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The Relationship of Stratospheric QBO with the Difference of Measured and Calculated NmF2

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Abstract

The relationship between stratospheric QBO and the difference (ΔNmF2) between NmF2 calculated with IRI-2012 and measured from ionosondes at the Singapore and Ascension stations in the equatorial region was statistically investigated. As statistical analysis, the regression analysis was used on variables. As a result, the relationship between QBO and ΔNmF2 was higher for 24:00 LT (local time) than 12:00 LT. This relationship is positive in the solar maximum epoch for both stations. In the solar minimum epoch, it is negative at 24:00 LT for Ascension and at 12:00 LT for Singapore. Furthermore, it was seen that the relationship of the ΔNmF2 with both the easterly and westerly QBO was negative for all solar epochs and every LT, at Ascension station. This relationship was only positive for solar maximum epoch and 12:00 LT, at Singapore station.

Key words: International Reference Ionosphere, QBO, NmF2, regression analysis.

1. INTRODUCTION

The empirical International Reference Ionosphere (IRI) model (Bilitza 2001) is actively used in a great variety of applied and research projects. It is well

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known that IRI is an empirical ionospheric model based on experimental observations of the ionospheric plasma, either ground-based or *in situ* measurements. In particular, IRI provides a basis for the simulation and prediction of the ionospheric radio wave propagation. The main purpose of IRI is to provide reliable ionospheric densities, composition, and temperatures (*e.g.*, Bilitza 2001, Bilitza *et al.* 1979). The IRI can be used as the "quiet ionosphere" reference in applications that detect and study ionospheric disturbances. The model takes into account daily and seasonal variations, as well as the impact of solar activity on ionospheric conditions.

The terrestrial ionosphere is a layer that starts at approximately 60 km and extends to about 1000 km above the planet's surface. This layer is generated due to the interaction between solar radiation and the atmospheric constituents (Rishbeth and Garriott 1969, Schunk and Nagy 2009). The electron density is one of parameters characterizing the ionospheric F region. The electron density at heights near the F2 layer could be more sensitive to changes of neutral composition, temperature, and horizontal winds (Buresova *et al.* 2014). One of the sources that affect the electron density are the dynamic processes in the lower atmosphere. The dynamic processes in the lower atmosphere affect the ionosphere through the electrical and electromagnetic waves and upward propagating waves in the neutral atmosphere. Upward propagating waves in the neutral atmosphere are the most important because they can store energy and have atmospheric modifications. The metrological effects in the ionosphere can be caused by upward propagating gravity waves, and tidal and planetary waves (Lastovicka 2006, Kazimirovsky *et al.* 2003).

The Quasi-Biennial Oscillation (QBO) is a quasi-periodic interannual oscillation of the tropical stratospheric zonal winds between easterlies and westerlies with a mean period of 28-29 months (Heaps *et al.* 2000, Baldwin *et al.* 2001). Easterly and westerly phase of QBO develops at the top of the stratosphere and propagates downward at ~1 km per month until they dissipate at the tropical tropopause (Lindzen 1987). The west phase of QBO whose amplitude is 10-20 m/s descends faster than the east phase of QBO whose amplitude is 20-30 m/s. The phases are coherent through the whole equatorial belt at any given time. Peak amplitudes are over the equator at an altitude of 24 km (~30 mb) and amplitudes decrease away from the equator. The QBO by means of the waves, as seen in Fig. 1, can influence the Mesosphere Lower Thermosphere (MLT) beyond the stratopause (Baldwin *et al.* 2001, Mohanakumar 2008). Then, it may affect the electrical field of ionospheric E region and, thus, QBO can reach up to the F layer along the geomagnetic field lines from the E region (Chen 1992).

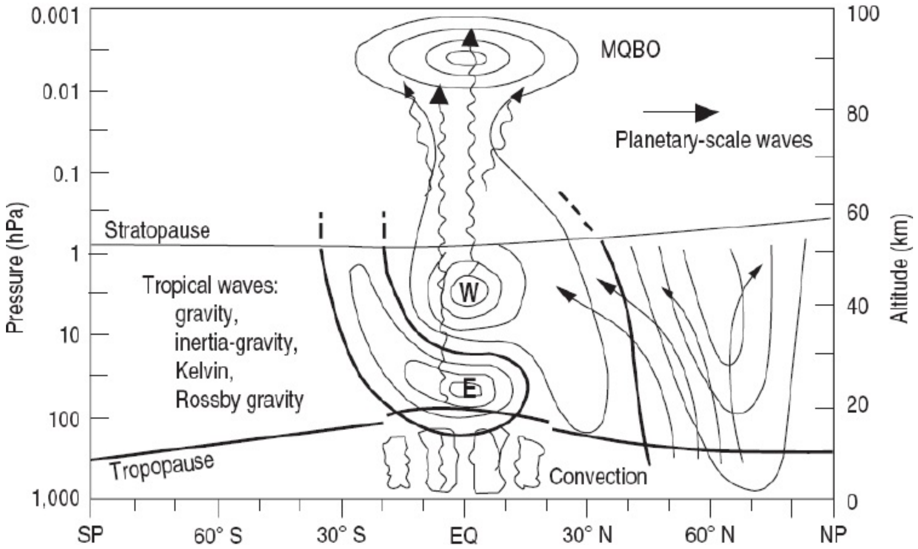

Fig. 1. The atmospheric waves affecting the spread of the QBO (Baldwin *et al.* 2001, Mohanakumar 2008).

In the present study, the relationship between QBO and difference (ΔNmF2) between NmF2 (maximum electron density of the ionospheric F2 region) calculated with IRI-2012 and measured at Singapore (01.22 °N, 103.55 °E) and Ascension (7.9 °S, 14.4 °W) stations in the equatorial region is statistically investigated. In this context, in order to study the relationship between variables, a multiple regression analysis is utilized.

2. THE STATISTICAL ANALYSES METHOD

A multiple regression analysis (Enders 2008, Sagir *et al.* 2015a, b) is used for processing of data measured at certain time intervals (Yadav *et al.* 2011). A prerequisite for this regression analysis is to determine the stability of variables. The stability of variables is determined by the Unit Root Test. 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 variables (D(QBO) and D(ΔNmF2)). Next stage is to determine whether there is a relationship between the dependent variable (foF2) and independent variable (QBO) or not. In this study, this condition is provided by co-integration test. If there is a long-term relationship between the variables, then the last stage is to establish the regression model to determine the coefficients of the variables (Sagir *et al.* 2015a, b). For more detail information associated with these tests, see Sagir *et al.* (2015a, b). Thus, the statistical analysis model is described by the following formula:

$$\mathrm{D}(\Delta\mathrm{NmF2}) = \mathrm{c} + \beta_0\left(\mathrm{D(QBO)}\right) + \beta_1\,\mathrm{Dummy\,Western} + \beta_2\,\mathrm{Dummy\,Eastern}\ , \quad (1)$$

where c is a constant, and β_0, β_1, and β_2 denote the variable coefficients. Dummy Western representing the western direction of QBO, and Dummy Eastern representing the eastern direction of QBO, are also included in the model (Sagir *et al*. 2015a, b).

To obtain NmF2 values, firstly, the F2 region critical frequency (foF2) data were taken from associated stations (SPIDR (data available at http://spidr.ngdc.noaa.gov)). foF2 is defined as the highest frequency at which radio waves can be transmitted vertically to the ionosphere and reflected by an ionospheric F region. It is denoted by f_c and defined as given in Hz, where NmF2 is the electron density in m^3 in the F2 region (Yesil *et al*. 2009). Then, these data were converted to NmF2 values through the formula $f_c = 9\times10^{-3}\sqrt{N_e}$. The obtained data were labeled "measured" data. Then, NmF2 values were calculated using the IRI-2012 model (URSI model was used as F-peak model) (http://omniweb.gsfc.nasa.gov/vitmo/iri2012) for the same stations at 12:00 LT and 24:00 LT. The obtained values were also called the "calculated" values. The difference (measured-IRI, ΔNmF2), which was not included in the IRI model, was calculated by subtracting the calculated NmF2 values from the measured NmF2 values. The relationship between determined ΔNmF2 values with QBO measured at 10 hPa height in the Singapore (for 1987 and the following years) and Canton Island (02.46 °S, 171.43 °W) (for the years between 1953 and 1965) stations (data available at the http://strat-www.met.fu-berlin.de/en/met) have been statistically investigated in solar maximum and solar minimum epochs.

3. RESULTS AND DISCUSSION

In this study, stations in the equatorial region, where the presence of QBO is clearly observed, were selected. Equation 1 given in Section 2 was applied to the data sets to investigate the effect of the stratospheric QBO on ΔNmF2. The monthly mean values of QBO and NmF2 data were used for the study. The monthly medians (Pancheva and Mukhtarov 1996, Ikubanni *et al.* 2014) of NmF2 values were adapted to the QBO data.

3.1 Results obtained for the Ascension station

The variations of ΔNmF2 and QBO for 24:00 LT and 12:00 LT have been indicated in Fig. 2 with graphs (a) and (c) for solar maximum and graphs (b) and (d) for solar minimum, respectively.

The time period from January 2001 to December 2003 was used for the solar maximum condition, and the period from January 2006 to December 2008 was used for the solar minimum condition (Kirov *et al.* 2014). In

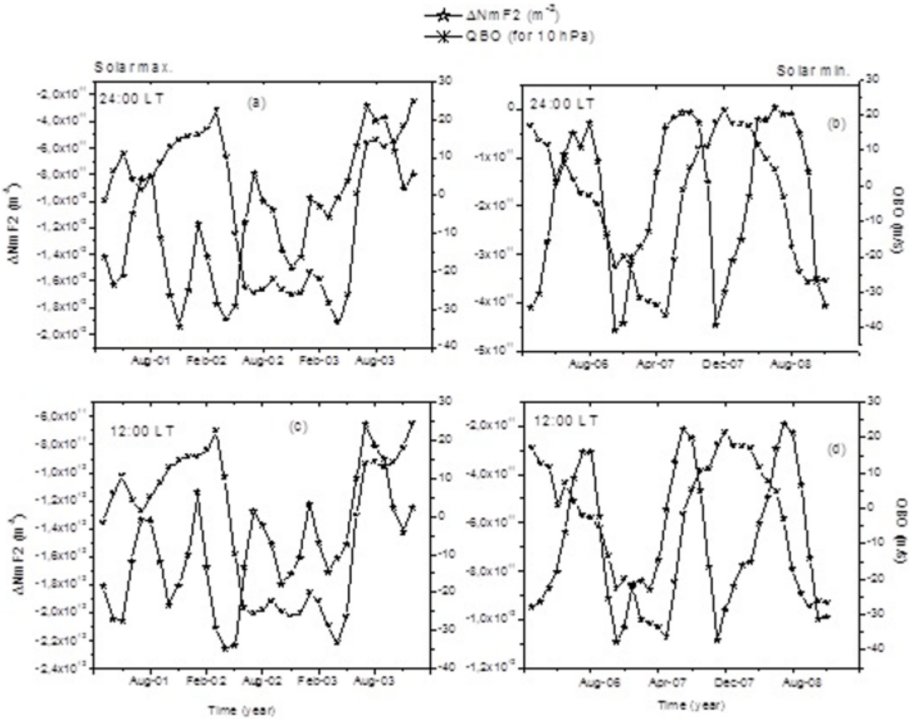

Fig. 2. The variation according to solar maximum and minimum cases of the relationship between QBO measured at 10 hPa altitude and ΔNmF2 for the Ascension station.

Fig. 2, for both times periods in the solar maximum epoch, while ΔNmF2 demonstrates a negative relationship for the easterly QBO (QBO values are less than zero), a positive relationship was observed for westerly QBO (QBO values are greater than zero). In the solar minimum epoch, a positive relationship was observed between westerly QBO and ΔNmF2. With regards to easterly QBO, a regular relationship was not observed at 24:00 LT; however, a positive relationship was observed for 12:00 LT in certain years.

Tables 1 and 2 give the unit root test results at Ascension in the solar maximum epoch for 24:00 LT and 12:00 LT, respectively. For the values to be stationary, each value given in the top section of the table should be larger in absolute values than the corresponding McKinnon (1996) critical values found at the bottom.

Table 1 shows that Δ(NmF2) and QBO contains the unit root in all three tests and the PP test with respect to their levels, respectively. So they are not stationary. Table 2 shows that Δ(NmF2) and QBO contain the unit root in Phillips–Perron Test (PP) and Kwiatkowski–Phillips–Schmidt–Shin Test

Table 1

The unit root test results at Ascension
in the case of solar maximum for 24:00 LT

Variables	for 24:00 LT		
	ADF	PP	KPSS
QBO	–4.25	–1.18	0.14
Δ(NmF2)	–0.48	–1.07	0.13
D(QBO)	–4.47	–2.49	0.20
D(Δ(NmF2))	–5.36	–5.60	0.50
The level of significance	McKinnon (1996) critical values		
1%	–4.27	–4.26	0.21
5%	–3.55	–3.55	0.14
10%	–3.21	–3.20	0.11

Table 2

The unit root test results at Ascension
in the case of solar maximum for 12:00 LT

Variables	for 12:00 LT		
	ADF	PP	KPSS
QBO	–0.48	–1.07	0.13
Δ(NmF2)	–5.08	–2.11	0.10
D(QBO)	–4.47	–2.49	0.20
D(Δ(NmF2))	–6.33	–5.63	0.38
The level of significance	McKinnon (1996) critical values		
1%	–4.27	–4.26	0.21
5%	–3.55	–3.55	0.14
10%	–3.21	–3.20	0.11

(KPSS) and Augmented–Dickey Fuller (ADF) and PP tests with respect to their levels (Kwiatkowski *et al.* 1992), respectively. So they are not stationary. The series become stationary in the first differences of QBO and Δ(NmF2) [D(QBO), D(Δ(NmF2))] in both tables.

Table 3 shows the co-integration test results obtained for the model in Eq. 1. Because the probability *p* values are smaller than 0.05 in the model and the ADF value is greater in absolute values than the McKinnon (1996)

Table 3

The co-integration test results for Ascension

Regression model	for 12:00 LT		for 24:00 LT	
	ADF	*p* value	ADF	*p* value
Model	–5.30	0.00	–6.20	0.00
The level of significance	McKinnon (1996) critical values			
1%		–2.65		
5%		–1.95		
10%		–1.60		

critical values at the bottom section of the table, $(|-5.30| > |-2.65|)$ for 12:00 LT and $(|-6.20| > |-2.65|)$ for 24:00 LT, there is a relationship between the variables. Furthermore, the level of statistical significance is at a rate of 1%.

Table 4 represents a multiple regression analysis results estimated by the model giving the relationship between QBO values at 10 hPa altitude and Δ(NmF2) for the Ascension in the solar maximum and minimum epochs.

Tables 4 and 5 list the results of the regression analysis. Ordinary Least Square (OLS) method forecasts are coherent 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 mutable has to also be greater than 0.05. The Durbin–Watson Test for serial correlation assumes that ε is stationary and normally perturbed with mean as zero. It tests the null hypothesis that the errors are not correlated and the values of variables require to be between 1.5 and 2.5. Probability (F statistics) (Prob. (F statistic)) tests the whole significance of the regression model and the value of this parameter has to be smaller than 0.05. Autoregressive (AR) processes have theoretical autocorrelation functions (ACFs) that decay toward zero, instead of cutting off to zero (Enders 2008, Sagir *et al.* 2015a, b).

An increase of 1 m/s in QBO measured at an altitude of 10 hPa in the solar maximum case for the Ascension station statistically leads to an increase of 7.6×10^{10} m^{-3} at 12:00 LT and a decrease of 1.64×10^{12} m^{-3} at 24:00 LT in Δ(NmF2). Furthermore, it is observed that easterly and westerly QBO causes a decrease in Δ(NmF2) for both LT. Similarly, QBO is more effective on Δ(NmF2) at 24:00 LT compared to 12:00 LT. The statistical relationship coefficient (R^2) is higher at night compared to the day.

Table 4

Regression analysis results for the Ascension station in the solar minimum and maximum epochs

Coefficient	Solar minimum epoch		Solar maximum epoch	
	for 12:00 LT	for 24:00 LT	for 12:00 LT	for 24:00 LT
c	–7.67E+11 (0.00)*	–2.51E+11 (0.00)*	–1.52E+12 (0.00)*	–6.8E+10 (0.74)
β_0	6.36E+9 (0.01)*	–3.24E+9 (0.05)**	7.6E+10 (0.00)*	–1.64E+12 (0.05)**
β_1	–8.13E+11 (0.00)*	–2.51E+11 (0.01)*	–1.52 E+12 (0.00)*	–1.64 E+12 (0.00)*
β_2	–7.67E+11 (0.00)*	–2.51E+11 (0.00)*	–1.51 E+12 (0.01)*	–1.71 E+12 (0.00)*
AR (1)	0.06 (0.59)	0.34 (0.24)	8.17E-6 (0.03)**	8.11E-6 (0.04)**
R^2	0.91	0.85	0.71	0.83
Adj. R^2	0.89	0.79	0.62	0.79
Durbin–Watson	1.66	1.77	2.06	2.14
Prob. (F statistics)	0.00	0.00	0.00	0.00
Serial Cor. LM	0.00	0.92	0.10	0.44
White Het.	0.07	0.15	0.08	0.41

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

An increase of 1 m/s in QBO measured at an altitude of 10 hPa in the solar minimum case for the Ascension station statistically leads to an increase of 6.36×10^9 m^{-3} at 12:00 LT and a decrease of 3.24×10^9 m^{-3} at 24:00 LT on Δ(NmF2). The easterly and westerly QBO lead to a decrease in both LT on Δ(NmF2). It is observed that QBO is more influential at 12:00 LT than at 24:00 LT on Δ(NmF2). The statistical relationship coefficient (R^2) is higher during the day compared to the night in a manner different to that in solar maximum. The relationship coefficient in the solar minimum epoch is greater than that of the solar maximum epoch.

The value of the Serial Correlation LM (Serial Cor. LM) test and the White Heteroskedasticity (White Het.) Test must be greater than 0.05. The Durbin–Watson Test value must be between 1.5 and 2.5. Probability (F-statistics) (Prob. (F-statistic)) must be smaller than 0.05 (Sagir *et al.* 2015a, b). Results of all these tests, given at the bottom of Table 4, indicate the accuracy of our model.

Table 5

Regression analysis results in the solar maximum and minimum epochs for the Singapore station

Coefficient	Solar minimum epoch		Solar maximum epoch	
	for 12:00 LT	for 24:00 LT	for 12:00 LT	for 24:00 LT
c	–6.68E+11 (0.00)*	–2.92E+11 (0.00)*	–4.24E+10 (0.09)***	–1.87E+12 (0.00)*
β_0	–6.60E+9 (0.03)**	1.20E+9 (0.09)***	4.48E+9 (0.06)**	–5.64E+9 (0.05)**
β_1	–7.12E+11 (0.00)*	–4.11E+11 (0.01)*	7.09E+10 (0.84)*	–1.75E+12 (0.00)*
β_2	–6.68E+11 (0.00)*	–2.92E+11 (0.00)*	4.24E+10 (0.91)*	–1.73E+12 (0.00)*
AR (1)	0.64 (0.54)	0.30 (0.24)	0.59 (0.54)	0.515 (0.01)*
R^2	0.64	0.79	0.75	0.89
Adj. R^2	0.58	0.69	0.69	0.84
Durbin–Watson	2.06	1.68	1.80	1.72
Prob. (F-statistics)	0.00	0.00	0.00	0.02
Serial Cor. LM	0.51	0.06	0.16	0.66
White Het.	0.46	0.91	0.12	0.07

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

Because the value of Prob. (F-statistic) in Table 4 is less than 0.05, it is shown that the model is meaningful. The *p* values in the model that are less than 0.1 (indicated by parenthesis) also show that the model is meaningful according to the variables. Since the Durbin–Watson value varies between 1.5 and 2.5 and the values of Serial Cor. LM and White Het. are greater than 0.05, as given in the bottom section of Table 4, these statistical parameters also support the accuracy of the model (Sagir *et al.* 2015a, b).

3.2 Results obtained for the Singapore station

The variation of ΔNmF2 and QBO for 24:00 LT and 12:00 LT, respectively, have been indicated in Fig. 3 with graphs (a) and (c) for solar maximum and graphs (b) and (d) for solar minimum. Data pertaining to the time periods from July 1958 to June 1961 and from January 1963 to December 1965 were used for the solar maximum and solar minimum epochs, respectively. In the

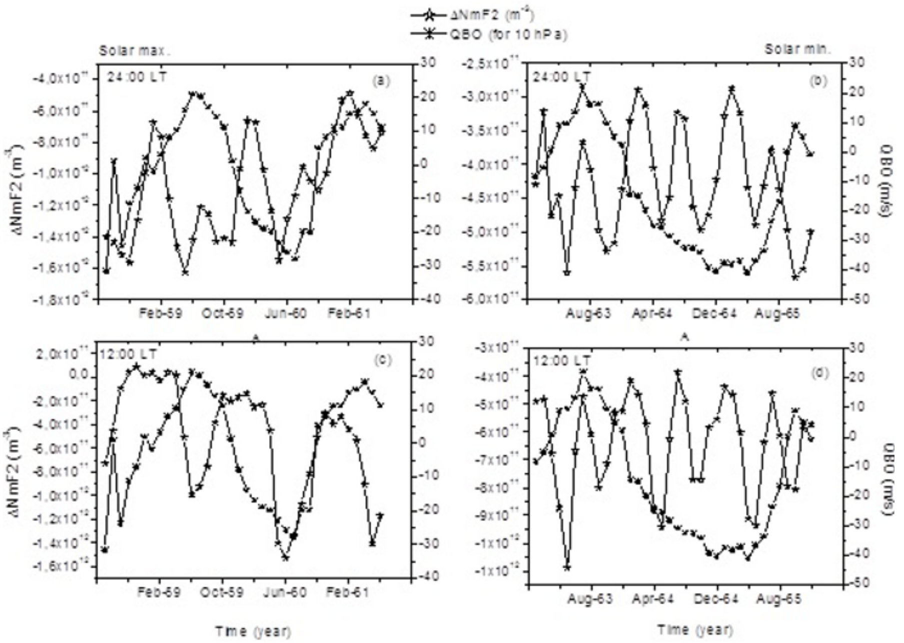

Fig. 3. The variation according to the solar maximum and minimum cases of the relationship between QBO measured at 10 hPa altitude and ΔNmF2 for the Singapore station.

solar maximum epoch, while QBO appeared to have a positive relationship for easterly 24:00 LT and a negative relationship for 12:00 LT, a negative relationship was observed for westerly QBO in both LT. With regards to the solar minimum epoch, a negative relationship is observed in both LT between both westerly and easterly QBO and ΔNmF2.

An increase of 1 m/s in QBO measured at an altitude of 10 hPa in the solar maximum case for the Singapore station statistically leads to an increase of 4.48×10^9 m^{-3} at 12:00 LT and a decrease of 5.64×10^9 m^{-3} at 24:00 LT in Δ(NmF2). Furthermore, it is observed that both the easterly and westerly QBO caused an increase in Δ(NmF2) for 12:00 LT and a decrease in Δ(NmF2) for 24:00 LT. QBO is more influential on Δ(NmF2) at 24:00 LT compared to 12:00 LT. The statistical relationship coefficient (R^2) between variables was higher at night compared to the day.

When the effect of QBO on Δ(NmF2) in the solar maximum case is compared between stations, it may be said that the QBO has a greater effect on electron density at the Ascension station.

For solar minimum epoch, an increase of 1 m/s in QBO for the Singapore station leads statistically to a decrease of 6.6×10^9 m^{-3} at 12:00 LT and an increase of 1.2×10^{9} m^{-3} at 24:00 LT in Δ(NmF2). It is observed that the easterly and westerly QBO lead to a decrease on Δ(NmF2) for both LT. Similarly, QBO has a greater effect on Δ(NmF2) at 12:00 LT compared to 24:00 LT. The statistical relationship coefficient (R^2) is higher at night compared to daytime. The relationship coefficient in the solar minimum epoch is lower than that of the solar maximum epoch.

The previous study (Lühr and Xiong 2010), that investigated the differences between the ionosonde data with the IRI-model, emphasized that the IRI model overestimated the electron density. The reason for this overestimation could be lower atmospheric effects, such as QBO, that were not induced to the IRI model, in the equatorial region.

4. CONCLUSION

In order to emphasize the need to include QBO in the IRI model, the relationship between Δ(NmF2) and QBO was statistically investigated in this study. Within this context, a multiple regression analysis was performed in order to investigate the relationship between variables. Obtained results have demonstrated a statistically high relationship between QBO with Δ(NmF2) in the solar maximum and minimum epochs for both LT. This statistical relationship is greater at night in both the Ascension and Singapore stations at solar maximum epoch. Under solar minimum epoch, this relationship is higher during the day at the Ascension station and during the night at the Singapore station. The overestimation of electron density, in the equatorial region of the semi-empirical IRI model, is an issue addressed by some authors (*e.g.*, Lühr and Xiong 2010). Even though these obtained statistical results do not propose any physical mechanism concerning the relationship between variables, the difference of the electron density between the values obtained with the IRI model and the values obtained by the ionosonde may be said to be due to QBO, especially in the equatorial regions. This case indicates that QBO needs to be added to IRI-model.

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