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Letter to the Editor

Solar-cycle variation of the daily *fo*F2 and M(3000)F2

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Abstract. Daily values of the ionospheric characteristics *fo* F2 and M(3000)F2 for a given hour and month are correlated with the corresponding daily values of sunspot number using measured data collected at seven European locations. The significance of applying different-order polynomials is considered and the times are confirmed when the higher-order terms are important. Mean correlation coefficients for combined data sets over all hours, months and stations are determined, together with the standard errors of estimates. Comparisons are made with corresponding figures for monthly median values derived from the same data sets.

Key words. Electromagnetics (Guided waves) · Ionosphere (Ionospheric disturbances) · Radio Science (Radio wave propagation)

1 Introduction

Many research workers have investigated the solar-cycle variation of the monthly median critical frequency foF2 using different solar and ionospheric indices (ITU-R, 1990; Bradley, 1993). Similar studies for the monthly median propagation factor M(3000)F2 have been more limited, but some exist (Kouris *et al.*, 1994). On the other hand, to date the present authors are not aware of any corresponding analysis applied to the daily values of these two quantities. This is understandable, in view of the facts that long-term propagation predictions in support of communications circuit planning seek to define median trends, and that changes from day to day, not necessarily due to solar variability, must inevitably degrade the degrees of correlation. However, it is clear that means are needed to be able to forecast ionospheric conditions on any given day of interest. According to Wilkinson (1995) daily values may be estimated by using "adjusted" solar or ionospheric indices. One step towards optimising that adjustment is to examine the extent to which daily values depend on daily solar activity. The present investigations therefore consider the correlation with daily sunspot number R, whereas monthly median values are known to correlate best with 12-month running mean sunspot number R_{12}.

2 Data and analyses

Measured characteristics values for the seven mid-latitude European locations of 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), Lannion (48.7°N 3.5°W), Poitiers (46.6°N 0.3°E) and Rome (41.9°N 12.5°E) for 30 days of each of 12 months and 24 h over the period 1974–1984 have been fitted to polynomial functions of the form:

$$foF2 = a_0 + a_1 R + a_2 R^2 + a_3 R^3 + \ldots \quad (1)$$

$$M(3000)F2 = b_0 + b_1 R + b_2 R^2 + b_3 R^3 + \ldots \,. \quad (2)$$

In particular, Student's t-test and Fisher's F-test have been applied to determine the significance of the higher-order polynomial coefficients and at what points truncation should be introduced.

3 Results

For *fo*F2 these tests show that a_3 is significant at the 95% level in about 40% of the regressions examined, being negative in winter and the equinoxes, and positive in summer. Moreover, this same general pattern of variation is experienced at all stations considered. As an example, Table 1 for Slough shows the months and hours for which the term a_3 is significant and for these whether it is positive or negative. Retention of a_2 results in substantial improvement, being significantly different from zero in 85% of cases (Table 2). a_2 is negative in all seasons and exhibits this same pattern at all stations, i.e. tending towards saturation at the higher R. By contrast, in the case of M(3000)F2, b_3

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Table 1. Hours and months for which the coefficient a_3 of the cubic polynomial term for *fo*F2 is significant in the case of Slough data, +: a_3 positive, –: a_3 negative, 0: a_3 zero

L.T	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0	0	–	–	0	0	0	0	0	–	–	–	0
1	0	–	–	–	0	0	0	0	–	–	–	0
2	0	–	–	–	0	0	0	0	–	–	–	0
3	0	–	–	–	0	0	0	0	–	–	–	0
4	+	–	–	–	0	0	0	0	–	–	–	0
5	+	–	–	0	0	0	0	0	–	–	–	0
6	0	–	0	0	0	0	0	0	–	0	–	0
7	0	–	0	–	0	0	0	0	–	0	0	0
8	0	–	–	–	0	+	0	0	–	0	0	0
9	0	–	–	0	0	+	0	0	–	0	0	0
10	–	–	0	0	0	0	0	0	–	0	0	0
11	0	–	0	0	0	0	0	0	–	0	0	0
12	–	–	0	0	0	0	0	0	–	0	0	0
13	0	–	0	0	0	+	0	0	–	0	0	0
14	0	–	0	0	0	+	0	0	–	0	0	0
15	–	–	0	0	0	+	0	0	–	–	0	0
16	0	0	0	0	0	+	0	0	–	0	0	0
17	0	–	0	0	0	+	0	0	–	0	–	0
18	0	–	0	0	0	+	0	+	–	0	–	0
19	0	–	0	0	0	+	0	0	–	0	–	0
20	0	–	0	0	0	+	0	0	–	0	–	0
21	0	–	0	0	0	+	0	0	–	0	–	0
22	0	–	0	0	0	+	0	0	–	0	–	0
23	0	–	0	0	0	+	0	0	–	–	–	0

Table 2. Hours and months for which the coefficient a_2 of the quadratic term for *fo*F2 is significant in the case of Slough data, +: a_2 positive, –: a_2 negative, 0: a_2 zero

L.T	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0	0	–	0	–	–	–	–		–	–	0	0
1	0	–	0	–	–	–	–		–	–	0	0
2	0	–	0	–	–	–	–		–	–	0	0
3	0	–	0	–	0	–	–	–			0	0
4	–	–	–	–	0	–	–	–	–	0	0	0
5	–	–	0	–	0	–	–		–	–	0	–
6	–	–	–	–	0	–	–	–	–	–	0	–
7	–	–	–	–	0	–	–	–	–	–	–	–
8	–	–	–	–	0	–	–	–	–	–	–	–
9	–	–	–	–	–	–	–	–	–	–	–	–
10	–	–	–	–	–	–	–	–	–	–	–	–
11	–	–	–	–	–	–	–	–	–	–	–	–
12	–	–	–	–	–	–	–	–	–	–	–	–
13	–	–	–	–	–	–	–	–	–	–	–	–
14	–	–	–	–	–	–	–	–	–	–	–	–
15	–	–	–	–	–	–	–	–	–	–	–	–
16	–	–	–	–	–	–	–	–	–	–	–	–
17	–	–	–	–	–	–	–	–	–	–	–	–
18	–	–	–	–	–	–	–	–	–	–	–	–
19	–	–	–	–	–	–	–	–	–	–	–	–
20	0	–	–	–	–	–	–	–	–	–	0	0
21	0	–	0	–	–	–	–	–	0	–	0	0
22	0	–	0	–	–	–	–	–	–	–	0	0
23	0	–	0	–	–	–	–	–	–	–	0	+

is found to be significant in only 12% of the cases, with little pattern consistence between stations. But b_2 is significantly different from zero in 60% of cases (Table 3) and unlike a_2 is positive in all seasons for all stations, in the sense which gives an increasing rate of rise for the higher R.

To compare the calculated correlation coefficients (Crow *et al.*, 1960), distributions of this parameter have been generated over all hours, days, months and stations (60480 values) and a Fisher's z-transformation has been applied to convert these from highly skew to approximately normal form. The usual tests of significance for a normal distribution confirmed, indeed, that the samples could then be regarded as drawn from the same normal population; hence it is valid to quote averaged combined correlation coefficients (Table 4), together with their associated standard errors. It is evident from these results that there is little difference, both for *fo*F2 and for M(3000)F2, between the correlation coefficients for the second and third-order relationships, and the usual test of differences shows that these are not statistically significant. But the correlation coefficients are significantly

Table 3. Hours and months for which the coefficient b_2 of the quadratic term for M(3000)F2 is significant in the case of Juliusruh data, +: b_2 positive, –: b_2 negative, 0: b_2 zero

L.T	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0	+	0	+	+	+	+	0	+	+	+	+	+
1	+	+	+	+	+	+	0	+	+	+	0	+
2	+	+	+	+	+	+	+	0	+	+	+	+
3	0	+	+	0	+	+	+	0	+	+	+	+
4	0	+	+	+	+	+	0	0	+	+	+	0
5	0	0	+	+	0	0	+	+	0	+	+	0
6	0	0	+	+	+	0	0	0	+	+	+	+
7	+	0	+	0	0	0	0	0	+	+	+	+
8	+	0	+	0	+	0	0	0	0	0	+	+
9	+	+	+	+	+	0	0	0	0	+	+	+
10	+	0	0	0	+	0	0	0	+	+	+	+
11	+	+	+	+	0	0	0	0	+	+	+	+
12	+	+	+	+	+	0	0	0	+	+	+	+
13	+	+	+	+	0	0	0	0	+	+	+	+
14	+	+	+	+	0	0	0	0	+	+	+	+
15	0	+	+	0	0	0	0	0	+	+	0	+
16	0	0	+	0	0	0	+	0	+	0	0	0
17	0	0	0	0	0	0	+	–	+	0	0	0
18	0	0	0	0	+	0	+	0	+	0	0	0
19	0	0	0	+	+	+	+	0	0	+	0	+
20	0	0	+	0	+	+	0	0	+	+	+	+
21	0	0	+	+	+	+	0	+	+	+	+	+
22	+	+	+	+	+	+	+	+	+	+	+	+
23	+	+	+	+	+	+	+	+	+	+	+	+

Table 4. Averaged combined correlation coefficients and their standard errors over all station-time data sets given by daily and monthly median analyses when different polynomial orders are adopted

Polynomial		*fo*F2/*R* daily	M(3000)F2/*R* daily	*fo*F2/*R* monthly median	M(3000)F2/*R* monthly median
Linear	*r*	0.743	0.617	0.95	0.87
	r ± s.e.	0.742–0.744	0.615–0.618	0.946–0.951	0.869–0.874
Quadratic	*r*	0.768	0.637	0.96	0.89
	r ± s.e.	0.767–0.769	0.635–0.638	0.955–0.960	0.888–0.892
Cubic	*r*	0.773	0.640	0.96	0.89
	r ± s.e.	0.772–0.774	0.638–0.641	0.959–0.963	0.890–0.893

Table 5. Overall standard errors of estimate given by daily analyses when different polynomial orders are adopted

Equation	*fo*F2/*R*	M(3000) F2/*R*
Linear	1.13 MHz	0.175
Quadratic	1.07 MHz	0.172
Cubic	1.06 MHz	0.172

greater when a quadratic as opposed to a linear dependence is adopted, and so the quadratic relationship is recommended be used. On the other hand, the reduction in standard error of estimate (Table 5) between the quadratic and linear relationships remains relatively small, particularly so in the case of *fo*F2 for which, as already noted, the a_2 term was significant in 85% of cases.

4 Discussion

Table 4 also shows for comparison, using the same measurement data sets, the combined correlation coefficients for a linear and a quadratic dependence when considering monthly median values. There are marked differences, with monthly median values close to unity in the case of *fo*F2, and likewise for M(3000)F2 some 25% greater than for daily results. On the other hand, the diurnal and seasonal trends in the correlation coefficients are found to be in the same sense whether dealing with daily or monthly median values, and this fact prompts us to attribute the observed differences to the influences of other effects than ionisation production in dominating the day-to-day variability of these two ionospheric characteristics. For example, at middle latitudes ionospheric disturbances can depress or enhance *fo*F2 by more than 50% in some particular days (Kouris *et al.*, 1998) such that a multiple regression of two variables, for instance *R* and the geomagnetic Ap index as advocated for the monthly median values by Kane (1992), might substantially improve the daily correlation. If so, this suggests that formulations based also on magnetic activity could be valuable in improving short-term ionospheric forecasts.

5 Conclusions

For European middle latitudes, daily values of both *fo*F2 and M(3000)F2 a second-degree relationship is shown to exist with daily sunspot number, though the degree of correlation is not as high as in the case of the monthly median values. This difference is attributed to the effects of ionospheric day-to-day variability not associated with ionisation production. Therefore, in day-to-day predictions daily sunspot numbers are not a good parameter and an adjusted solar or ionospherically derived index might give better results.

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