The interaction between stratospheric monthly mean regional winds and sporadic-E

Kenan Çetin[1,†], Osman Özcan[2], and Serhat Korlaelçi[1]

[1] *Department of Physics, Art and Science Faculty, Mus Alparslan Universitiy*, 49250 *Turkey*
[2] *Department of Physics, Science Faculty, Firat Universitiy*, 23100 *Turkey*

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In the present study, a statistical investigation is carried out to explore whether there is a relationship between the critical frequency (foEs) of the sporadic-E layer that is occasionally seen on the E region of the ionosphere and the quasi-biennial oscillation (QBO) that flows in the east–west direction in the equatorial stratosphere. Multiple regression model as a statistical tool was used to determine the relationship between variables. In this model, the stationarity of the variables (foEs and QBO) was firstly analyzed for each station (Cocos Island, Gibilmanna, Niue Island, and Tahiti). Then, a co-integration test was made to determine the existence of a long-term relationship between QBO and foEs. After verifying the presence of a long-term relationship between the variables, the magnitude of the relationship between variables was further determined using the multiple regression model. As a result, it is concluded that the variations in foEs were explainable with QBO measured at 10 hPa altitude at the rate of 69%, 94%, 79%, and 58% for Cocos Island, Gibilmanna, Niue Island, and Tahiti stations, respectively. It is observed that the variations in foEs were explainable with QBO measured at 70 hPa altitude at the rate of 66%, 69%, 53%, and 47% for Cocos Island, Gibilmanna, Niue Island, and Tahiti stations, respectively.

Keywords: multiple regression model, equatorial region, sporadic-E, quasi-biennial oscillation (QBO)

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1. Introduction

Ionosphere is an electrically neutral atmosphere layer starting from nearly 50 km altitude and reaching up to 1000 km.[1,2] It is influenced by the processes like the Sun, galactic-cosmic rays, and heavenly bodies coming from the upper side of the ionosphere.[3–6] In addition to this, the ionosphere is also influenced by meteorological processes like stratospheric monthly mean regional winds, lightning, earthquakes, and volcanic eruptions coming from lower areas.[3,4,6–15] Based on these processes, the ionosphere is separated into three regions, which are called D, E, and F, that have different densities.

The E region of the ionosphere has a relatively high electric conductivity. For this reason, it plays an important role in the electron dynamics of the ionosphere. Under some conditions, a thin layer that has intense ionization appears in the E region. This thin layer is called as the sporadic-E layer. These types of layers occur rarely, and can be observed at all altitudes in the E region.[16] Radio waves can be reflected in the sporadic E-region partly or as a whole up to very high frequencies ($>$ 75 MHz). This effect can be beneficial or harmful for radio communication. The Es layer may expand the beneficial frequency range, and its existence can be used in a productive manner in system design works.[17–19] The physical structure of the ionization of the sporadic-E layer is not fully known. However, it is widely accepted that the mechanism can be different for the auroral, mid-latitude and geographical equator zone.[18,19] In mid-latitudes, the Es layer is explained by the upwards atmosphere winds and the wind-shear theory.[19] The formation of the sporadic-E layer in equator region is explained by the theories based on plasma.[20–22]

QBO is the release of the winds occurring in the east–west direction in the equatorial stratosphere with about 28–29 monthly periods.[23,24] QBO has a high influence in the equatorial region. It moves in the direction of east with nearly 30 m/s and in the direction of west with nearly 20 m/s speed. Although the maximum amplitude of QBO is generally at 10 hPa level, it may also reach 100–2 hPa values. QBO is influential in the processes occurring in the upper stratosphere, in the mesosphere and even in the F region of ionosphere.[3,4,7,8,25–27]

The purpose of this study is to investigate the possible effect of QBO on the sporadic-E layer. In this paper, the statistical analysis method is explained in the second section. The results and discussions are given in the third section. The conclusions are drawn in the fourth section.

2. Statistical analysis method

The multiple regression model has been used in this study as the statistical tool. This model can be used for many different cases.[3,4,7,8,28] The first step in the multiple regression model is the application of the unit root test in which the stationary status of the variables (sporadic-E layer critical frequency, foEs, and QBO obtained at 10 and 70 hPa altitudes) is checked. After the stationary status of the variables is provided, the issue of whether or not there is a long-term relation-

†Corresponding author. E-mail: kenanfizik@hotmail.com

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ship between the variables is tested by a co-integration test in the second step. If there is a long-term relationship between the variables, the relationship coefficients of the variables are obtained with the regression model in the last step. For detailed information on these tests, please check Refs. [3], [4], [7], [8], and [10]. Based on these references, the regression equation used in the study, is given as follows:

$$\begin{aligned} \text{foEs} &= \beta_0 + \beta_1 \text{QBO} + \beta_2 \text{DummyEast} \\ &\quad + \beta_3 \text{DummyWest} + \varepsilon. \end{aligned} \tag{1}$$

Here, β_0 is constant, β_1, $\beta_{1,}$ and β_3 represent the regression coefficients, and ε_t represents the error term. DummyEast represents the eastward component of QBO, while DummyWest the westward component of QBO. This equation has been rewritten for the four stations investigated in this study depending on the stationary status of the variables, and the forms are given Section 3.

3. Results and discussion

The QBO data used in the computations have been obtained online[29] for 10 hPa and 70 hPa altitudes. The foEs data were also obtained online[30] for Cocos Island (12.18 G, 96.83 D), Gibilmanna (37.6 N, 14.0 E), Niue Island (19.1 K, 169.9 D), and Tahiti (17.7 G, 149.3 B) Station. Since the QBO data have been obtained on a monthly basis, the foEs values are adapted to QBO, and their monthly median values[31,32] are taken to be used in statistical computations.

3.1. The results for the QBO obtained in 10 hPa altitude

The unit root test results for Cocos Island station are given in Table 1. To have a stationary situation in this test the absolute value of each variable given in the upper part of Table 1 must be greater than the absolute value of the critical values[33] given in the bottom part of the table. When the values in Table 1 are analyzed, it is observed that neither of our variables at 10 hPa are stationary in augmented–dickey Fuller test (ADF), Phillips–Perron test (PP), but both values are stationary according to Kwiatkowski–Phillips–Schmidt–Shin test (KPSS). For this reason, the first differences of our variables (D(QBO), D(foEs)) are taken in order to make them become stationary.

Table 1. The unit root test results for Cocos Island station.

Variables	Tests for 10 hPa		
	ADF	PP	KPSS
QBO	–2.32	–1.72	0.14
foEs	–2.99	–2.96	0.15
D(QBO)	–3.93	–3.90	0.13
D(foEs)	–6. 63	–8.93	0.05
Significance levels	McKinnon (1996) critical values		
1%	–4.24	–4.24	0.21
5%	–3.54	–3.54	0.14
10%	-3.20	-3.20	0.11

The co-integration test has been done to determine whether or not there is a long-term relationship between the variables. The results are given in Table 2. The existence of a long-term relationship has been determined in the table with the ADF value, which is bigger than the critical values [33] as an absolute value, and the p-value is smaller than 0.05. The existence of the long-term relationship has been determined at a rate of 1%, which is a very strong rate.

Table 2. Co-integration test results for Cocos Island station.

Regression model	For 10 hPa	
	ADF	p-Value
Model	–6.74	0.00
Significance levels	McKinnon (1996) critical values	
1%	–2.63	
5%	–1.95	
10%	–1.61	

After the existence of a long-term relationship is determined, our regression model equation given in Eq. (1) has been updated as follows by considering the stationary analysis for all stations:

For Cocos Island station,

$$\begin{aligned} D(\text{foEs}) &= \beta_0 + \beta_1 D(\text{QBO}) + \beta_2 \text{DummyEast} \\ &\quad + \beta_3 \text{DummyWest} + \varepsilon, \end{aligned} \tag{2}$$

for Gibilmanna station,

$$\begin{aligned} \text{foEs} &= \beta_0 + \beta_1 D(\text{QBO}) + \beta_2 \text{DummyEast} \\ &\quad + \beta_3 \text{DummyWest} + \varepsilon, \end{aligned} \tag{3}$$

for Niue Island station,

$$\begin{aligned} D(\text{foEs}) &= \beta_0 + \beta_1 D(\text{QBO}) + \beta_2 \text{DummyEast} \\ &\quad + \beta_3 \text{DummyWest} + \varepsilon, \end{aligned} \tag{4}$$

for Tahiti station,

$$\begin{aligned} D(\text{foEs}) &= \beta_0 + \beta_1 D(\text{QBO}) + \beta_2 \text{DummyEast} \\ &\quad + \beta_3 \text{DummyWest} + \varepsilon. \end{aligned} \tag{5}$$

The regression analysis results calculated with the help of the model are given in Table 3. The accuracy of the model is supported with the values given in the four lines at the bottom of Table 3. It is necessary that the Durbin Watson value here is between 1.5 and 2.5; the Prob. (F-statistics) value is below 0.05; and the Serial Cor. LM and White Het. values are bigger than 0.05. The expressions given in parenthesis under each variable in the table provide the significance value of the results given for the variable.

Nearly 69% of the changes (Adj. R^2) in foEs can be explained with QBO and Dummies in the model established with QBO at 10 hPa altitude in Cocos Island station. In this explanation, 1 m/s increase/decrease in QBO causes 0.007 MHz increase/decrease in foEs. It is observed that the Dummy values,

which represent both directions of QBO, are significant in the change of foEs. Atici and Sagir [7] investigated the foE–QBO relationship for this station, and found the relationship to be 50% (Adj. $R^2 = 0.50$), and the relationship coefficient to be −0.008.

In the model established for Gibilmanna station with QBO at 10 hPa altitude, 94% of the changes in foEs, as a significant rate, can be explained with QBO and Dummies. In this explanation, an increase/a decrease of 1 m/s in QBO causes an increase/a decrease at a rate of 0.01 MHz in foEs. It is seen that the Dummy values that represent both directions have an effect in foEs change.

Table 3. The regression analysis results at the Cocos Island, Gibilmanna, Niue Island, and Tahiti stations for QBO values obtained at 10 hPa altitude.

Coefficients	Cocos Island	Gibilmanna	Niue Island	Tahiti
β_0 (constant)	4.91	3.52	3.68	2.90
	(0.00)[a]	(0.00)[a]	(0.00)[a]	(0.00)[a]
β_1 (D(QBO))	0.007	0.01	0.01	0.02
	(0.09)[c]	(0.00)[a]	(0.06)[b]	(0.02)[b]
AR (1)	0.06	0.72	0.63	0.586
	(0.01)[a]	(0.00)[a]	(0.00)[a]	(0.00)[a]
β_2 (DummyEast)	4.91	3.52	3.68	2.90
	(0.00)[a]	(0.00)[a]	(0.00)[a]	(0.00)[a]
β_3(DummyWest)	4.99	3.34	3.64	2.60
	(0.00)[a]	(0.00)[a]	(0.00)[a]	(0.00)[a]
R^2	0.76	0.97	0.85	0.65
Adj. R^2	0.69	0.94	0.79	0.58
Durbin Watson	1.96	2.25	2.01	1.74
Prob. (F-statistics)	0.00	0.00	0.00	0.00
Serial Cor. LM	0.55	0.42	0.54	0.74
White Het.	0.49	0.65	0.92	0.55

[a]1% significance level.
[b]5% significance level.
[c]10% significance level.

In Niue Island station, 79% of the changes in foEs, as a significant rate, can be explained with QBO and Dummies in the model established with QBO. An increase/a decrease of 1 m/s in QBO causes an increase/a decrease at a rate of 0.01 MHz in foEs. It is also observed that the Dummy values are significant in the change of foEs. Nearly 58% of the changes in foEs can be explained with QBO and Dummies in the model established with QBO at 10 hPa altitude in Tahiti station. A positive relationship is observed between foEs and QBO at this altitude. In this situation, an increase/a decrease of 1 m/s in QBO causes an increase/decrease at a rate of 0.01 MHz in foEs. It is observed that the Dummy values that represent both sides are significant in foEs change.

The existence of the relationship between QBO and foEs measured at 10 hPa altitude is mentioned, and the coefficients are 0.47, 0.46, 0.32, and 0.44 for Jicamarca, Ascension, Manila, and Kwajealin Stations, respectively.[8] In addition, it is also mentioned from their investigation of the relationship between QBO and the other ionospheric parameters that the QBO might have an influence on the ionosphere. The relationship coefficients in these studies are also reported by other researchers: 0.704 from the investigation of the relationship between QBO and TEC values,[5] 0.65 from the investigation of the relationship between QBO and foF2,[25] and 0.65 for Okinowa Station, and 0.67 for Tucuman Station.[26]

3.2. Results for QBO obtained at 70 hPa altitude

The unit root test results at the Cocos Island station for QBO and foEs values obtained at 70 hPa altitude are given in Table 4. In order for stationary status to occur in this test, the absolute value of the variable given in the upper part of the table for each variable must be bigger than the critical values given at the bottom part of Table 4.[33] It is observed from the analysis of the values in the table that both variables at 70 hPa altitude are not stable in ADF and PP tests. For this reason, the first differences (D(QBO), D(foEs)) of the variables have been taken in order to make them become stable.

The co-integration test is made to determine whether there is a long-term relationship between the variables. The results are given in Table 5. The existence of a long-term relationship has been determined in the table with the ADF value, which is bigger than the McKinnon[33] critical values as an absolute value, and the p value is lower than 0.05. The existence of a long-term relationship has been determined at a very strong rate of 1%.

After the determination of a long-term relationship, equations (2)–(5) are updated depending on the stationary status of the variables. The results are obtained as shown in Table 6.

Table 4. The unit root test results for Cocos Island station.

Variables	Tests for 70 hPa		
	ADF	PP	KPSS
QBO	–1.74	–2.00	0.12
foEs	–2.99	–2.90	0.15
D (QBO)	–4.80	–4.80	0.07
D (foEs)	–6.63	–8.93	0.05
Significance levels	McKinnon (1996) critical values		
1%	–4.24	–4.24	0.21
5%	–3.54	–3.54	0.14
10%	–3.20	–3.20	0.11

Table 5. Co-integration test results for Cocos Island station.

Regression model	For 70 hPa	
	ADF	p-Value
Model	–3.98	0.00
Significance levels	McKinnon (1996) critical values	
1%	–2.63	
5%	–1.95	
10%	–1.61	

Table 6. The regression analysis results at all stations for QBO values obtained at 70 hPa altitudes.

Coefficients	Cocos Island	Gibilmanna	Niue Island	Tahiti
β_0 (constant)	–0.01	3.66	3.33	3.05
	(0.01)[a]	(0.00)[a]	(0.00)[a]	(0.00)[a]
β_1 (D(QBO))	–0.01	0.05	0.02	–0.04
	(0.01)[a]	(0.02)[b]	(0.00)[a]	(0.09)[b]
AR (1)	–	0.60	–0.85	–0.04
	(0.00)[a]	(0.49)	(0.00)[a]	(0.85)
β_2 (DummyEast)	4.73	3.66	3.33	3.05
	(0.00)[a]	(0.00)[a]	(0.00)[a]	(0.00)[a]
β_3 (DummyWest)	4.50	3.61	3.55	3.07
	(0.00)[a]	(0.00)[a]	(0.00)[a]	(0.00)[a]
R^2	0.70	0.77	0.63	0.59
Adj. R^2	0.66	0.69	0.53	0.47
Durbin Watson	2.31	2.00	1.89	1.65
Prob. (F-statistics)	0.00	0.00	0.00	0.00
Serial Cor. LM	0.06	0.92	0.80	0.42
White Het.	0.30	0.24	0.19	0.86

[a]1% significance levels.
[b]5% significance level.
[c]10% significance level.

For Cocos Island station, in the model established with QBO at 70 hPa altitude, nearly 66% (Adj.R^2) of the changes in foEs can be explained with QBO and Dummies. An increase/a decrease of 1 m/s in QBO causes an increase/a decrease at a rate of 0.01 MHz in foEs. It is observed that the Dummy values are significant in the change of foEs.

For Gibilmanna station, nearly 69% of the changes in foEs can be explained with QBO and Dummies. An increase/a decrease of 1 m/s in QBO causes a 0.05 MHz increase/ decrease in foEs. It is observed that the Dummy values are significant in the change of foEs.

For Niue Island station, nearly 53% of the changes in foEs can be explained with QBO and Dummies. There is a positive relationship between QBO and foEs. This means that an increase/a decrease of 1 m/s in QBO causes an increase/a decrease of 0.05 MHz in foEs. In addition, it is observed that the dummy values are significant in the change of foEs.

For Tahiti station, nearly 47% of the changes in foEs can be explained with QBO and Dummies. A negative relationship is observed between foEs and QBO at 70 hPa altitude. This means that an increase/a decrease of 1 m/s in QBO causes an increase/a decrease of 0.05 MHz in foEs. In addition, it is observed that the dummy values are significant in the change of foEs.

When the relationship between the QBO and foEs obtained at 10 hPa and 70 hPa altitudes are compared, it is observed that the relationship coefficient (Adj. R^2) between the QBO and foEs obtained at 10 hPa altitude is higher than that at 70 hPa. This result can be explained by two possible reasons. First, the QBO values measured at 10 hPa altitude can be greater than those at 70 hPa altitude. Second, the 10 hPa altitude is closer than 70 hPa altitude to the sporadic-E altitude. Besides, it is observed that the effect of QBO on foEs at 10 hPa is positive in all stations whereas it is negative in Cocos Island and Tahiti Stations at 70 hPa.

In addition, it has also been observed from the β_0 coefficient that is not included in the model that the influences from the sun, cosmic influences, regional influences, and the other atmospheric influences like lightning[34,35] are much higher than the influence of the full set of QBO for both altitude values at all stations.

4. Conclusions

The ionosphere is affected by the forces coming from lower atmosphere and solar activities. Although the sun is the source of the changes occurring in the ionosphere, there are also other sources that occur via the vertical duplication coming from lower atmosphere[3–8,35] and these sources are not negligible. In this context, the QBO is transferred as energy and momentum from the stratosphere to the mesosphere through Rossby-Gravity, Kelvin, gravity, and inertia-gravity waves.[12] This transferred energy and momentum affect the electron density (thus foEs) of ionospheric E-region and sporadic-E layer.[8]

The following results have been obtained by studying the relationship between QBO and foEs.

(i) QBO and foEs are related to each other in all stations involved;

(ii) The changes in foEs can be explained by the fact that the QBO measured at 10 hPa altitude is higher than that at 70 hPa altitude;

(iii) QBO measured at 10 hPa altitude has a positive relationship with foEs;

(iv) QBO at 70 hPa and foEs are in negative relationship at Tahiti and Cocos Island stations, whereas they are in positive relationship at Niue Island and Gibilmanna stations;

(v) The β_2 (DummyEast) and β_3 (DummyWest), which show the directions of QBO, are influential in explaining foEs;

(vi) The changes in foEs can be explained by QBO measured at 10 hPa altitude for Cocos Island station at a rate of 69%, for Gibilmanna station at a rate of 94%, for Niue Island station at a rate of 79%, and for Tahiti station at a rate of 58%;

(vii) It has also been observed that the changes in foEs can be explained by QBO measured at 70 hPa altitude for Cocos Island station at a rate of 66%, for Gibilmanna station at a rate of 69%, for Niue Island station at a rate of 53%, and for Tahiti station at a rate of 47%.

References

[1] Rishbeth H and Garriott O K 1969 *Introduction to Ionospheric Physics* (New York: Academic Press)
[2] Rishbeth H 1973 *J. Atmos. Sol.-Terr. Phys.* **1** 47
[3] Sagir S, Karatay S, Atici R, Yesil A and Ozcan O 2015 *Adv. Space Res.* **55** 106
[4] Sağir S, Atici R, Özcan O and Yüksel N 2015 *Ann. Geophys.* **58** A0331
[5] Tang W, Xue X H, Lei J and Dou X K 2014 *J. Atmos. Sol.-Terr. Phys.* **107** 36

[6] Yiğit E, Knížová P K, Georgieva K and Ward W 2016 *J. Atmos. Sol.-Terr. Phys.* **141** 1
[7] Atici R, and Sagir S 2016 *Adv. Space Res.* **10** 012
[8] Atici R and Sagir S 2016 *J. Phys. Sci. App.* **6** 10
[9] Canyilmaz M, Atici R and Guzel E 2013 *Acta Phys. Pol. A* **123** 78
[10] Kurt K, Yeşil A, Sağir S and Atici R 2016 *Acta Geophys.* **64** 61
[11] Lastovicka J 2006 *J. Atmos. Sol.-Terr. Phys.* **68** 479
[12] Mohanakumar K 2008 *Stratosphere Troposphere Interaction* (Doc. Goghin: Springer)
[13] Schunk R and Nagy A 2009 *Ionospheres: Physics, Plasmaphysics, and Chemistry* (Cambridge University Press)
[14] Sağir S, Yesil A, Sanac G and Unal I 2014 *Ann. Geophys.* **57** A0216
[15] Yiğit E and Medvedev A S 2015 . *Adv. Space Res.* **55** 983
[16] Matsushita S 1962 *Ionospheric Sporadic E* (New York: A Pergamon-Press) p. 344
[17] Bowhill S A 1966 *Radio Sci.* **1** 248
[18] Whitehead J D 1970 *Rev. Geophys.* **8** 65
[19] Matushita S and Reddy C A 1968 *J. Atmos. Terr. Phys.* **30** 747
[20] Farley D T 1963 *J. Geophys. Res.* **68** 6083
[21] Waldteufel P 1965 *Ann. Geophys.* **21** 579
[22] Axford W I and Cunnold D M 1968 *Radiosci. New Series* **2** 191
[23] Baldwin M, Gray L, Dunkerton T, Hamilton K, Haynes P, Randel W, Holton J, Alexander M, Hirota I and Horinouchi T 2001 *Rev. Geophys.* **39** 179
[24] Heaps A, Lahoz W and O'Neill A 2000 *Department of Meteorology*, University of Reading UK
[25] Chen P 1992 *Geophys. Res. Lett.* **19** 1089
[26] De Artigas M Z, de Adler N O and Elias A G 2004 *Geofísica Int.* **43** 199
[27] Echer E 2007 *J. Atmos. Sol-Terr. Phys.* **69** 621
[28] Xiao Q, Wang S, Zhang Z and Xu J 2015 11*th International Conference on Computational Intelligence and Security (CIS)*, 19 - 20 Dec 2015, Shenzhen, China, pp. 215–218
[29] http://strat-www.met.fu-berlin.de
[30] http://spidr.ionosonde.net/spidr
[31] Pancheva D V and Mukhtarov P Y 1996 *Ann. Geophys.* **39** 807
[32] Ikubanni S O, Adeniyi J O and Obrou O K 2014 *Adv. Space Res.* **53** 635
[33] MacKinnon J G 1996 *J. App. Econometrics* **11** 601
[34] Haldoupis C 2012 *Space Sci. Rev.* **168** 441
[35] Atici R, Güzel E, Canyilmaz M and Sağir S 2016 *Kuwait J. Sci.* **43** 143