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Correlation of foF2 and M(3000)F2 over low latitude stations during low solar activity period

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This paper aims to investigate the relationship between propagation parameter M(3000)F2 and F2-layer critical frequency (foF2) during 2006-2010. Data from three low latitude stations, namely Jicamarca (12ºS, 283ºE), Kwajalein (09ºN, 167ºE) and Madimbo (22ºS, 031ºE) for the months of January (winter) and July (summer) during 2006-2010 are used for the study. It is found that the daily values of M(3000)F2 cannot be estimated from foF2 using a simple linear equation. It is concluded that that two procedures (day-to-day and hour-to-hour) do not give different results and the correlation coefficients between the daily values of M(3000)F2 and foF2 are generally lower than 0.6 and could be positive or negative.

Keywords: Radio propagation, Ionosphere, F2-layer critical frequency, Propagation factor M(3000)F2, Low solar activity

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1 Introduction

Our knowledge about the state of the ionosphere has been derived primarily from routine ionosonde measurements, though *in situ* measurements from rockets and satellites also play an important role. The statistical study mainly correlation of the various ionospheric parameters, such as critical frequency of the F2 layer (foF2), propagation factor [M(3000)F2], maximum height of the F2 layer (hmF2) and others provide the most widely spread information about the complex phenomenon that take place in the ionosphere. The results of these studies are used to develop empirical prediction models and maps[1].

The time variability of the F2-layer characteristics is very complicated and cannot be represented analytically. In order to improve individual days forecasting, the study of daily variability of F2-layer ionospheric characteristics is of great importance. The basic ionospheric data used in predictions are E, F1, F2 layer's critical frequencies (foE, foF1, foF2) and propagation factor [M(3000)F2] as well. M(3000)F2 is one of the important ionospheric characteristic, which depends on the dynamical process of the ionosphere. This parameter represents the optimum frequency to broadcast a signal that is to be received at a distance of 3000 km. The parameter is expressed as:

$$M(3000)\mathrm{F}2 = \frac{MUF(3000)}{foF2}$$

where, *MU*F(3000) is the maximum usable frequency at which a radio wave can be reflected and received at a horizontal distance of 3000 km propagation factor is essential for planning HF propagation radio links and also useful for ionospheric modeling because of its close anti-correlation with the height of the F2 peak[2].

Many researchers[3-6] have investigated the long term changes in foF2 seeking to establish empirical relationship in terms of indices of solar activity. An empirical model can provide reliable simulation data for effective forecasting. Different solar, ionospheric and mapping indices have been considered. The most commonly used techniques for investigating the relationship between two quantitative variables are correlation and linear regression. Rush[2] discussed the correlations in terms of requirements for an ionospheric observational network to be used for short-term forecasting of radio propagation conditions. Yu *et a*l.[7] used the partial correlation between the global total electron content (TEC), perturbation index (σ_{DGEC}), solar radio flux at 10.7 cm ($F_{10.7}$) and its perturbation $dF_{10.7}$, geomagnetic index (Ap) as well as seasonal factors S [cos (4πd/365) & sin(4πd/365)]; and A [cos(2πd/365)

& sin(2πd/365)]; where, d, specifies the day of the year. The result reveals that σ_{DGEC} is very much correlated with $F_{10.7}$ and Ap; and also correlated with the products of different factors, such as $F_{10.7}\times S$, $F_{10.72}$, $F_{10.7}\times A$ and $dF_{10.72}$. They also created a multiple regression model of σ_{DGEC} on the basis of the most influential factors. Falayi *et al.*[8] studied the semi-annual variation of geomagnetic disturbance using different indices. They used the correlation coefficient to determine the reliability of the variation, which lies in the range 0.595 - 0.988. Ehinlafa *et al.*[9] observed a strong correlation with its coefficients R^2 for all the seasons ranging 0.562 - 0.857 for $hmF2_{obs}$ values and ranging 0.876 - 0.968 for $hmF2_{IR1\text{-}2007}$ in the linear regressions of $hmF2_{obs}$ and $hmF2_{1R1\text{-}2007}$ with M(3000)F2 inverse. More recently, Bruevich *et al.*[10] analyzed the correlation coefficient of the linear regression of six solar indices [relative sunspot numbers (SSN), 530.3 nm coronal line flux (F_{530}), total solar irradiance (TSI), Mg II 280 nm core-to-wing ratio UV index, Flare index (FI) and counts of flares] versus $F_{10.7}$ cm radio flux in solar cycle 21, 22 and 23. They also analyzed the inter-connection between these indices and $F_{10.7}$ with the help of approximation by polynomial of second order. They found that the linear correlation was violated not only for maximums of solar activity cycles but for minimum of the cycles also, twice during each 11-year cycle. It is clear that methods are needed to forecast ionospheric conditions on any given day. It is well known that foF2 is connected only with maximum electron concentration but M(3000)F2 depends on the height of maximal electron concentration (hp), as can be seen in simple empirical relation provided by Shimazaki[11] :

$$\text{hpF2} = \frac{1490}{\text{M(3000)F2}} - 176\,\text{km}$$

Assuming that the F2 layer has an approximately parabolic shape and where, hp, is the virtual height at the frequency 0.834 (foF2) and M(3000)F2 is a transmission factor. This formula is generally presented as:

$$\text{hmF2} = \frac{1490}{\text{M(3000)F2}} - 176\,\text{km}$$

Further, in 1973, an important improvement was proposed by Bradley & Dudeney[12] introducing the following relation:

$$\text{hmF2} = \frac{1{,}490}{\text{M(3000)F}_2 + \Delta\text{M}} - 176\,\text{km};$$

where,

$$\Delta M = \frac{0.18}{X - 1.4};\ \text{and}\ X = \frac{foF2}{foE}$$

The propagation factor, M(3000)F2, is a fair measure of the height of the maximum electron density on a reciprocal scale. Nevertheless, it has been assumed that there is close correlation between these two parameters, which may be used successfully for forecasting. Also, dependency between solar indices and foF2 is the basis of any numerical or computerized prediction models of the ionosphere developed to support HF communications[13]. Correlation studies may help to make improvement in the existing models, like IRI (International Reference Ionosphere), CCIR (International Radio Consultative Committee), etc.[14]. Kouris & Nissopoulos[15] have examined the correlation of foF2 with separate indices for six European stations over two solar cycles and found slightly increased correlation with twelve-month smoothed sunspot number R12. Their results show that there is little improvement in correlation for the different indices and best fit is established with a parabolic dependence. It will be useful to establish a kind of relationship that might exist between the daily variations of the factor M(3000)F2 and the daily values of the foF2. There are some limited studies[16-19] on correlation between propagation factor M(3000)F2 and foF2. Kouris *et al.*[17] investigated the correlation between the hourly daily deviations from the median of foF2, M(3000)F2 and h'F and also made an attempt to correlate the coefficients of regression line with the geomagnetic Ap index. There is another way to investigate the correlation of the hourly daily deviations from the corresponding monthly-median values of ionospheric characteristics foF2 and M(3000)F2. The hourly daily values of the factor M(3000)F2 with the corresponding values of foF2 have been correlated using simple linear regression relationship for hour-to-hour variations and day-to-day variations for both seasons winter and summer[18]. To establish a relationship between foF2 and M(3000)F2, a statistical analysis of the hourly daily values of the propagation factor M(3000)F2 and the F2-layer critical frequency foF2 is carried out first for each hour of the day throughout a given month/year/station (hour-to-hour variation) and also for each day of a given month and year at a given station (day-to-day variation).

2 Data and Method of Analysis

Hourly daily values of the factor M(3000)F2 and the corresponding values of foF2 are correlated using the simple linear regression relationship

y= a0+a1*x

For statistical analysis, data is used from three low latitude locations namely, Jicamarca (12°S, 283°E), Kwajalein (09°N, 167°E) and Madimbo (22°S, 031°E) for the months of January (winter) and July (summer) during the years 2006-2010 obtained from SPIDR (Space Physics Interactive Data Resource) of NOAA Satellite and Information Services (http://spidr.ngdc.noaa.gov/). Two procedures mainly used to study the relationship between the propagation factor M(3000)F2 and foF2 are:

i. The linear regression equation is fitted by the least squares method to the M(3000)f2 values for every hour of the day throughout the given month of a given year at a given station and the corresponding values of foF2 (hour-to-hour variations);

ii. The same linear regression is fitted by the least squares method to the M(3000)F2 hourly values for every day of a given month of a given year at a given station and the corresponding values of foF2 (day-to-day variations).

The coefficients a0 and a1 for the least squares line are calculated as:

$$\mathrm{a1} = \frac{\mathrm{s}^2 x}{\mathrm{s}_{xy}}$$

where,

$$S^2 x = \frac{\sum_{i=1}^{i=n} (x_i - \bar{x})^2}{n-1} \quad \text{and}$$

$$Sxy = \frac{\sum_{i=1}^{i=n} (x_i - \bar{x})(y_i - \bar{y})}{n-1}$$

while, $\mathrm{a0} = \bar{y} - \mathrm{a1}\,\bar{\mathrm{x}}$

where, $\bar{y} = \frac{\sum_{\mathrm{i=1}}^{\mathrm{i=n}} \mathrm{y_i}}{\mathrm{n}}$, and $\bar{x} = \frac{\sum_{i=1}^{i=n} x_i}{n}$

To assess the linear equation, the sum of squares for error (SSE) is calculated as:

$$\mathrm{SSE} = (\mathrm{n}-1)(S^2 x - \frac{S^2_{xy}}{S^2_{x}})$$

and is used in the calculation of standard error of estimate, $\mathrm{MSE} = \sqrt{\frac{SSE}{n-p}}$

where, n, is number of cases; p, calculated parameters (a0, a1). If MSE is zero, all the points fall on the regression line.

Degree of freedom (DF) can be calculated as p-1 in case of a simple linear regression the degree of freedom are always 1.

Hourly value of the factor M(3000)F2 are correlated using the simple linear regression coefficient R. If $R^2=1$, there is no residual and each point is on the regression line while if $R^2=0$ means no relation exists between x and y; and the regression line will be over the mean of y ($\bar{y}$).

3 Results

The results of the statistical analysis following the above procedures are reported in Figs 1 and 2 and Table 1 for hour-to-hour variations; and in Figs 3 and 4 and Table 2 for day-to-day variations. For hour-to-hour variations, it is found that the pattern of regression coefficient a0 and a1 show high variability in both seasons. One can hardly ascertain the seasonal differences in their average behaviour. The correlation is poor and contradictory. Sometimes, it is upto 0.6. Further, Figs 3 and 4 illustrate the trends of regression coefficients a0, a1 and correlation coefficient R for day-to-day variations. One can ascertain the winter-summer differences in the behaviour of regression line coefficient and correlation coefficient. For day-to-day variations during summer, the correlation coefficients are found better but yet poor. To compare the two procedures, the average value of standard errors (SE) were also computed and listed in Tables 1 and 2 for hour-to-hour and day-to-day variations, respectively for all the three stations. All the results show that two procedures do not give different results and the correlation between the daily values of M(3000)F2 and foF2 is rather poor.

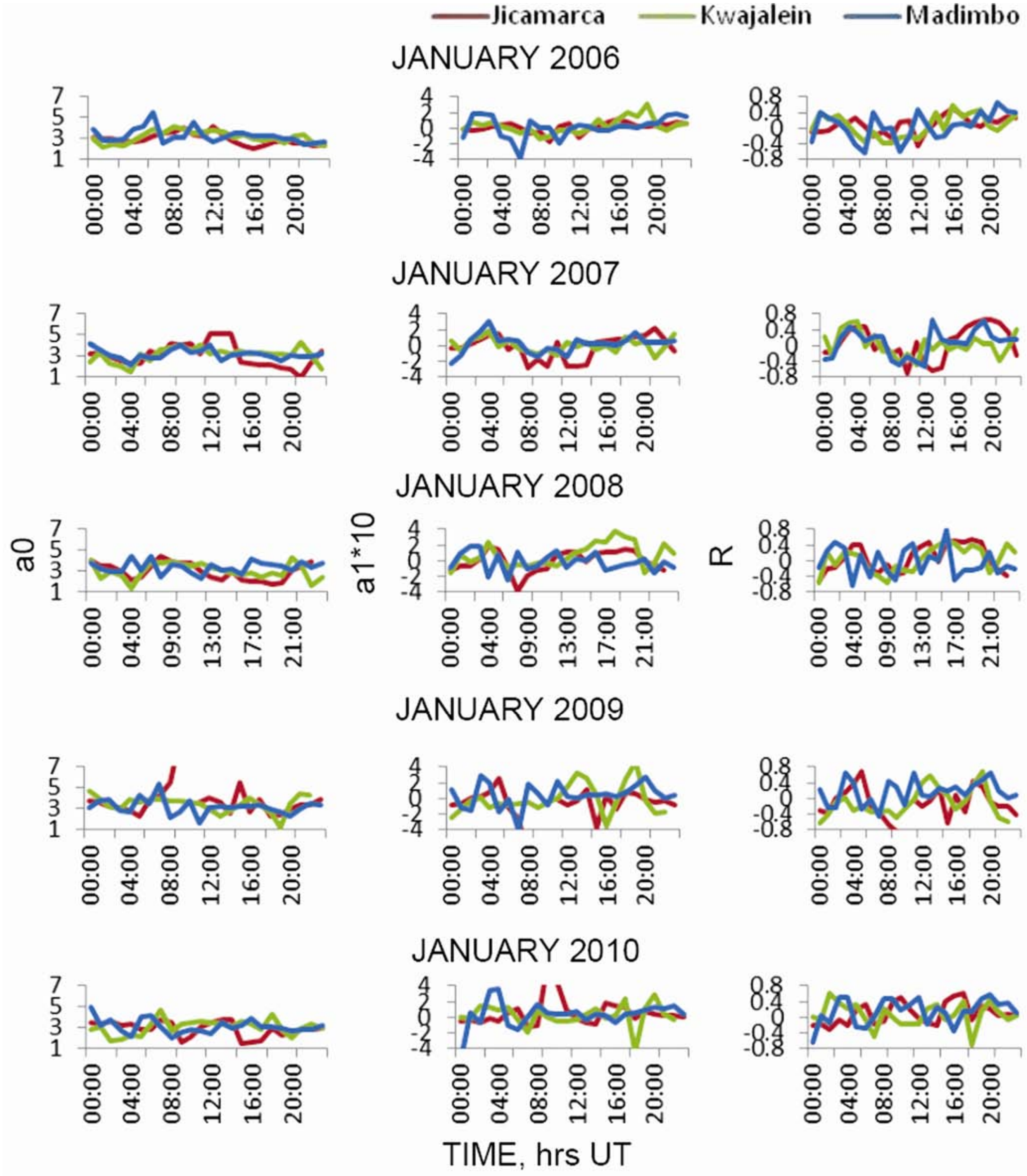

Fig. 1 — Hour-to-hour variations of the coefficient a0, a1 and correlation coefficient R at three low latitude stations for January months during the period 2006-2010

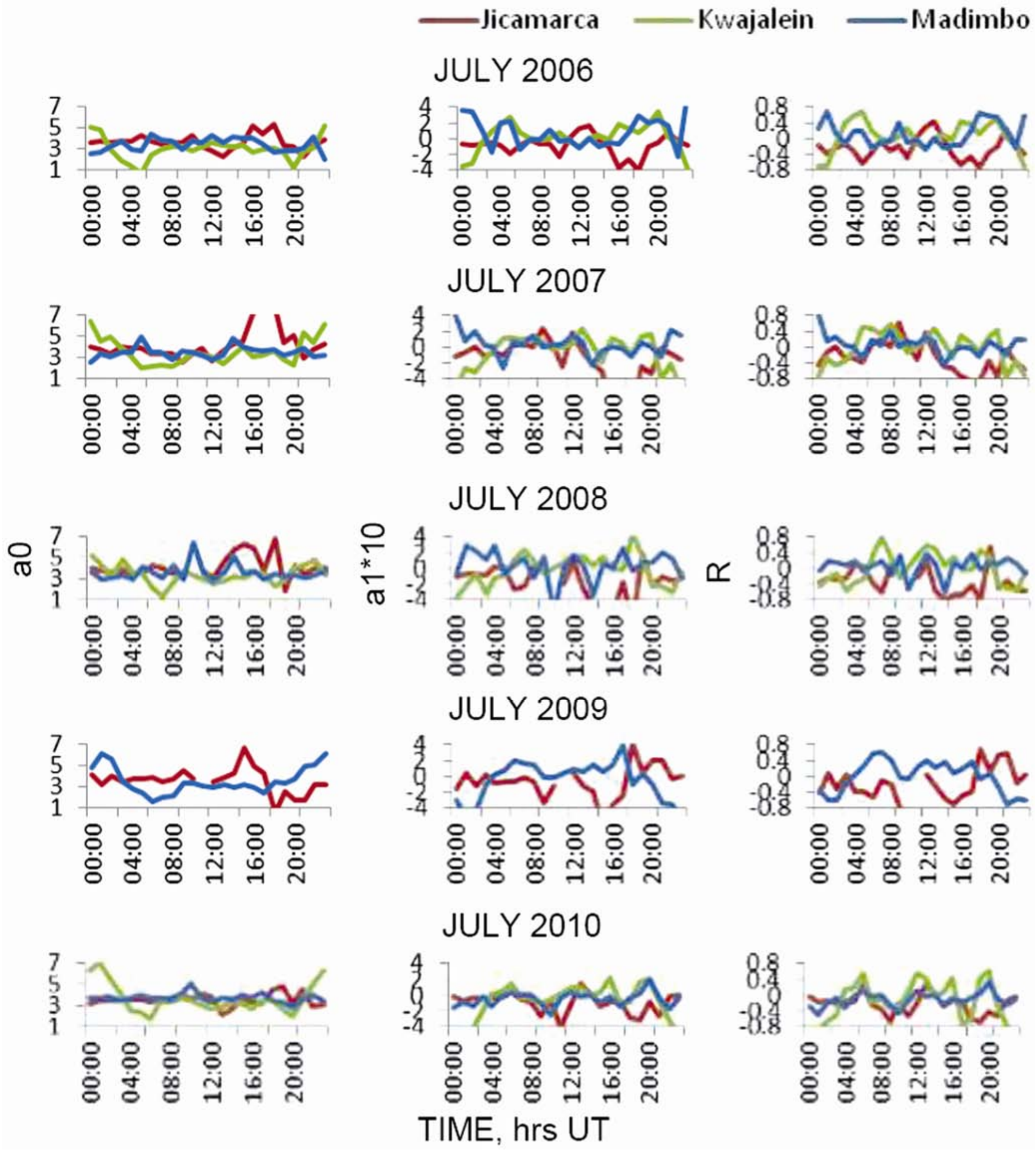

Fig. 2 — Hour-to-hour variations of the coefficient a0, a1 and correlation coefficient R at three low latitude stations for July months during the period 2006-2010

Table 1—Average value of standard error of estimate for hour-to-hour variation

	Jicamarca				Kwajalein				Madimbo			
Time, hrs UT	January		July		January		July		January		July	
	N	SE	N	SE	N	SE	N	SE	N	SE	N	SE
00:00	135	0.29	119	0.27	127	0.31	133	0.40	87	0.29	109	0.29
01:00	135	0.31	120	0.30	131	0.31	141	0.45	86	0.28	112	0.27
02:00	136	0.32	118	0.30	133	0.22	144	0.44	90	0.30	103	0.31
03:00	137	0.32	120	0.29	135	0.23	144	0.36	87	0.28	96	0.24
04:00	130	0.33	122	0.28	134	0.50	143	0.25	91	0.23	108	0.27
05:00	123	0.28	125	0.32	135	0.26	151	0.23	92	0.21	119	0.28
06:00	111	0.35	120	0.29	132	0.22	143	0.25	93	0.29	119	0.20
07:00	89	0.33	114	0.26	132	0.19	145	0.24	93	0.28	119	0.22
08:00	80	0.34	104	0.26	132	0.28	149	0.25	95	0.29	118	0.19
09:00	63	0.36	85	0.29	131	0.25	148	0.25	96	0.17	120	0.22
10:00	41	0.23	60	0.23	132	0.22	149	0.25	101	0.24	119	0.32
11:00	135	0.20	120	0.18	131	0.24	148	0.25	103	0.23	117	0.27
12:00	125	0.23	120	0.15	130	0.27	147	0.32	99	0.20	120	0.25
13:00	126	0.25	120	0.18	127	0.32	150	0.30	96	0.16	121	0.24
14:00	125	0.28	117	0.25	123	0.35	147	0.31	94	0.13	120	0.20
15:00	126	0.33	117	0.27	120	0.36	133	0.38	95	0.22	120	0.19
16:00	127	0.25	112	0.25	107	0.31	122	0.34	98	0.20	117	0.21
17:00	122	0.30	111	0.30	92	0.44	114	0.39	95	0.18	112	0.28
18:00	122	0.26	115	0.35	83	0.50	126	0.48	96	0.15	115	0.30
19:00	128	0.24	115	0.28	133	0.24	153	0.17	94	0.19	120	0.23
20:00	126	0.25	117	0.22	136	0.24	151	0.24	94	0.17	120	0.23
21:00	125	0.25	121	0.24	136	0.25	149	0.27	94	0.25	119	0.22
22:00	129	0.24	122	0.23	134	0.30	148	0.27	93	0.22	113	0.32
23:00	138	0.26	122	0.27	134	0.31	142	0.36	90	0.24	109	0.25

4 Discussion

A search of correlations between ionospheric parameter and its influence factor is of a great scientific interest. Ionospheric behaviour is affected by solar, geomagnetic and meteorological activities and behaves in a complex pattern of seasonal variation. The mixing effects of various influence factors bring about difficulties for studying the coupling of the ionosphere with the atmosphere above or below it. A highly inefficient leakage of energy from below might in principle disturb the energy distribution in the thermosphere and affect the ionospheric behaviour. Shimazki[11] had established a strong anti-correlation between hmF2 and M(3000)F2. Later, Bilitza *et al.*[19] formulated a model that not only established a strong anti-correlation between hmF2 and M(3000)F2 but also introduced a correction factor ΔM_{est}.

In the present study, statistical analysis shows that the two inosospheric characteristics have a different behaviour. In summer season, the correlation coefficients are found much better for day-to-day variations. But no linear correlation between M(3000)F2 and foF2 can be established having a significant value for prediction purpose. Kouris *et al.*[17] reported that the regression analysis between the hourly daily deviations from the corresponding monthly median values ΔM(3000)F2 and ΔfoF2, and Δh'f and ΔfoF2, respectively are poorly correlated. When hourly monthly median values of M(3000)F2 are correlated with corresponding foF2 values in a linear or second order relation, there is little difference between the correlation coefficients being slightly greater in the latter case[20]. Morena *et al.*[18] stated that there is no linear correlation between M(3000)F2 and foF2 having a significant value for prediction purpose and showed that the correlation is poor and contradictory for hour-to-hour variations (in winter and summer) and day-to-day variations in summer, but the correlation is significantly higher and positive for day-to-day variations in winter.

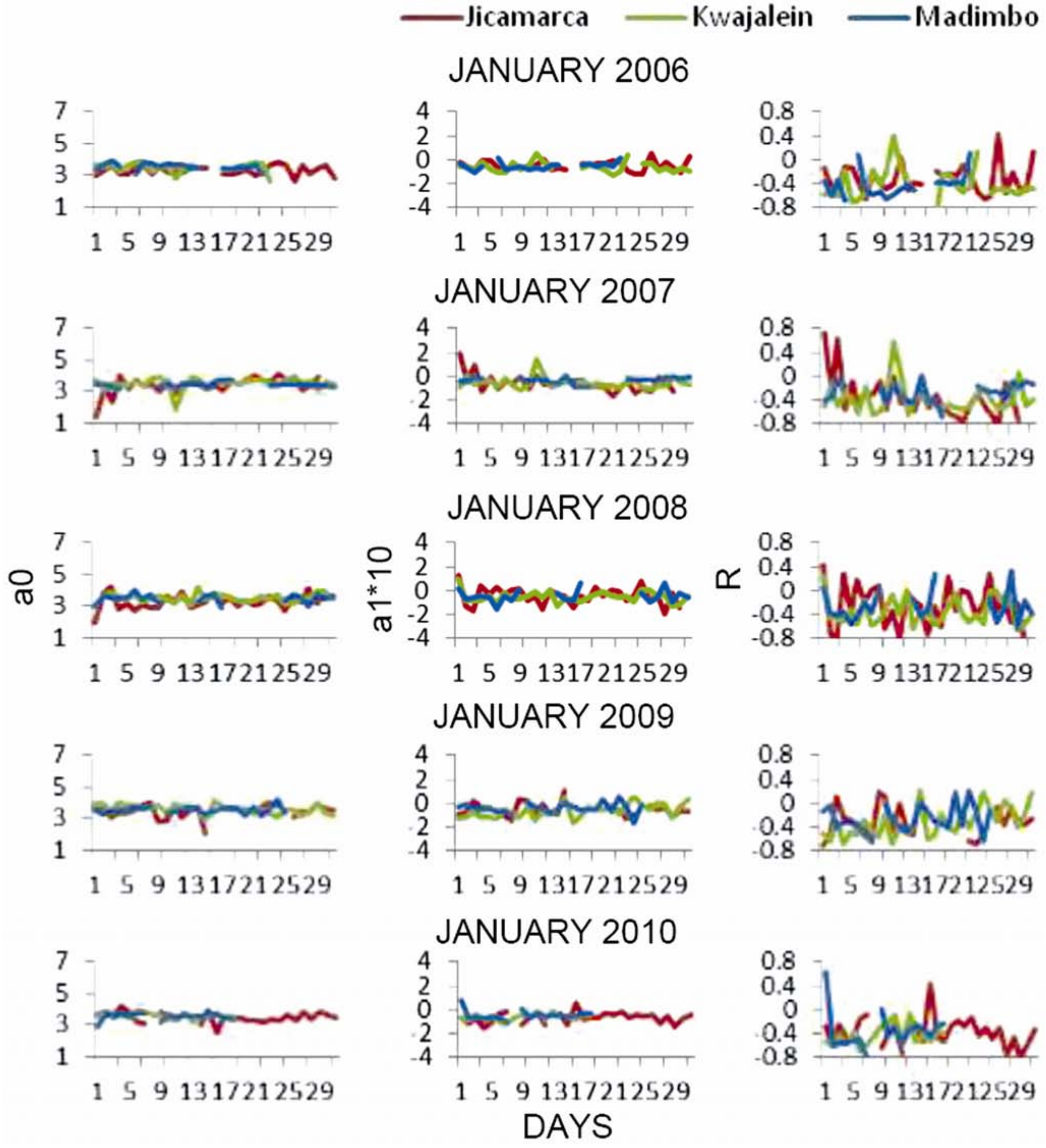

Fig. 3 — Day-to-day variation of the coefficients a0, a1 and correlation coefficient R at three low latitude stations for January months during the period 2006-2010

According to Xu *et al.*[21], the study of correlations between multiple correlative variables, the partial correlation method compared with simple correlation method can reveal the true correlation between two variables by eliminating the influences of other correlative variables. They suggested that the simple correlation coefficient between NmF2 and h(100) is affected by other influence factors such as solar and geomagnetic activities, and the seasonal factors. McNamara & Wilkinson[22] drew attention to the

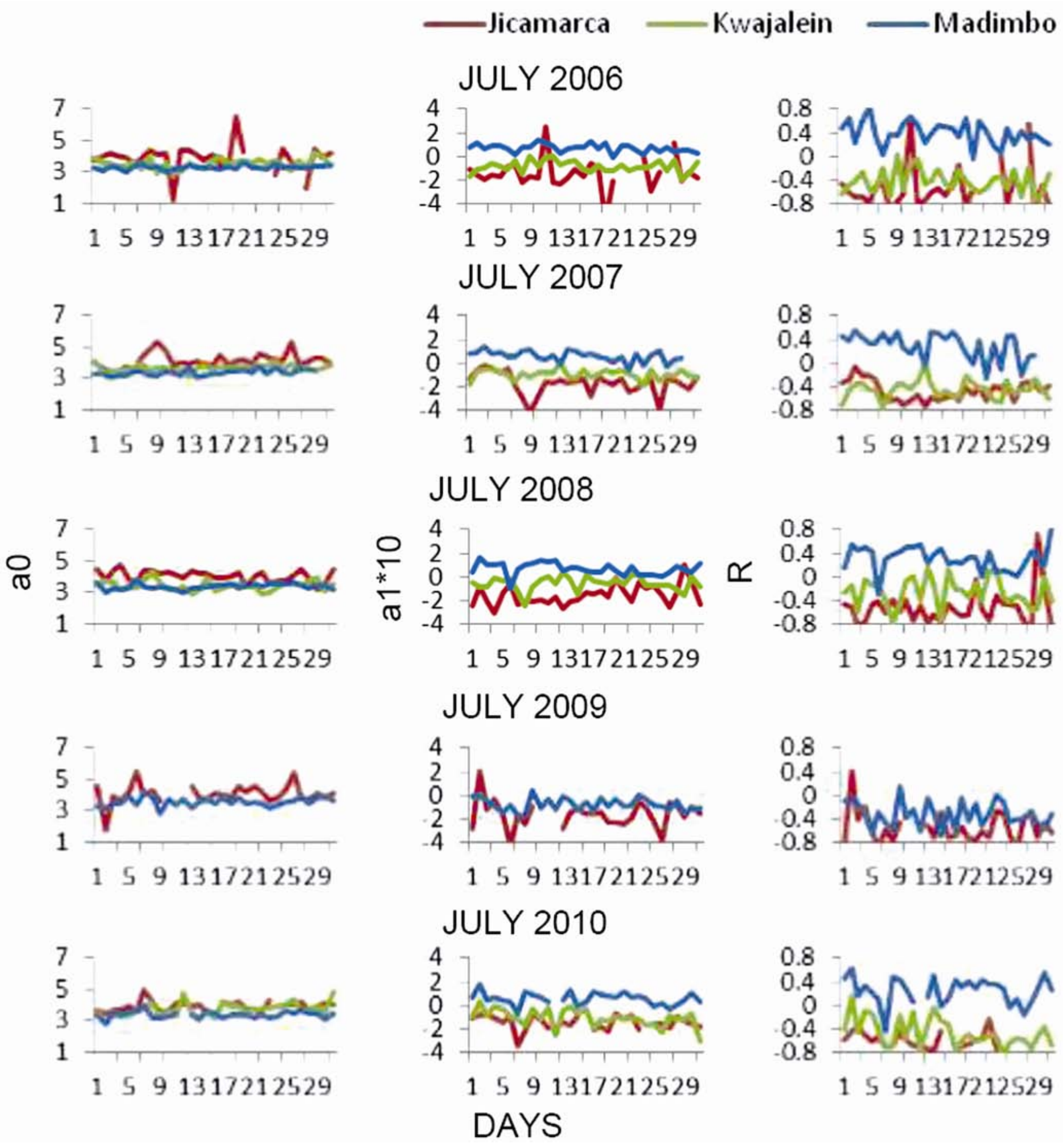

Fig. 4 — Day-to-day variation of the coefficients a0, a1 and correlation coefficient, R at three low latitude stations for July months during the period 2006-2010

importance of separating the data into magnetically quiet and disturbed days, since lumping the data together can lead to correlation coefficients that apply neither the quiet nor disturbed days. In this connection, McNamara & Wilkinson[23] studied the correlations between deviations of foF2 from the monthly median for magnetically quiet days (Ap <25) and found that the correlation coefficients decrease approximately linearly with station separation and they decrease with decreasing solar activity.

Table 2—Average value of standard error of estimate for day-to-day variation

	Jicamarca				Kwajalein				Madimbo			
	January		July		January		July		January		July	
Days	N	SE	N	SE	N	SE	N	SE	N	SE	N	SE
1	63	0.34	92	0.33	96	0.56	117	0.39	36	0.26	93	0.23
2	68	0.28	88	0.28	91	0.27	100	0.38	46	0.23	92	0.29
3	91	0.32	74	0.3	86	0.35	117	0.39	48	0.25	88	0.3
4	105	0.32	72	0.31	93	0.31	110	0.35	36	0.21	91	0.23
5	95	0.3	83	0.31	94	0.28	104	0.34	41	0.15	93	0.29
6	106	0.33	89	0.28	95	0.31	115	0.37	62	0.26	92	0.31
7	105	0.34	78	0.32	89	0.39	106	0.38	71	0.29	84	0.35
8	79	0.34	82	0.33	93	0.29	113	0.31	60	0.26	91	0.3
9	102	0.34	90	0.28	94	0.35	109	0.37	60	0.21	91	0.31
10	106	0.33	71	0.36	89	0.39	113	0.36	62	0.23	88	0.28
11	95	0.3	74	0.29	75	0.38	111	0.35	72	0.3	82	0.29
12	94	0.31	75	0.28	92	0.33	109	0.35	72	0.18	72	0.24
13	86	0.28	89	0.22	87	0.32	107	0.36	63	0.18	82	0.25
14	83	0.3	91	0.28	92	0.35	113	0.38	72	0.19	91	0.24
15	102	0.33	102	0.27	91	0.38	111	0.33	107	0.21	92	0.24
16	68	0.28	81	0.28	91	0.31	107	0.36	120	0.24	96	0.26
17	82	0.33	97	0.31	91	0.28	118	0.36	115	0.29	108	0.25
18	85	0.28	69	0.27	115	0.31	111	0.4	62	0.19	93	0.25
19	86	0.32	80	0.36	112	0.33	115	0.39	49	0.27	95	0.29
20	84	0.29	80	0.35	111	0.33	111	0.36	39	0.27	94	0.58
21	93	0.29	74	0.34	115	0.33	117	0.28	47	0.28	93	0.26
22	94	0.29	82	0.31	119	0.35	108	0.34	64	0.25	94	0.29
23	103	0.32	77	0.34	96	0.33	99	0.35	83	0.25	93	0.33
24	91	0.32	52	0.39	92	0.37	105	0.38	95	0.21	94	0.26
25	83	0.32	89	0.32	94	0.35	118	0.34	109	0.23	92	0.23
26	87	0.35	69	0.33	99	0.3	116	0.39	120	0.25	91	0.28
27	97	0.28	66	0.35	101	0.33	112	0.36	95	0.31	93	0.27
28	107	0.33	79	0.37	116	0.29	115	0.32	95	0.36	92	0.25
29	102	0.37	70	0.33	111	0.34	112	0.38	86	0.26	78	0.26
30	94	0.3	84	0.38	104	0.28	106	0.36	81	0.26	72	0.24
31	99	0.29	84	0.28	116	0.33	95	0.36	84	0.23	65	0.24

5 Conclusion

The statistical analysis shows that the two inosospheric parameters have a different behaviour. Therefore, no linear correlation between M(3000)F2 and foF2 can be established having a significant value for prediction purpose. For day-to-day variations, the winter-summer differences in the behaviour of regression line coefficient and correlation coefficient cannot be neglected. All these findings suggest that although a better correlation exists between M(3000)F2 and foF2 when day-to-day variation is examined but yet it is poor. More investigation by taking data for high solar activity may provide a clear inside picture of the phenomenon.

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