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The solar-cycle variation of $M(3000)F_2$ and its correlation with that of f_0F_2

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Abstract
Using hourly monthly-median measured values from nine long-standing ionospheric sounding stations with data sets extending over several decades, best-fit empirical relationships are established for $M(3000)F_2$ with different solar and ionospheric indices representative of state of the solar cycle. The statistical analysis shows that there is no difference in the degree of correlation in using one index over another. Comparisons are also made with similar relationships for monthly median f_0F_2 determined from the corresponding measurement data sets and the degree of correlation between the two ionospheric parameters is established.

Key words *ionosphere – solar-cycle dependence – long-term prediction*

1. Introduction

It is well established that the morphology of the F-region and the various processes, which can produce its electron density variations are complex and sophisticated. Thus, presentations of the variations of its electron density and hence of its critical frequency f_0F_2 or any other characteristic parameters cannot be derived from theoretical considerations which only take account of production by photoionization but through the statistical analysis of past measurements.

Many research-workers have investigated the solar-cycle variation of monthly median f_0F_2 (*e.g.*, Dominici and Zolesi, 1987; Kane, 1992; Kouris and Agathonikos, 1992; Sizun, 1992; Mikhailov, 1993; Ortiz *et al.*, 1993; Bradley, 1994) using different solar and ionospheric indices (ITU-R, 1990; Bradley, 1993a). To be useful to operational telecommunication predictions the correlation with index must be high, values of the index must be accurately predictable and readily available. Kouris and Nissopoulos (1994) have shown that there is little improvement in correlation for the different indices and best fit is established with a parabolic dependence. Thus, retention of a dependence on R_{12}, the 12-monthly smoothed sunspot number, is advocated, especially in view of its widespread predictability and availability (Kouris *et al.*, 1993). On the other hand, similar analyses for the propagation factor $M(3000)F_2$ have received relatively limited treatment assuming merely that the same form of dependence applies. However, it has been shown recently, that there exist some substantial differences in their respective changes with solar activity (Kouris, 1995) and some limited results have been reported in a couple of preliminary studies (Bradley, 1993b, 1994; Kouris *et al.*, 1994).

In the present work a more extensive statistical investigation is attained on the one hand and on the other hand a more representative sample of European locations is considered.

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Furthermore, the correlations between the monthly median values of f_0F_2 and $M(3000)F_2$ for a given month, hour and location in the different years are investigated.

2. Data and analysis

In this work hourly monthly-median values of f_0F_2 and $M(3000)F_2$ are examined. The data used are those measured at nine European stations: Moscow (55.5°N, 37.3°E), Kaliningrad (54.7°N, 20.6°E), Juliusruh (54.6°N, 13.4°E), Slough (51.5°N, 0.6°W), Dourbes (50.1°N, 4.6°E), Lannion (48.4°N, 3.5°W), Poitiers (46.6°N, 0.3°E), Grocka (44.8°N, 20.5°E) and Rome (41.8°N, 12.5°E) with long periods of available data. The $M(3000)F_2$ values are compared with the corresponding 12-month running mean values of each of the following indices of state of the solar-cycle: the sunspot number R, the solar flux at 10.7 cm Φ, the Australian T index (IPSD, 1968) and the ionospheric index IF_2 (Minnis and Bazzard, 1959). The analysis is carried out for each hour of a given month at each station over a period of two solar cycles almost for all stations examined.

In the present statistical study consistent with the earlier analyses (Kouris and Agathonikos, 1992; Kouris and Nissopoulos, 1994) the following curvilinear regressions of higher-order terms are investigated

$$(M(3000)F_2)^n = a_0 + a_1X + a_2X^2 + a_3X^3 \quad (2.1)$$

and

$$(M(3000)F_2)^n = = b_0 + b_1 f_0F_2 + b_2 (f_0F_2)^2 + b_3 (f_0F_2)^3 \quad (2.2)$$

where n = 1, 2, 3 or 4 and X is the appropriate solar-cycle index under study. The eqs. (2.1) and (2.2) are fitted by the method of least squares to the observed data of each hour of a given month at each location. For each model of observed data described by the eqs. (2.1) and (2.2) the hierarchy of regressions

$$(M(3000)F_2)^n = a_0 + a_1X \quad (2.3)$$

$$(M(3000)F_2)^n = a_0 + a_1X + a_2X^2 \quad (2.4)$$

$$(M(3000)F_2)^n = a_0 + a_1X + a_2X^2 + a_3X^3 \quad (2.5)$$

or

$$(M(3000)F_2)^n = b_0 + b_1 f_0 F_2 \quad (2.6)$$

$$(M(3000)F_2)^n = b_0 + b_1 f_0F_2 + b_2 (f_0F_2)^2 \quad (2.7)$$

$$(M(3000)F_2)^n = = b_0 + b_1 f_0F_2 + b_2 (f_0F_2)^2 + b_3 (f_0F_2)^3 \quad (2.8)$$

is tested to see whether the coefficients a_2 and a_3 or b_2 and b_3 of the non-linear terms differ significantly from zero. The criteria and the statistical tests to assess the relative merits of the various models are those used also in the f_0F_2 statistical investigation (Kouris and Nissopoulos, 1994), where it is found that the variation of f_0F_2 with each of the solar-cycle index under study is described by a second-degree relation.

3. The dependence of $M(3000)F_2$ on solar activity

The statistical analysis shows that the coefficient a_3 in eq. (2.5) is not significant at the 5% level. Indeed, less than 10 regressions out of 100 required a third-order term for all indices considered here. Furthermore, the usual test of significance of the difference of two correlation coefficients has shown that the correlation coefficients evaluated using the third-order models were not higher than those obtained when the linear or the quadratic equations (with n = 1, 2, 3, 4) were fitted to the measured data.

The tests of significance at the 5% level (Student's test and F-test) for the coefficient a_2 in eq. (2.4) show that the relation with n = 1 gives the best fit to for all indices. The coefficient a_2 of the second-order term is significantly different from zero in about 1/5 of the regressions in the case of $n = 1$ as can be seen from table I, where the percentage of non-linear regressions giving improved correlation over the total of 2592 (24 h x 12 months x 9 stations) cases for each of the models and each of the considered indices is reported. However, it is to be noted that although there is a need for the second-order term in more than 20 regressions out of 100 in the case of the model with $n = 1$, it does not follow the same pattern in each station and for each index (figs. 1 and 2), unlike what happens in the case of f_0F_2 (Kouris and Nissopoulos, 1994). Analyses of $M(3000)F_2$ data for other stations and indices are given elsewhere (Kouris *et al.*, 1994) where the obtained results are similar to those of figs. 1 and 2.

Further, to assess whether the linear eq. (2.3) or the second-degree eq. (2.4) with $n = 1$ gives the highest correlation coefficient, the same data for each hour of each month at each station are fitted to eqs. (2.3) and (2.4), respectively. Table II shows the overall combined correlation coefficients for the linear and the quadratic regression, respectively and for each index used, together with the standard errors of the combined correlation coefficients resulting from a total of 2592 correlation coefficients.

An inspection of the results reported in table II reveals that there is no significant difference between the correlation coefficients of the linear and the quadratic model, and that for all the considered indices of solar activity. Nevertheless, the usual test of significance of the difference of two correlation coefficients was applied to each pair of r's reported in table II. These tests confirmed that virtually there is no significant difference between the correlation coefficients although the second-degree relation gives slightly higher correlation coefficient. Therefore, from all the results obtained from the statistical analysis it is concluded there is no significant advantage in using the quadratic relation over the linear, and retention

Table I. Percentage of sets of data requiring a second-order regression at the 5% significance level.

Model	Index			
	R	Φ	T	IF_2
$n = 1$	20	24	21	23
$n = 2$	25	26	25	30
$n = 3$	41	40	42	48
$n = 4$	53	51	56	56

Table II. Overall combined correlation coefficients, r, for the linear and the quadratic relations and the different indices. Data from nine stations.

Index	Relation	Linear	Quadratic
$X = R_{12}$	r	0.87	0.89
	$r \pm$ s.e.	0.869 - 0.874	0.888 - 0.892
$X = \Phi_{12}$	r	0.87	0.89
	$r \pm$ s.e.	0.869 - 0.873	0.889 - 0.894
$X = T_{12}$	r	0.87	0.89
	$r \pm$ s.e.	0.869 - 0.874	0.889 - 0.893
$X = IF_{2_{12}}$	r	0.87	0.89
	$r \pm$ s.e.	0.867 - 0.872	0.888 - 0.892

L.T.	J	F	M	A	M	J	J	A	S	O	N	D
0:00	+	0	+	+	+	+	0	0	0	0	0	0
1:00	+	0	+	+	+	+	+	0	0	0	0	0
2:00	+	+	+	0	+	+	+	0	0	0	0	+
3:00	0	0	+	0	+	+	0	0	0	0	0	0
4:00	0	0	+	0	+	0	0	0	0	0	0	0
5:00	0	0	+	0	0	0	0	0	0	0	0	0
6:00	0	0	0	0	0	0	0	0	0	0	0	0
7:00	0	0	0	0	0	0	0	0	0	0	0	0
8:00	0	0	0	-	0	0	0	0	0	0	-	0
9:00	0	0	0	0	0	0	0	0	0	0	-	0
10:00	0	0	0	0	0	0	0	0	0	0	0	0
11:00	0	0	0	0	0	0	0	0	0	0	0	-
12:00	0	0	0	0	0	0	0	0	0	0	0	0
13:00	0	0	0	-	0	0	0	0	0	0	0	0
14:00	0	0	0	-	0	0	0	-	0	0	0	0
15:00	0	0	0	-	0	0	-	-	0	0	-	0
16:00	0	0	0	-	0	0	0	0	0	0	-	-
17:00	0	0	0	-	0	0	0	0	0	0	-	0
18:00	0	0	0	-	0	0	0	0	0	0	-	0
19:00	0	0	0	-	0	0	0	0	-	0	0	0
20:00	0	0	0	0	0	0	0	0	0	0	0	0
21:00	0	0	0	0	0	0	0	0	0	0	0	0
22:00	+	+	+	+	0	0	0	0	0	0	0	0
23:00	+	+	+	+	0	+	0	0	0	0	0	0

L.T.	J	F	M	A	M	J	J	A	S	O	N	D
0:00	+	0	+	+	+	0	0	0	0	0	0	0
1:00	+	0	+	+	+	0	+	0	0	0	0	0
2:00	+	0	+	0	+	+	+	0	+	0	0	+
3:00	0	0	+	0	0	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0	0	0	0	0	0
6:00	0	0	0	0	0	0	0	0	0	0	0	0
7:00	0	0	0	0	0	0	0	-	0	0	0	0
8:00	0	0	0	-	0	0	0	-	0	0	-	0
9:00	0	-	0	0	0	0	0	0	0	0	-	0
10:00	0	0	0	0	0	0	0	-	0	0	0	0
11:00	0	0	0	-	0	0	0	-	0	0	0	-
12:00	0	0	0	-	0	0	0	-	0	0	-	0
13:00	0	0	0	-	0	0	0	-	0	0	-	0
14:00	0	0	0	-	0	0	-	-	0	0	0	0
15:00	0	0	0	-	0	0	-	-	0	0	-	0
16:00	-	0	0	-	0	0	-	0	-	0	-	-
17:00	0	0	0	-	0	0	0	0	0	0	0	0
18:00	0	0	0	-	-	0	0	0	0	0	-	0
19:00	0	0	0	-	0	0	0	0	-	0	0	0
20:00	0	0	0	0	0	0	0	-	0	0	0	0
21:00	0	0	0	0	0	0	0	0	0	0	0	0
22:00	0	0	+	0	0	0	0	0	0	0	0	0
23:00	+	+	+	+	0	+	0	0	0	0	0	0

Fig. 1. Significance at the 5% level of the coefficient a_2 in eq. (2.4) with $n = 1$ and $X \equiv R_{12}$ (top panel) and $X \equiv T_{12}$ (bottom panel), respectively. + Stands for a_2 different from zero and positive, – for a_2 different from zero and negative, and 0 for a_2 equal to zero. Data from Slough.

L.T.	J	F	M	A	M	J	J	A	S	O	N	D
0:00	0	0	0	0	0	0	0	0	0	0	0	0
1:00	0	0	0	0	0	0	0	0	0	0	0	0
2:00	0	0	0	0	0	0	0	0	0	0	0	0
3:00	0	0	0	0	0	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0	0	0	0	0	0
6:00	0	0	0	0	-	0	0	0	0	0	0	0
7:00	0	0	0	0	0	0	-	0	0	0	0	0
8:00	0	0	0	0	-	0	0	0	0	0	0	0
9:00	0	0	0	0	-	0	0	-	0	0	0	0
10:00	0	0	0	0	0	0	0	0	0	0	0	0
11:00	-	0	0	0	0	0	0	0	0	0	0	0
12:00	0	0	0	0	-	0	0	0	0	0	0	0
13:00	0	0	0	0	-	0	-	-	0	0	0	0
14:00	0	0	0	0	-	0	0	0	0	0	0	0
15:00	0	0	0	-	-	0	-	-	0	0	0	0
16:00	0	0	0	-	-	0	-	-	0	0	-	0
17:00	0	0	0	-	0	0	-	0	0	0	0	0
18:00	0	0	0	0	-	0	0	0	0	0	0	-
19:00	0	0	0	0	-	0	0	0	0	0	0	0
20:00	0	0	0	0	0	0	0	0	0	0	0	0
21:00	0	0	0	0	0	0	0	0	0	0	0	0
22:00	0	0	0	0	0	0	0	0	0	0	0	0
23:00	0	0	0	0	0	0	0	0	0	0	0	0

L.T.	J	F	M	A	M	J	J	A	S	O	N	D
0:00	0	0	0	0	0	0	0	0	0	0	0	0
1:00	0	0	0	0	0	0	0	0	0	0	0	0
2:00	0	0	0	0	0	0	0	0	0	0	0	0
3:00	0	0	0	0	0	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0	0	0	0	0	0
5:00	0	0	0	0	-	0	0	0	0	0	0	0
6:00	0	0	0	-	-	0	0	0	0	0	0	0
7:00	0	0	0	0	0	0	-	0	0	0	0	0
8:00	0	0	0	-	-	0	0	0	0	0	0	0
9:00	0	0	0	0	-	0	0	-	0	0	0	-
10:00	0	0	-	0	0	0	0	0	0	0	0	0
11:00	-	0	0	0	-	0	0	-	0	0	0	0
12:00	0	0	-	0	-	0	-	0	0	0	0	0
13:00	0	0	-	0	-	0	-	-	0	0	0	0
14:00	0	0	-	-	-	0	0	0	0	0	-	0
15:00	-	-	-	-	-	0	-	-	-	0	0	0
16:00	0	-	-	-	-	0	-	-	-	0	-	0
17:00	0	0	0	-	0	-	-	0	0	0	0	0
18:00	0	0	-	-	-	0	0	0	-	0	0	-
19:00	0	0	0	-	-	0	0	0	0	0	0	0
20:00	0	0	0	0	-	-	0	0	0	0	0	0
21:00	0	0	0	0	0	0	0	0	0	0	0	0
22:00	0	0	0	0	0	0	0	0	0	0	0	0
23:00	0	0	0	0	0	0	0	0	0	0	0	0

Fig. 2. Significance at the 5% level of the coefficient a_2 in eq. (2.4) with $n = 1$ and $X \equiv R_{12}$ (top panel) and $X \equiv T_{12}$ (bottom panel), respectively. + Stands for a_2 positive, – for a_2 negative and 0 for a_2 equal to zero. Data from Lannion.

of a linear dependence of $M(3000)F_2$ with solar activity is advocated, especially because of the fact that the need for the second-order term does not follow the same pattern in each station and for each index.

4. The correlation between monthly median $M(3000)F_2$ and f_0F_2

The correlation between the propagation factor $M(3000)F_2$ and the critical frequency f_0F_2, using hourly monthly-median values from the above-referred nine European stations is investigated. The curvilinear regressions of higher-order terms given by eq. (2.2) are fitted by the method of least squares to the monthly median data of each hour in a given month of each station. The results of the analysis indicate that the coefficient b_3 in eq. (2.8) is not significant at the 5% level. The same is valid for the coefficient b_2 in eq. (2.7). Indeed, out of a total number of 2592 (24 h x 12 months x 9 stations) curvilinear regressions for each model (n = 1, 2, 3, 4) less than 1/5 of them require a second-order term in the case of n = 4 and less than 1/6 in the case of n = 1. For example fig. 3 shows that the coefficient b_2 is significantly different from zero in less than 16% of the regressions examined for the model with n = 1 in the case of data from Slough but it is still much less when data from other locations are used. Moreover, the condition b_2 different from zero does not follow the same pattern in all stations examined.

When the opposite correlation is investigated, *i.e.* the relation

$$f_0F_2 = c_0 + c_1 M(3000)\, F_2 + c_2\, [M(3000)\, F_2]^2 \tag{4.1}$$

L.T.	J	F	M	A	M	J	J	A	S	O	N	D
0:00	0	0	+	+	0	0	0	0	0	0	0	0
1:00	0	+	+	+	0	0	0	0	0	0	+	0
2:00	0	0	+	0	0	0	0	0	0	0	0	0
3:00	0	0	+	0	0	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0	0	0	0	0	+
5:00	0	+	+	0	0	0	0	0	0	0	0	0
6:00	0	+	0	0	0	0	0	0	0	0	0	0
7:00	0	0	0	0	0	0	0	0	0	0	0	0
8:00	0	0	0	0	0	0	0	-	0	0	0	0
9:00	0	0	0	0	0	0	0	0	0	0	0	0
10:00	0	0	0	0	0	0	0	-	0	0	0	0
11:00	0	0	0	0	0	0	-	-	0	0	0	0
12:00	0	0	0	0	0	0	-	0	0	0	0	0
13:00	0	0	0	0	0	0	0	-	0	0	0	0
14:00	0	0	0	-	-	0	-	-	0	0	0	0
15:00	0	0	0	-	-	-	-	-	0	0	-	0
16:00	0	0	0	-	-	0	0	0	-	0	0	-
17:00	0	0	0	-	0	-	-	-	0	0	0	0
18:00	0	0	0	-	0	0	0	0	0	0	0	0
19:00	0	0	-	0	0	0	0	0	-	0	0	-
20:00	0	0	0	0	0	0	0	0	0	0	0	0
21:00	0	0	0	0	0	0	0	0	0	0	0	0
22:00	0	0	+	0	0	0	0	0	0	0	0	+
23:00	0	+	+	+	0	0	0	0	0	+	0	0

Fig. 3. Significance at the 5% level of the coefficient b_2 in eq. (2.7) with $n = 1$. + Stands for b_2 different from zero and positive, – for b_2 different from zero and negative, and 0 for b_2 equal to zero. Data from Slough.

Table III. Combined correlation coefficients using data from nine stations.

$M(3000)F_2/f_0F_2$	Linear	Quadratic
r	0.85	0.87
$r \pm$ s.e.	0.848 - 0.853	0.867 - 0.872

it is found that the coefficient of the second-order term is significantly different from zero at the 5% level in much fewer regressions (about 7%) than when eq. (2.7) with $n = 1$ is fitted to the data.

To test which value of n gives the highest correlation coefficient, the same procedure described in the previous paragraph is applied. The result is that $n = 1$ is the best for the linear and also for the quadratic relationship. Finally, the comparison of the combined correlation coefficients (table III) reveals that the difference in the degree of correlation between the variates $M(3000)F_2$ and f_0F_2 in the linear eq. (2.6) and the quadratic eq. (2.7) with $n = 1$ is not so significant. This fact together with the results when eq. (4.1) is applied and the fact that $b_2 \neq 0$ does not follow the same pattern in every station suggests that there is not much difference between the quadratic and the linear law in this case. On the other hand, the degree of correlation between these two variates is rather satisfactory in comparison with the correlation coefficients obtained when hourly daily values of $M(3000)F_2$ and f_0F_2 are considered (Kouris *et al.*, 1998).

5. Conclusions

The statistical analysis of the variation of the hourly monthly-median values of the propagation factor $M(3000)F_2$ with each of the most used indices of solar activity shows that the first power of the measured $M(3000)F_2$ is proportional to the intensity of the solar ionizing radiation. Moreover, it is shown that the second-order relation gives only a slight improvement in the degree of correlation over the linear. On the other hand, the need for the second-order term does not follow the same pattern in each station and for each index. Therefore, a retention of a linear dependence of $M(3000)F_2$ with solar activity is advocated.

Furthermore, when hourly monthly-median values of $M(3000)F_2$ are correlated with corresponding f_0F_2 values in a linear or second-order relation there is little difference between the correlation coefficients, being slightly greater in the latter case. On the other hand, the need for the second-order term in the regressions examined (2592) is less than 15% and is random from one location to another.

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