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The Effect on Sporadic-E of Quasi-Biennial Oscillation

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Abstract: In this study, the relationship between the QBO (quasi-biennial oscillation), which is seen at the equatorial stratosphere, and critical frequency of layer (Es) sporadically observed at the ionospheric E region was analyzed by using multiple regression model. For this analysis, Es layer critical frequency (foEs) obtained from four different stations at equatorial region and QBO measured at 10 hPa altitude values were used. The positive relationship between foEs and QBO was observed at all stations. An increase of 1 m/s at QBO leads to an increase of 0.01 Mhz, 0.02 Mhz, 0.02 Mhz and 0.01 Mhz (Jicamarca, Ascension, Manila and Kwajalein) on foEs, respectively. Expect for Manila station, westerly phase of QBO has greater effect on foEs compared to easterly phase of QBO at all other stations. It is seen that the changes occurred on foEs can be explained by the QBO at rates 47%, 46%, 32% and 44% for Jicamarca, Ascension, Manila and Kwajalein stations, respectively.

Key words: Sporadic E, QBO, multiple regression model, ionospheric E-Region.

1. Introduction

Ionospheric E region has a relatively higher electrical conductivity and therefore plays a crucial role in the ionosphere electron dynamics. Under some certain, a thin layer of enhanced ionization would appear in the E region, which named as sporadic E, Es. Es has been considered widely both theoretically and experimentally in the past century. The occurrence of Es is controlled by multiple factors, including tidal wind, Earth's geomagnetic field, and meteoric deposition of metallic material in the background thermosphere. These factors result in variations of Es occurrence with respect to local time, altitude, latitude, longitude, and season [1]. It is usually accepted that Es is composed of metallic ions of meteoric basis converged vertically mainly by a wind shear particularly in the middle latitude region [2, 3]. The wind shear theory has been confirmed by many independent observations and simulations [1, 4]. However, this theory fails at the dip equator where the Earth's magnetic field is nearly horizontal [5]. Reddy and Devasia [6] proposed theories to explain the formation of Es at equatorial latitudes, which are based on the horizontal convergence of ions. Furthermore, in the high latitude region, the occurrence of Es is more significantly influenced by the local electric field rather than the wind shear due to the geomagnetic field difference [7, 8].

In recently carried out the study, it is emphasized that there is now enough evidence to suggest that mid- and low-latitude sporadic *E* is not as "sporadic" as the name implies but a regularly occurring ionospheric phenomenon. This may suggest that the sporadic *E* layer physics can be incorporated in large-scale atmosphere-ionosphere coupling models [9]. One of the most significant large-scale atmospheric phenomena is the QBO (quasi-biennial oscillation) represented by the cyclical exchange of zonal wind direction in the equatorial lower stratosphere. The QBO as energy and momentum is transferred from the lower stratosphere to the upper stratosphere through gravity and inertia-gravity waves, and from the upper stratosphere to the mesosphere through Rossby-Gravity and Kelvin waves (see Fig. 1) [10]. The presence of the QBO in the equatorial zonal wind, which affects the whole stratosphere, is the cause to

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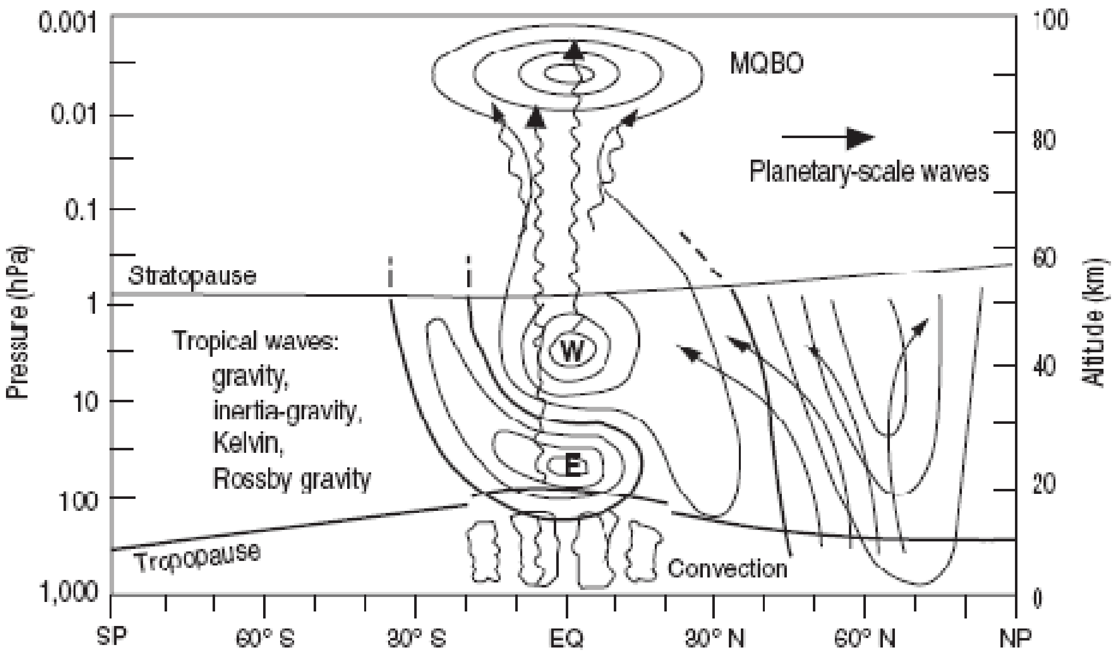

Fig. 1 The atmospheric waves affecting to spread of the QBO [10, 12].

investigate a predictable impact of this phenomenon on ionospheric parameter variations with the same periods. If one suggests that this effect is possible, its mechanism may be highly complicated because dynamic processes of shorter time-based scale may mediate a QBO effect in ionosphere. Thus, equatorial stratospheric QBO may influence on activity of the 10-30-day planetary waves in the mid-latitude MLT-region [11].

In this study, the effect on sporadic-E critical frequency (foEs) of QBO which is one of the most significant large-scale atmospheric phenomena was statistically investigated. In this context, a multiple regression analysis was used to explore the relationship between the variables.

2. The Statistical Analysis

A multiple regression [13, 14] is used for data processing and to collect observations of well-defined data items obtained through repeated measurements over time. This 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 this serie is made stationary by calculating the first order of D(QBO) (difference of QBO). There are three basic tests that are commonly used in the statistical studies for stationarity, namely ADF (Augmented-Dickey Fuller Test), PP (Phillips-Perron Test) and KPSS (Kwiatkowski-Phillips-Schmidt-Shin Test). 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 [13, 14]:

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

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 eliminate the auto-correlation in the model. Instead, it is adapted by the Newey-West estimator [13]. 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 [15]. 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 [13].

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 [16]. In the first stage of the Engle-Granger method, a relationship between the variables is estimated by the OLS (Ordinary Least Square) method. 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 [14].

By taking into account that QBO is a wind, Dummy Western (positive marked QBO) representing the western direction of QBO and Dummy Eastern (negative marked QBO) representing the eastern direction of QBO are also included in the model [14].

In this study, the statistical analysis model is given as follows:

$$\mathrm{foEs} = c + \beta_1 D(\mathrm{QBO}) + \beta_2 \mathrm{Dummy\ Western} + \beta_3 \mathrm{Dummy\ Eastern} \qquad (2)$$

where c is constant, β_0, β_1 and β_2 denote the variable coefficients. Firstly, E region critical frequency (foEs) data which are dependent variable were taken from associated stations (Ascension, Jicamarca, Kwajalein and Manila) (SPIDR (data available at http://spidr.ngdc.noaa.gov)). QBO measured at 10 hPa height in the Singapore stations (data available at the http://strat-www.met.fu-berlin.de/en/met).

3. Results and Discussion

This study carried out by accepting QBO being one of meteorological phenomena affecting the occurance of sporadic-E region [11]. In this study, stations in the equatorial region, where the presence of QBO is clearly observed, were selected. Eq. (2) was applied to the data sets to investigate the effect of the stratospheric QBO on foEs. The monthly mean values of QBO and foEs data were used for the study. The monthly medians [17, 18] of foEs values obtained for lacking values in the data sets were adapted to the QBO data.

The variations of stratospheric QBO and foEs to years are shown in Fig. 2. The changes, according to years of QBO and foEs measured at Ascension station, are given in Fig. 2a. A clear relationship was not observed between foEs and westerly QBO. A positive relationship between foEs and easterly-QBO was generally observed.

Changes of QBO and foEs measured at Jicamarca station to years are shown in Fig. 2b. It is seen that the period of QBO is about 28-29 month in the figure. However, several increases and decreases in critical frequency are observed during this time. A positive relationship between foEs and westerly-QBO is commonly observed. There is usually a negative relationship between foEs and easterly-QBO.

Changes of QBO and foEs measured at Kwajalein station to years are illustrated by Fig. 2c. Generally, relationship between QBO and foEs in the first and

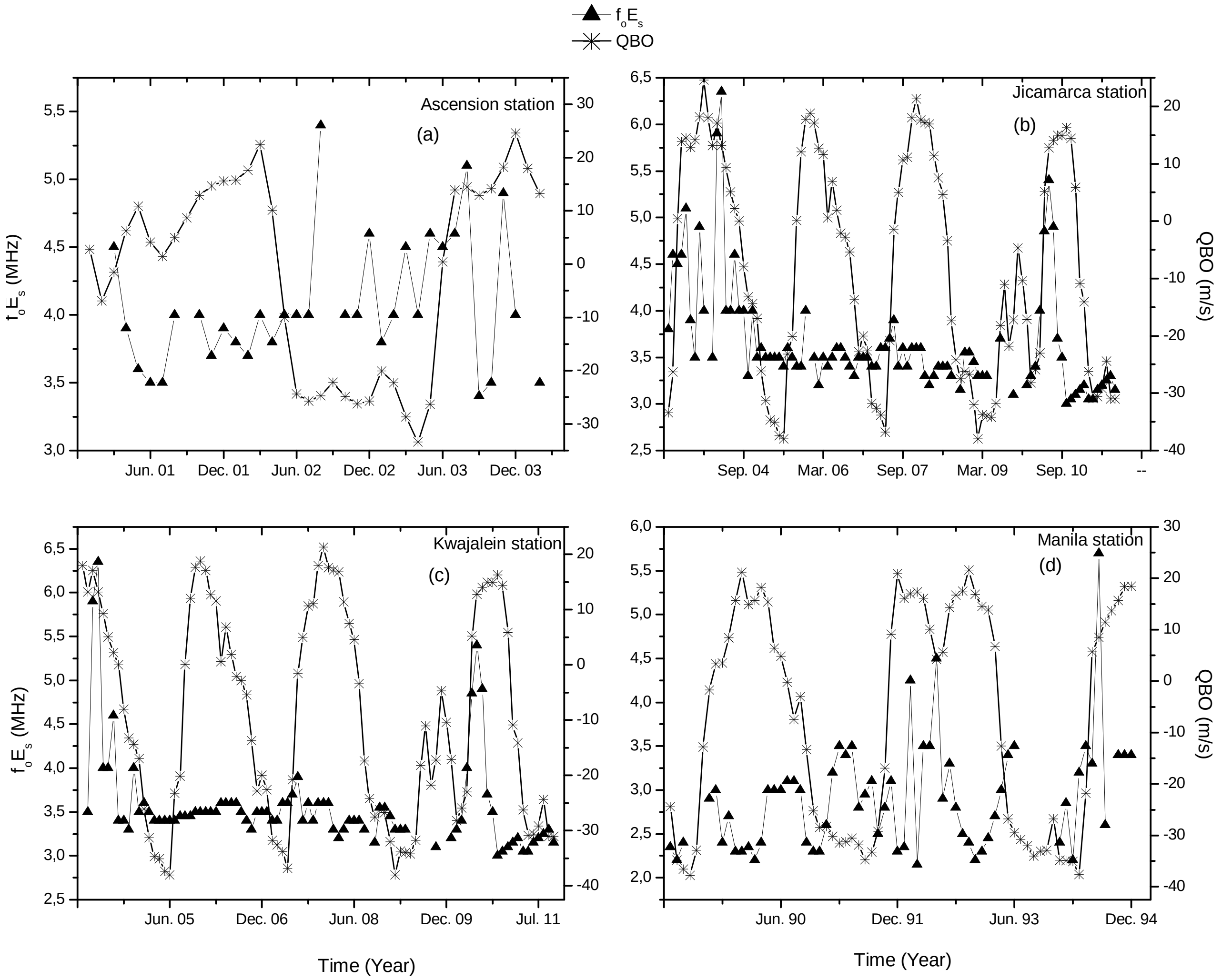

Fig. 2 The variation with years of relationship between QBO obtained at 10 hPa altitude and foEs calculated at Ascension, Jicamarca, Kwajalain and Manila stations.

last QBO period for the westerly-QBO was positive, while a clear relationship was not observed in other periods. There was usually a negative relationship between foEs and easterly QBO.

Changes of QBO and foEs measured at Manila station according to years are given in Fig. 2d. A positive relationship was generally observed between foEs and westerly-QBO, while there was usually a negative relationship between foEs and easterly QBO.

The first condition to determine the existence of a relationship between variables is to determine whether they are stationary or not. The method to determine this is to look at their unit root test results. Therefore, the unit root test was applied to all stations, but only unit root test results of Jicamarca station are given below.

Unit root test results for Jicamarca station are given in Table 1. According to test results, foEs values are stationary for all three tests. However, it is observed that QBO values were low of stationary levels in ADF and PP tests and were not stationary in KPSS test. Therefore, the first D(QBO) was taken to make the stationary of its values, and it was taken into account to Eq. (2).

After we set up regression equation (Eq. (2)) with variables that defined to stationarity, we look at the co-integration test that indicates the significance of the established model.

Co-integration test results obtained by Eq. (2) are given in Table 2 for Jicamarca station. It is indicated that there is a relationship between variables because of p-values are smaller than 0.05 and the ADF values are greater than McKinnon critical values as the absolute values ($|-5.91| > |-2.63|$) and our model is significant at highest rate (1%).

Table 3 lists the results of the regression analysis for four stations used to the study. OLS (Ordinary Least Square) method estimates are consistent in the presence of heteroskedasticity, but the standard errors are no longer valid. The White Het. (White Heteroskedasticity) 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 ε 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

Table 1 The unit root test results for Jicamarca station.

Variables	ADF	PP	KPSS
QBO	-3.57	-3.34	0.03
foEs	-5.29	-5.31	0.15
D(QBO)	-6.31	-6.22	0.13
The level of significance	McKinnon [19] critical values		
1%	-4.05	-4.05	0.21
5%	-3.45	-3.45	0.14
10%	-3.15	-3.15	0.11

Table 2 The results of co-integration test for Jicamarca station.

	ADF	*p*-value
Model	-5.91	0.00
The level of significance McKinnon [19] critical values		
1%		-2.63
5%		-1.95
10%		-1.61

Table 3 Results of regression analysis for all stations.

	Jicamarca	Ascension	Manila	Kwajalein
c	3.19 (0.00)*	4.20 (0.00)*	2.58 (0.00)*	2.92 (0.00)*
β_1	0.01 (0.06)***	0.02 (0.02)**	0.02 (0.01)*	0.01 (0.03)**
β_2	0.97 (0.02)**	4.27 (0.00)*	2.58 (0.00)*	0.60 (0.03)**
β_3	0.81 (0.06)***	4.06 (0.00)*	2.73 (0.00)*	0.50 (0.08)***
AR (1)	0.54 (0.00)*	1.00 (0.01)**	-0.30 (0.03)**	-0.30 (0.03)**
R^2	0.51	0.62	0.43	0.50
Adj. R^2	0.47	0.46	0.32	0.44
Durbin Watson	1.80	2.39	2.19	1.61
Prob. (F-statistics)	0.00	0.04	0.00	0.00
Serial Cor. LM	0.06	0.46	0.51	0.61
White Het.	0.12	0.51	0.59	0.67

*, **, *** represent the significant level at 1%, 5%, and 10%, respectively.

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 [13, 14]. The results are significant for all stations.

In the model established for Jicamarca station, it is observed that β_1 and β_3 coefficients are statistically significant at rate of 10% and β_2 coefficient is significant at rate of 5%. The value of β_1 (0.01) represents that an increase of 1 meter per second of D(QBO) causes an increase of 0.01 MHz in foEs values. The value of Adj. R^2 (0.47) shows that 47% of changes in foEs according to this model can be explained by QBO. When the direction of the QBO is investigated, the coefficients of both direction of QBO are significant and their effects are higher than those whole set of QBO on foEs. When the QBO blows in eastern and the western direction, it has effect on foEs values. Westerly phase of QBO leads to more changes than easterly phase of QBO on foEs.

In the model carried out for Ascension station, it is observed that β_1 and β_3 coefficients are significant at rate of 1% and β_2 coefficient is significant at rate of 5%. The value of β_1 (0.02) represents that an increase of 1 meter per second of D(QBO) causes an increase of 0.02 MHz in foEs. When the direction of the QBO was investigated, the coefficients of both direction of QBO are significant. When QBO blows either the eastern or the western direction, this level of significance demonstrates that direction of QBO has an effect on foEs. Westerly phase of QBO leads to more changes than easterly phase of QBO on foEs. Also, large coefficient values of QBO phases (east-west) draw attention. It is indicated that Adj. R^2 value of 0.46 can be explained by QBO of 46% of changes on foEs values. The rest parts (54%), which cannot be explained in this model, are thought to be explainable by other parameter that we have not included in our model.

All coefficients in the model established for Manila station are significant at rate of 1%, which is the highest level of significant. This case is statistical evidence that our model could give more accurate results at this station. The value of β_1 (0.02) coefficient indicates that an increase of 1 meter per second in QBO gives rise to an increase of 0.02 MHz in foEs value. The large level of significance of coefficients, that indicate direction of QBO, shows effect on foEs of both its easterly and westerly values. The size of the coefficient values in any direction indicates that it requires to discrete in phases (east-west) of QBO rather than deal with as a whole of QBO and its direction is important. Easterly phase of QBO has more influence than its westerly phase on foEs contrast to the previous two stations in this station. Adj. R^2 value (0.32) is indicated that it can be explained by QBO of 32% of changes in foEs values. The rest part (68%), which cannot explained in this model are thought explainable by other parameters that we have not included in our model but it is hidden in c coefficient.

In the model established for Kwajalein station, it is observed that β_1 and β_2 coefficients are significant at rate of 5% and β_3 coefficient is significant at rate of 10%. The value of β_1 (0.01) coefficient indicates that an increase of 1 meter per second in D(QBO) leads to an increase of 0.01 MHz in foEs value. When the directions of QBO are analyzed, it is observed that the coefficients indicating both (east-west) wind directions are significant. This level of significance indicates that both easterly and westerly values of QBO affect the foes values. Also, the westerly phase of QBO has more influence than its easterly phase on foEs as in the first two stations at this station. The Adj. R^2 value (0.44) is indicated that it can be explained by QBO of 44% of changes in foEs values. The rest part (56%), which cannot explained in this model, are thought to be explainable by other parameters that we have not included in our model, but it is hidden in c coefficient.

When the results obtained are analyzed for all stations, it is observed that variable coefficients (c, β_1,

β_2 and β_3) are statistically significant. It is found out that β_1 coefficient which shows effect of whole set of QBO is smaller than β_2 and β_3 coefficients at the all stations, indicated the effect of phases (east-west) of QBO. The time interval used in our study covers the 3-6 QBO period. In this case, the analysis carried out by the whole set of the QBO (i.e., β_1 coefficient) includes the effects of both its western and its eastern directional phase. Thus, when the whole set of QBO (i.e. β_1 coefficient) taken into consideration, this case reduces its impact on foEs. Because of the β2 and β3 show eastern and western direction of QBO separately, these effects support each other since there are several oscillations at the same direction during each time interval used here, and thus, the effects on foEs of β2 and β3 will increase. It is obtained that the westerly phase of QBO has more effect than its easterly phase on foEs at all other stations apart from Manila station. This result is consistent with the results of Egorava [20] who expressed that Es values during westerly phase of QBO are higher 20% than easterly phase of QBO. It is observed that the effects based on directions of QBO on foEs are highest at Ascension station. Thus, usage of QBO not as a whole set but according to its directions will provide to obtain more accurate results in the sporadic-E studies. In addition, these obtained results represent that changes at foEs may be associated with QBO which is one of meteorological effects as suggested by [11]. QBO is an easterly-westerly wind and this wind effects on ionospheric-Es by atmospheric waves (planetary waves, tidal, gravity waves) [10, 12].

4. Conclusions

In this study, the relationship between QBO and the foEs obtained from four different stations in the equatorial region was analyzed by using multiple regression model. The results obtained can be summarized as follows:

Positive relationship was observed at all stations between whole set of QBO and foEs.

It was observed that both directions of QBO have positive effect on foEs at all stations.

An increase of 1 meter per second in QBO gives rise to an increase of 0.01 Mhz, 0.02 Mhz, 0.02 Mhz and 0.01 Mhz (at Jicamarca, Ascension, Manila and Kwajalein stations), respectively.

The westerly phase of QBO has more effect on foEs at Jicamarca, Ascension and Kwajalein stations than its easterly phase.

The changes that occur on foEs in Jicamarca, Ascension, Manila and Kwajalein stations can be explained by the QBO at rates 47%, 46%, 32% and 44%, respectively.

Also, other parameters (Geomagnetic and solar indices, lightning, earthquakes, tidal and waves given in Fig. 1 and so on.) that affect the foEs at all stations will be considered in next studies to include in this model.

Although all these statistical results do not give a physical mechanism, as noted in previous studies [14, 21], but QBO reaches MLT-region by atmospheric waves. And thus, it can be said that equatorial QBO has an impact on foEs.

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