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The Effect of IMF-Bz and F10.7 Solar Flux on Neutral Molecule Density of Ionospheric E-Region

Ramazan Atıcı[1] and Serhat Korlaelçi[2]

1. The Department of Basic Education, Mus Alparslan University, Mus 49250, TURKEY

2. The Department of Physics, Mus Alparslan University, Mus 49250, TURKEY

Abstract: In this study, the relationship between the neutral components (N_2 and O_2) in the E-region of the ionosphere (at 110 km altitude) for the Singapore (01.23 N; 103.55 E) station in the equatorial region and the F10.7 solar flux and z-component of Interplanetary Magnetic Field (IMF-Bz) was investigated. This relationship was determined by means of statistical multiple regression model. As a result, it was observed that the changes in F10.7 solar flux and IMF-Bz were inversely proportional to the changes in N_2 and O_2. 92% and 83% of changes in N_2 and O_2 were found to be explained by F10.7 solar flux and IMF-Bz, respectively. When the F10.7 solar flux is changed by 1 s.f.u., it causes a decrease of 2.61×10^{14} m^{-3} in N_2 and 2.96×10^{14} m^{-3} in O_2. Change of 1 nT in IMF-Bz causes a decrease of 9.95×10^{15} m^{-3} in N_2 and 1.69×10^{15} m^{-3} in O_2.

Key words: Dynamo region, F10.7 solar flux, IMF-Bz, ionospheric-E-region, neutral density.

1. Introduction

The ionosphere is affected by a variety of processes from below (meteorological processes) [1-9] and from above (such as solar, magnetospheric and geomagnetic processes) [10-12]. The Earth's ionosphere is a partially ionized gas that surrounds the Earth, a transition zone between the atmosphere and space. The ionosphere is divided into different regions called D, E and F at all latitudes according to electron density. The different regions are generally characterized by a density maximum and by a density reduction at a certain height at both sides of the maximum. In D and E regions, chemical processes are very important and suppress molecular ions. N_2, O_2 and O are the most abundant neutral species. The basic chemical reactions in E region are not complicated. The total ion concentration in this region is 10^{11} m^{-3} while the neutral density is greater than 10^{17} m^{-3} [13]. For this reason, the neutral density is more dominant in the E-region. Through ionization and ion-neutral-electron collisions, the neutral density is very important in terms of basic ionospheric properties such as density, conductivity, refraction index, diffusion in E-region where it is the dynamo region. This region is affected by different external sources at daytime and nighttime. Daytime E-layer is very stable due to strong solar control. In addition to electromagnetic wave radiation, the Sun continuously emits energy-charged particles (mainly protons and electrons). These particles interact with the geomagnetic field in a complex way and with gases in the upper atmosphere [14]. The Sun ionizes neutral components, especially in the daytime, causing an increase in electron and ion density in this region. With this increased density, the conductivity of the dynamo region increases, and this conductivity effects up to the upper ionosphere along geomagnetic field lines of the Earth. Thus, the neutral density of the dynamo region affects the F2 region, which is an important region for radio wave communication [6, 7, 15].

This study will determine the effect of the solar processes on the neutral components of the

Corresponding author: Ramazan ATICI, Ph.D., assistant professor, research fields: plasma physics, ionospheric physics, electromagnetic waves, QBO.

ionospheric dynamo region, which are important to the various aspects. The statistical method to be used will be able to express how solar processes are effective on neutral density. Thus, the effect of F10.7 Solar flux and IMF-Bzon the neutral components (N_2 and O_2) was investigated by means of a statistical multiple regression model, taking into account the fact that the variation of the neutral components in the E-region of the ionosphere is largely related to the solar parameters. The statistical model, statistical results and discussion and conclusions are given in Section 2, 3, and 4, respectively.

2. Material and Methods

In the present study, N_2 and O_2 values obtained from model "NRLMSISE00" (https://ccmc.gsfc.nasa.gov/modelweb/models/nrlmsise00.php) for 110 km altitude in the equatorial region station (Singapore (01.23 N; 103.55 E)) and F10.7 solar flux and IMF-Bz data obtained from "OMNIweb" model (https://omniweb.gsfc.nasa.gov/form/dx1.html) were used. Daily values of the variables are used at 12:00 UT for the period of 01.01.1997-31.12.2015.

To investigate the relation between many ionosphere parameters and external parameters, a multiple regression model was used. The detailed knowledge of this model is given by Atici and Sagir [16, 17]. The regression equation used in these reference works has been updated for this study after looking at the stationarity of the variables (F10.7, IMF-Bz, N_2 and O_2):

For N_2,

$$N_{2t} = \beta_0 + \beta_1 (F10.7_t) + \beta_2 (IMF\text{-}Bz_t) + \varepsilon_t \quad (1)$$

For O_2,

$$O_{2t} = \beta_0 + \beta_1 (F10.7_t) + \beta_2 (IMF\text{-}Bz_t) + \varepsilon_t \quad (2)$$

where β_0 is constant, β_1 and β_2 are regression coefficient, t is time and ε_t is the term error.

3. Results and Discussion

The multiple regression model used for the analysis of the data is composed of three steps in this study. The first step is the analysis of the unit root test that the stability of the variables is determined. The second stage is the ADF co-integration test, which is used to determine whether there is a long-term relationship between the stationary variables. The final stage is the regression analysis in which the relationship between variables are determined [16, 17].

Table 1 shows the results of the unit root tests of our variables. Since stationarity is a very important prerequisite for the multiple regression model, stationarity of variables with three separate tests (ADF (Augmented-Dickey Fuller Test), PP (Phillips-Perron Test) and KPSS (Kwiatkowski-Phillips-Schmidt-Shin Test)) was analyzed. In order to the variables to be stable, the values at the top of the table should be larger as absolute values than the McKinnon critical values given bottom section of the table [6, 7, 18, 19]. This condition is provided in all test evaluations except the N_2 variable in KPSS test. All variables were statistically stable at the rate of 1% for all test groups, except for the ADF test result of F10.7 solar flux and the KPSS test results of N_2.

Table 1 The unit root test results for variables used in the regression analysis.

Variables	ADF	PP	KPSS
N_2	-18.04	-11.74	0.08
O_2	-12.29	-5.24	0.74
F10.7	-3.89	-6.70	1.21
IMF-Bz	-5.54	-7.10	1.35
The level of McKinnon (1996) critical significance values			
1%	-4.27	-4.26	0.21
5%	-3.55	-3.55	0.14
10%	-3.21	-3.20	0.11

Since all variables are stationary at the current levels, a direct long-term relationship between the expressions in Eqs. (1) and (2) was examined by the ADF co-integration test. Table 2 shows the ADF co-integration test results obtained for the models established by Eqs. (1) and (2). Because the *p*-values are smaller than 0.05 in the model and the ADF value is greater—in absolute values—than the McKinnon critical values at the bottom section of the table, (|− 8.10|> |− 2.58| for model installed with Eq. (1) and |− 6.40| > |− 2.58| for model installed with Eq. (2) we can say that there is a long-term relationship between the dependence variables (N_2 and O_2) and the independence (F10.7 solar flux and IMF-Bz) variable for both equations. Furthermore, the level of statistical significance of this relationship is at the rate of 1% that is highest level. As a result of the investigations, it was determined that there is a long-term relationship between our dependent variables and independent variables in the models established for both N_2 (Eq. (1)) and O_2 (Eq. (2)).

After determining the long-term relationship between the variables, the regression analysis results for both models are given in Table 3. ARCH (Autoregressive Conditionally Heteroscedastic), Durbin-Watson, Prob. (F-statistic) tests given at bottom of the Table 3 are other tests which indicate the accuracy of our model. The reference values of these tests are as follows: ARCH test value must be greater than 0.05. Durbin-Watson test values must be between 1.5 and 2.5. Prob. (F-statistic) test value must be less than 0.05 [6, 16, 17, 20]. Since the values obtained for these tests in our model provide their reference values, the established model is statistically accurate.

According to the results given in Table 3, it is understood to be meaningful of the variables that the coefficients obtained from the models established for

Table 2 The ADF co-integration test results for Eq. (1) and Eq. (2).

	For Eq. (1)		For Eq. (2)	
Regression model	ADF	*p*-value	ADF	*p*-value
Model	8.10	0.00	6.40	0.00
The level of significance	McKinnon (1996) critical values ADF			
1%		-2.58		
5%		-1.94		
10%		-1.61		

Table 3 The result of regression analysis.

Coefficient	N_2	O_2
β_0 (Constant)	9.47×10^{33}	3.44×10^{32}
	(0.000)	(0.000)
β_1 (F10.7)	-2.61×10^{14}	-2.96×10^{14}
	(0.000)[a]	(0.000)[a]
β_2 (IMF-Bz)	-9.95×10^{15}	-1.69×10^{15}
	(0.000)[a]	(0.000)[a]
AR (1/2)	0.921	0.857
	(0.000)[a]	(0.000)[a]
R^2	0.92	0.83
Adj. R^2	0.92	0.83
Durbin Watson	2.102	1.652
Prob. (F-statistic)	(0.000)	(0.000)
ARCH	(0.293)	(0.842)

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

both N_2 (Eq. (1)) and O_2 (Eq. (2)) are less than 0.05 of p-values given in parentheses.

The coefficients (left column) in the model established for N_2 have shown that an increase/decrease of 1 s.f.u. in F10.7 solar flux causes a decrease/increase of 2.61×1014 m^{-3} in N_2 density. It is also seen that an increase/decrease of 1 nT occurring in IMF-Bz causes a decrease/increase of 9.95×10^{15} m^{-3} in N_2 density. In addition, it can be seen that about 92% (Adj.R^2) of changes in N_2 can be explained by the changes in F10.7 solar flux and IMF-Bz.

From the coefficients in the model established for O_2 (right column), it is seen that an increase/decrease of 1 s.f.u. occurred in F10.7 solar flux causes a decrease/increase of 2.96×10^{14} m^{-3} in O_2 density. It is also seen that an increase/decrease of 1 nT occurring in IMF-Bz caused a decrease/increase of 1.69×10^{15} m^{-3} in N_2 density. In addition, it can be seen that the about 83% (Adj.R^2) of changes in O_2 can be explained by the changes in F10.7 solar flux and IMF-Bz.

These results are in agreement with the fact that in the mesosphere-lower-thermosphere region, which is expressed in some previous studies [21-23], the processes coming from below and above are almost equally effective at an altitude of about 100 km. At the altitude of the work here is expected to be more dominant processes from above. The results obtained confirm this hypothesis.

4. Conclusions

In this study, the effect of the F10.7 solar flux and IMF-Bz on the N_2 and O_2 neutral molecules density obtained for the altitude of 110 km of ionospheric E region at noon for the period 01/1997-12/2015 in the equatorial region was examined statistically. As a result of this investigation, it has been found that the neutral components of the ionospheric dynamo region change inversely with both F10.7 solar flux and interplanetary magnetic fields. The reason why the F10.7 solar flux has a negative effect on the neutral components is that it causes a reduction in neutral species through various chemical reactions due to the ionization effect, especially at noon. Similarly, the inverse proportional effect of IMF-Bz on neutral species can be caused by the transport of neutral species out of the dynamo region due to electromagnetic drift.

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