to the foF2 change of QBO: β_1	β_3	β_4	β_5	β_6	β_7
Kodaikanal	12392	1264	3063	10	7	0.046	0.0026	−0.592	−0.44	M	–
				70	13	0.053	0.0025	−1.138	M	M	–
Bogota	10862	–	–	10	5	0.066	0.0076	M	M	1.091	M
				70	3	0.054	−0.013	M	M	1.543	M
Madras	12021	–	–	10	2	0.02	−0.0026	−0.638	−0.398	−0.355	−0.698
				70	2	0.04	0.0069	M	M	M	M
Manila	7570	5556	2441	10	2.3	0.046	0.0016	−0.382	−0.387	−0.23	–
				70	1.6	0.055	−0.0029	M	M	M	–
Tahiti	–	14960	11864	10	5.6	0.07	−0.0045	−0.851	−1.393	−2.093	M
				70	3	0.073	−0.007	M	M	M	M

M: statically meaningless.

(F-statistic) test value must be <0.05 [28–30]. Since the values obtained for these tests in our model provide their reference values, the established model is statistically accurate.

In table 5, in the model established for QBO measured at 10 hPa altitude, an increase of one unit in D(SSN) causes an increase in D(foF2) by 0.045 and 0.046 MHz in Models I and II. The obtained results are compatible with those reported by Yadav *et al* [27]. This accordance supports the accuracy of the model used in the study. When QBO measured at 10 hPa altitude is put in Model II, an increase of 1 m/s in QBO causes an increase of 0.0026 MHz in foF2. The R^2 values describing the relationship between the variables are 0.775 and 0.854 in Models I and II. In the literature, it is expressed by de Artigas *et al* [34] that the correlation coefficients between foF2 and QBO measured at 40 hPa altitude are 0.65 and 0.67 for Okinawa and Tucuman. Also, the Adjusted R^2 (Adj. R^2) value indicates how much of the changes to the dependent variable (foF2) can be explained by the independent variables (QBO and SSN) and these values are 0.771 and 0.844 in Models I and II. A difference of ∼8% between the models is based on QBO included in Model II. The coefficients of the variables β_4 and β_5 that represent the direction of the QBO are statistically meaningful at a significance level of 5 and 10%, respectively. The increase of 8% in the explicable level of foF2 can be based on β_4 and β_5 (eastern directional phase of the QBO). The correlation coefficient is 0.65 for the east directional winds in [23]. It is also observed that the β_6 value is not statistically significant.

In table 5, in the model established for QBO measured at 70 hPa altitude, an increase of one unit in D(SSN) causes an increase of 0.045 and 0.053 MHz in D(foF2) in both the models. An increase of 1 m/s in QBO causes an increase of 0.0025 MHz in foF2 in Model II. The R^2 values are 0.775 and 0.913 for Models I and II, respectively and Adj. R^2 values are 0.771 and 0.902 for both the models. An approximate difference of 13% between the models is based on QBO included in Model II. The variable β_4 indicating the western direction of QBO in the model is statistically significant at a level of 1%. The increase of 13% in the level explicable in foF2 caused by QBO can be based on β_4.

The statistical analysis method was also applied to the datasets obtained for the other four stations (Bogota, Madras, Manila and Tahiti). In the results obtained for these stations (see table 6), the Adj. R^2 values caused by QBO measured at 10 hPa altitude were obtained at the rates of 5, 2, 2.3 and 5.6%, respectively. It is observed that QBO affected foF2 when the dummy variables representing the direction and the magnitude of the QBO were in the order of β_6; β_4, β_5, β_6 and β_7; β_4, β_5 and

β_6; and β_4, β_5 and β_6, respectively. For Bogota, Madras, Manila and Tahiti, the Adj. R^2 values caused by the QBO measured at 70 hPa altitude were also obtained at the rates of 3, 2, 1.6 and 3%, respectively. The QBO at this altitude affected foF2 when the Dummy variables were also in the order of β_5 and β_6; β_4, β_5 and β_6; β_5 and β_6 and β_6.

It is seen in this table that the effect of QBO on foF2 tends to decrease on the northern latitudes when moved away from the equator [23]. However, the situation is reversed in the Kodaikanal station. This situation can be explained with two possible reasons. The first of these is that the Kodaikanal station is closer (1264 km to Gan Maldives and 3063 km to Singapore) to the station where the QBO is measured than the other stations. The second may be due to the proximity of the Kodaikanal station to the magnetic equator that is dominant on the dynamo effect [34]. Although the Adj. R^2 values (7 and 13% for 10 and 70 hPa altitudes) obtained at the Kodaikanal station were higher compared to the other stations, they were still lower than the correlation coefficient ($r = 0.65$) obtained at Okinawa (26°N, 128°E) station by Chen [23] and $r = 0.704$ obtained by Tang *et al* [35]. Also, the effect of QBO measured at both 10 and 70 hPa altitudes on foF2 was very low at the Madras and Manila stations which are close to each other in the geographic latitude and are almost identical to each other. This result is compatible with the results obtained by de Artigas *et al* [34] and Echer [25]. Besides, this result coincides with the results obtained by Chen [23] for equatorial anomaly region. The results obtained at the Tahiti station located on the southern part of the equator were greater than that at the Madras and Manila stations located on the northern part of the equator, but they are less than the Kodaikanal station's results. The result acquired at this station was less than the result obtained by de Artigas *et al* [34] at the Huancayo (12°S, 75°W) station located on the ionosphere at the crests of the equatorial anomaly.

The stratospheric QBO is transported from the upper stratosphere to the lower stratosphere (with the help of gravity and inertia gravity waves) and from the upper stratosphere to the mesosphere (with the help of Kelvin and Rossby gravity waves) as energy and momentum, which is also the case in other stratospheric events. The E-region, which is the ionospheric dynamo region, and also the current in the region are affected from the interaction of QBO and planetary waves in the mesosphere. The dynamo electric fields produced by the thermospheric winds in the equatorial E-region are transmitted along the dipole magnetic field lines to the F-region altitudes due to the high parallel conductivity [23,34–37]. In this way, the QBO starting in the lower stratosphere is transported up to the upper ionosphere.

It has been emphasised in many studies that the stratospheric QBO, reaching the F2 region with ∼4–5 steps, can have an effect (about 2–13% according to our study) on this region [22–25,35]. It is not possible today to express clearly the reason for the negative and positive results obtained as a result of the study. This region is affected by forces from above (such as large sun, galactic and cosmic rays) and in the region (chemical reactions, electrical forces, Coriolis force, etc.) from below (QBO as well as earthquakes, lightning, sudden stratospheric warmings, volcanoes, etc. meteorological processes). In the study conducted by Borchevkina and Karpov [38], it was stated that the meteorological storms could be caused by 30% reduction in the critical frequency of the F2 region through atmospheric waves (especially acoustic–gravity waves). Therefore, it can be possible that there will be an effect on the foF2 of the QBO, which occurs at higher altitudes than the altitudes at which meteorological processes occur. Although the effect of QBO on the E-region is expressed as positive in some studies [26,29,30], it is difficult to think that QBO influences the F2 region regardless of the total effect of the processes. Thus, it is highly likely that the effect of many other factors, which occur especially in the related station, on the negative and positive results obtained in this study is present.

4. Conclusion

In this study, in addition to improving the study of Yadav *et al* [27], the underlying effects and the structure of the ionospheric irregularities caused by stratospheric QBO were examined by using multiple regression model. It is critical to say that the statistical results obtained in this study do not provide any physical mechanism about the relationship between the variables, but different responses might indicate where the fundamental relations take place. To study the possible effect of QBO and SSN on foF2, the multiple regression model was used to the datasets foF2, SSN and QBO. The obtained results are as follows:

- Although the results obtained for the foF2 show differences, as a result of analysis of the coefficients, it was observed that the critical frequency is affected by QBO at the rates between 2 and 13% in all the five stations.
- For QBO measured at 10 hPa altitude, the relationship between foF2 and QBO was positive for Bogota, Kodaikanal and Manila; and negative for Madras and Tahiti.

- For QBO measured at 70 hPa altitude, the relationship was positive for Madras and Kodaikanal; and negative for Bogota, Manila and Tahiti.
- The direction and the magnitude of QBO vary depending on the chosen station and the measured height of QBO. There was a statistically significant effect of QBO, which was observed in foF2 values.
- This effect of QBO was about 8 or 45 times smaller than SSN although there were differences between the stations. This rate was about 10% in [25].
- The effect of the whole sets of QBO for both 10 and 70 hPa on foF2 was smaller than that of the directions (east and west) of QBO.
- The directions of QBO affect the foF2 negatively while the whole sets of QBO affect positively.

Thus, this study suggests that the effect of QBO can be considered for the accurate determination of the critical frequency range of the F2 region, which has great importance in radio communication. The investigation of the effect of this parameter on foF2 by separating its directions is provided to obtain more accurate results. Yet, the investigated periods and the datasets are still limited, and the accuracy of the applied statistical tools needs to be developed to determine the relationship between foF2 and QBO.

Acknowledgements

The authors thank the Russian Academy of Sciences, Geophysical World Data Center for SSN data, Freie Universitat Berlin for QBO data and SPIDR Home director for foF2 data.

References

[1] H Rishbeth and O K Garriott, *Introduction to ionospheric physics* (Academic Press, New York, 1969) Vol. 1, p. 47
[2] S Ostrow and M Pokempner, *J. Geophys. Res.* **57**(**4**), 473 (1952)
[3] M Pietrella and L Perrone, *Ann. Geophys.* **26(2)**, 323 (2008)
[4] J Liu, L Li, B Zhao, W Wan and Y Chen, *Sci. China Technol. Sci.* **55**(**5**), 1169 (2012)
[5] I G Zakharov and O F Tyrnov, *Phys. Chem. Earth Pt. C* **24**(**4**), 371 (1999)
[6] E B Judson, *Proc. Inst. Radio Eng.* **25**(**1**), 38 (1937)
[7] L R Cander and L Ciraolo, *Acta Geophys.* **58**(**3**), 468 (2010)
[8] K Sharma, R Dabas and S Ravindran, *Astrophys. Space Sci.* **341**(**2**), 277 (2012)
[9] A Jeevarekha and P Philominathan, *Pramana – J. Phys.* **86**, 1031 (2016)
[10] J Lastovicka, *J. Atmos. Sol.-Terr. Phys.* **68**(**3–5**), 479 (2006)
[11] K Mohanakumar, *Stratosphere troposphere interactions: An introduction* (Springer Science & Business Media, 2008)
[12] E Kazimirovsky and V Kokourov, *Geomagn. Aeron.* **35,** 303 (1995)
[13] J M Forbes, S E Palo and X Zhang, *J. Atmos. Sol.-Terr. Phys.* **62**(**8**), 685 (2000)
[14] H Rishbeth and M Mendillo, *J. Atmos. Sol.-Terr. Phys.* **63**(**15**), 1661 (2001)
[15] E Kazimirovsky, M Herraiz and B De la Morena, *Surv. Geophys.* **24**(**2**), 139 (2003)
[16] D Altadill, E M Apostolov, J Boska, J Lastovicka and P Sauli, *Ann. Geophys.* **47**, 1106 (2004)
[17] J Lastovicka, *J Atmos. Sol.-Terr. Phys.* **67**(**1–2**), 83 (2005)
[18] A Krivolutsky, *Izv. Atmos. Ocean. Phys.* **45**(**4**), 528 (2009)
[19] M Baldwin, L Gray, T Dunkerton, K Hamilton, P Haynes, W Randel, J Holton, M Alexander, I Hirota and T Horinouchi, *Rev. Geophys.* **39**(**2**), 179 (2001)
[20] A Heaps, W Lahoz and A O'Neill, Centre for Global Atmospheric Modelling, University of Reading, UK (2000)
[21] S Sağır, R Atici, O Ozcan and N Yuksel, *Ann. Geophys.* **58**(**3**), A0331 (2015)
[22] K Kurt, A Yeşil, S Sağir and R Atici, *Acta Geophys.* **64**(**6**), 2781 (2016)
[23] P R Chen, *Geophys. Res. Lett.* **19**(**11**), 1089 (1992)
[24] R Kane, *J. Atmos. Sol.-Terr. Phys.* **57**(**4**), 415 (1995)
[25] E Echer, *J. Atmos. Sol.-Terr. Phys.* **69**(**4**), 621 (2007)
[26] K Çetin, O Özcan and S Korlaelçi, *Chin. Phys. B* **26**(**3**), 039401 (2017)
[27] S Yadav, R Dabas, R M Das, A Upadhayaya, S Sarkar and A Gwal, *Adv. Space Res.* **47**(**1**), 124 (2011)
[28] W Enders, *Applied econometric time series* (John Wiley & Sons, New York, 2008)
[29] R Atici and S Sagir, *J. Phys. Sci. Appl.* **6**(**2**), 10 (2016)
[30] R Atıcı and S Sağır, *Adv. Space Res.* **60**(**2**), 357 (2017)
[31] R F Engle and C W Granger, *Econometrica* **55(2)**, 251 (1987)
[32] D Kwiatkowski, P C Phillips, P Schmidt and Y Shin, *J. Econom.* **54,** 159 (1992)
[33] J G MacKinnon, *J. Appl. Econ.* **11(6)**, 601 (1996)
[34] M Z de Artigas, N O de Adler and A G Elias, *Geofí. Int.* **43,** 199 (2004)
[35] W Tang, X H Xue, J Lei and X K Dou, *J. Atmos. Sol.-Terr. Phys.* **107**, 36 (2014)
[36] O Özcan and M Aydoğdu, *J. Atmos. Sol.-Terr. Phys.* **66**(**11**), 997 (2004)
[37] R Schunk and A Nagy, *Ionospheres: Physics, plasma physics, and chemistry* (Cambridge University Press, USA, 2009)
[38] O Borchevkina and I Karpov, *Geomagn. Aeron.* **57**(**5**), 624 (2017)