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Interplanetary magnetic field and its possible effects on the mid-latitude ionosphere III

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Abstract
Using critical frequencies, f_0F_2 from the Lannion, Slough, Poitiers, Garchy, Dourbes, Rome, Juliusrud, Gibilmanna, Pruhonice, Uppsala, Kaliningrad, Miedzeszyn, Sofia, Athens and Kiev ionosonde stations, the possible effects of the orientation of the Interplanetary Magnetic Field (IMF) on mid-latitude ionosphere are further investigated. This time, only the southward polarity changes in IMF B_z with seasonal effects were considered. The same method of analysis was employed to facilitate a comparison between the recent results presented here with those which appeared in the preceding papers in the series. That is, the regular diurnal, seasonal and solar cycle variations in the f_0F_2 data were removed by subtracting the mean of the f_0F_2 for the same UT on all magnetically quite days ($A_p < 6$) within 15 days around the IMF B_z turnings (Tulunay, 1994). This last paper also includes the seasonal effects on the ionospheric data. The results confirm that much of the day-to-day variability of the mid-latitude ionosphere may be related to the orientation of the southward IMF B_z, characterized by the ionospheric winter anomaly. Day-to-day ionospheric variability becomes more significant towards higher latitudes.

Key words *ionospheric variability – interplanetary B_z reversals*

1. Introduction

The day-to-day ionospheric variability of f_0F_2 has remained unpredictable, despite many scientific studies to find its origins (Aravindan and Iver, 1990, 1993). This unpredictable variability greatly limits the efficiency of operation of communication, radar and navigation systems which employ HF radio waves (Lockwood *et al.*, 1993, private communication; Tulunay, 1994, 1995a). The objective of this paper is to search further to the possible effects of the orientation of the Interplanetary Magnetic Field (IMF) on the critical frequency of the ionospheric F-layer at mid-latitudes. This paper includes some more results of the recent work conducted by employing frequencies from the fifteen PRIME ionospheric stations between 1967 and 1984. The critical frequencies are studied in conjuction with simultaneous satellite measurements of the IMF. In particular, significant effects of polarity changes of IMF B_z in Geocentric-Solar-Magnetospheric (GSM) and the seasonal, latitudinal effects on

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Table I. Some statistical results.

Station names	Geographic coordinates	Data coverage	Major southward IMF B_z turnings					
			Min value	Max value	Median	Mode	Lower decile	Upper decile
Annual $\delta f_0 F_2$ (0.1 MHz)								
Lannion	(49°N, 3°W)	(1971-1984)	−8.9	5	−0.3	−0.1	−1.8	0.9
Slough	(51°N, 1°W)	(1967-1984)	−8.5	4.8	−0.2	0	−1.7	0.9
Poitiers	(47°N, 0°E)	(1967-1984)	−9.1	4.9	−0.1	0	−1.5	1
Garchy	(47°N, 3°E)	(1969-1973)	−3.7	4.4	−0.1	0	−1.2	0.7
Dourbes	(50°N, 5°E)	(1967-1984)	−9.2	6	−0.2	0	−1.6	0.9
Rome	(42°N, 13°E)	(1967-1972; 1976-1984)	−7.2	5.8	−0.1	0	−1.5	1.1
Juliusrud	(55°N, 13°E)	(1974-1984)	−9.2	4.3	−0.3	0	−1.9	0.8
Gibilmanna	(38°N, 14°E)	(1976-1980; 1983-1992)	−3.2	3.9	0.1	0.2	−0.9	1.5
Pruhonice	(50°N, 15°E)	(1967-1968; 1976-1984)	−6.5	4.5	−0.2	0	−1.7	0.8
Uppsala	(60°N, 18°E)	(1967-1984)	−8.4	6.3	−0.3	0	−2	0.8
Kaliningrad	(55°N, 21°E)	(1967-1984)	−8.6	5.9	−0.2	0	−1.7	0.8
Miedzesyn	(52°N, 21°E)	(1967-1984)	−7.9	7.5	−0.2	0	−2.1	1
Sofia	(43°N, 23°E)	(1967-1974; 1976-1983)	−7.5	4.3	−0.1	0	−1.7	1.1
Athens	(38°N, 24°E)	(1967-1974; 1976-1984)	−4.5	4.9	0	0	−1	1.2
Kiev	(51°N, 31°E)	(1967-1984)	−5.4	5	0	0	−1.1	1
Winter $\delta f_0 F_2$ (MHz)								
Lannion	(49°N, 3°W)	(1971-1984)	−8.9	5	−0.1	−0.1	−1.4	1.3
Slough	(51°N, 1°W)	(1967-1984)	−8.5	4.8	−0.1	0	−1.4	1.1
Poitiers	(47°N, 0°E)	(1967-1984)	−9.1	4.4	0	0	−1.1	1.3
Garchy	(47°N, 3°E)	(1969-1973)	−3.7	4.4	0	0	−0.9	0.8
Dourbes	(50°N, 5°E)	(1967-1984)	−9.2	6	0	0	−1.2	1.1
Rome	(42°N, 13°E)	(1967-1972; 1976-1984)	−7.2	5.8	0.1	0	−1	1.4
Juliusrud	(55°N, 13°E)	(1974-1984)	−9.2	4.3	−0.1	−0.2	−1.5	1.1
Gibilmanna	(38°N, 14°E)	(1976-1980; 1983-1991)	−2.2	3.3	0.2	0.4	−0.7	1.3
Pruhonice	(50°N, 15°E)	(1967-1968; 1976-1984)	−6.5	4.5	0	0	−1.3	1
Uppsala	(60°N, 18°E)	(1967-1984)	−8.4	6.3	−0.1	0	−1.7	1
Kaliningrad	(55°N, 21°E)	(1967-1984)	−8.6	5.9	−0.1	0	−1.3	1
Miedzeszyn	(52°N, 21°E)	(1967-1984)	−7.9	7.5	0	0	−1.7	1.3
Sofia	(43°N, 23°E)	(1967-1974; 1976-1983)	−5.6	4.3	0	0	−1.3	1.3
Athens	(38°N, 24°E)	(1967-1974; 1976-1984)	−3.6	4.9	0.2	−0.1	−0.7	1.4
Kiev	(51°N, 31°E)	(1967-1984)	−5.4	5	0	0	−1	1.1

Table I (*continued*).

Station names	Geographic coordinates	Data coverage	Major southward IMF B_z turnings Min value	Max value	Median	Mode	Lower decile	Upper decile
			Summer δf_0F_2 (MHz)					
Lannion	(49°N, 3°W)	(1971-1984)	−8.8	3.9	−0.4	0	−1.9	0.7
Slough	(51°N, 1°W)	(1967-1984)	−8.3	4.4	−0.4	0	−1.9	0.6
Poitiers	(47°N, 0°E)	(1967-1984)	−8.4	4.9	−0.3	0	−1.8	0.7
Garchy	(47°N, 3°E)	(1969-1973)	−3.1	3	−0.4	0	−1.5	0.5
Dourbes	(50°N, 5°E)	(1967-1984)	−8.3	4.2	−0.4	0	−1.9	0.6
Rome	(42°N, 13°E)	(1967-1972; 1976-1984)	−6.9	3.5	−0.3	0	−1.9	0.8
Juliusrud	(55°N, 13°E)	(1974-1984)	−7.8	3.4	−0.4	0	−2	0.6
Gibilmanna	(38°N, 14°E)	(1976-1980; 1983-1991)	−3.2	3.9	−0.1	−0.9	−1.5	1.7
Pruhonice	(50°N, 15°E)	(1967-1968; 1976-1984)	−6.2	3.1	−0.4	0	−2	0.7
Uppsala	(60°N, 18°E)	(1967-1984)	−7.2	2.9	−0.4	0	−2.1	0.6
Kaliningrad	(55°N, 21°E)	(1967-1984)	−7.2	3.7	−0.4	0	−2	0.6
Miedzesyn	(52°N, 21°E)	(1967-1984)	−6.7	2.9	−0.4	0	−2.3	0.7
Sofia	(43°N, 23°E)	(1967-1974; 1976-1983)	−7.5	4.2	−0.4	−0.1	−2.1	0.9
Athens	(38°N, 24°E)	(1967-1974; 1976-1984)	−4.5	3.8	−0.2	0	−1.4	0.9
Kiev	(51°N, 31°E)	(1967-1984)	−3.3	2.3	−0.1	0	−1.3	0.7

the results are revealed. In order to improve the statistics a larger subset of the IMF B_z southward turnings (key data) were employed this time.

2. The data sets

The data concerning the interplanetary medium used in this work were taken from a compilation of solar wind plasma and IMF data prepared by the US National Space Science Data Center (NSSDC) (Hapgood *et al.*, 1991).

The ionospheric critical frequency data used here were taken from the COST 238 PRIME data base at the CNET Laboratories (Hanbaba and Sizun, 1993, private communication). The critical frequencies were obtained from the ionosonde stations at Lannion, Slough, Poitiers, Garchy, Dourbes, Rome, Juliusrud, Gibilmanna, Pruhonice, Uppsala, Kaliningrad, Miedzeszyn, Sofia, Athens and Kiev whose geographical coordinates are given in table I. The table also lists periods of data coverage.

In order to study the day-to-day variability of the ionospheric densities about the regular diurnal variations, some form of «quiet-time» diurnal variations must be subtracted from the variations observed (Tulunay, 1994). In order to achieve this, for each hourly value of f_0F_2 all quiet-time soundings with 15 days of the sounding in question were identified: quiet-time-values were defined as those corresponding to times with simultaneous magnetic A_p index less than 6. The mean quiet-day control value was then subtracted from the value that was actually observed: the resulting value is

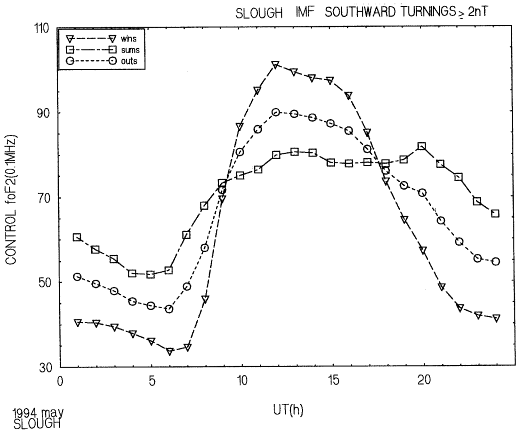
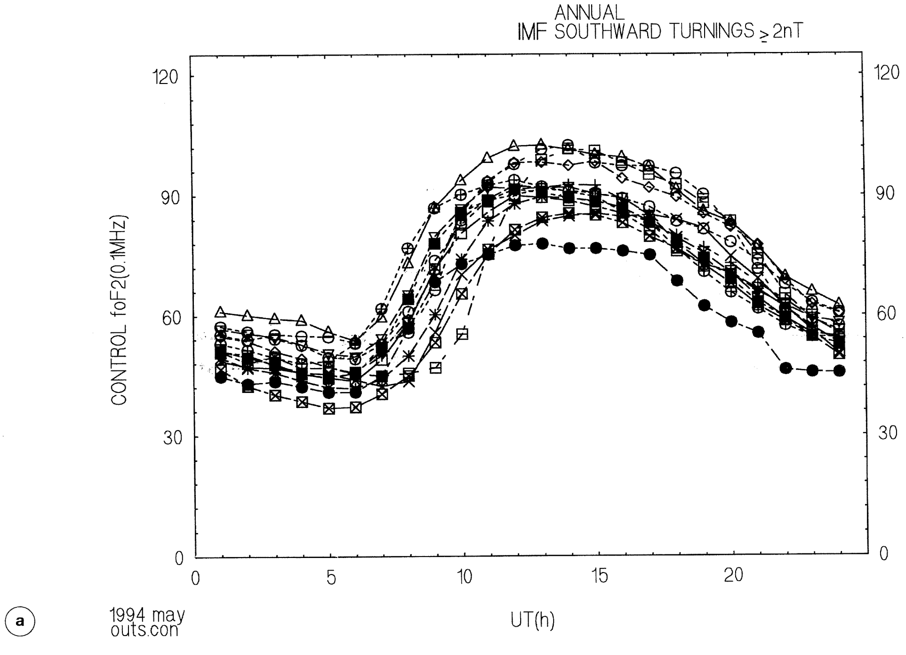


Fig. 1. The quiet-time (control) diurnal variations of the Slough f_0F_2 data during the IMF southward turnings («wins», «sums», «outs» stand for winter, summer and all seasons or annual). The data points are jointed by a polynomial fit.

here termed δf_0F_2. Only ionospheric data which were available in digital form were employed. Figure 1 exhibits the diurnal behavior of the quiet-day f_0F_2 control values for Slough. Superimposed on the annual control (or-quiet-time) values (outs) when the southward IMF B_z turnings occurred, are the control (or-quiet-time) values corresponding to the winter period of six months centered on the winter solstice, and the summer period of six months centered on the summer solstice. For both of the winter and summer diurnal control curves the main criterion was the southward turning of the IMF B_z. Figure 2a-c shows the diurnal variation of the control values of the ionospheric critical frequencies, f_0F_2, obtained at the 15 PRIME stations of interest, annually, for winter and summer periods during the southward IMF B_z turnings. As clearly seen in figs. 1 and 2a-c, the winter f_0F_2 control values are greater in magnitude than those of the summer ones. This seasonal anomaly does not appear before, approximately, 08 h UT and after dusk hours.

Figure 3 exhibits the latitudinal behavior of the averaged δf_0F_2 at fixed UT hours. In general, δf_0F_2 is greater at low latitudes than at higher latitudes. The maximum spread in



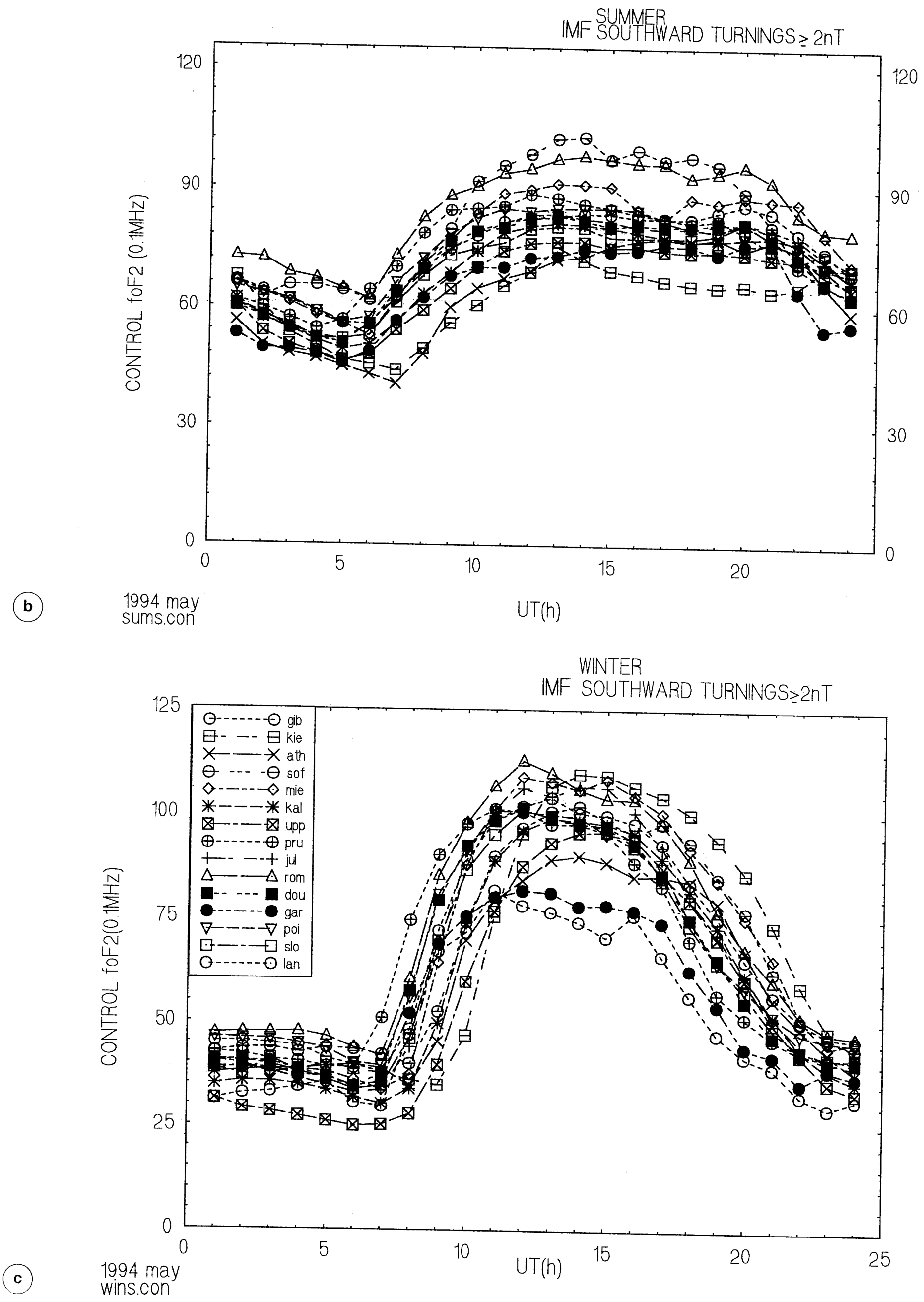


Fig. 2a-c. The quiet-time (control) diurnal variations of the f_0F_2 data obtained from 15 PRIME stations for all observations in the period of interest during the IMF southward turnings: a) for all seasons (annual); b) for summer; c) for winter. The dashed lines are polynomials fits.

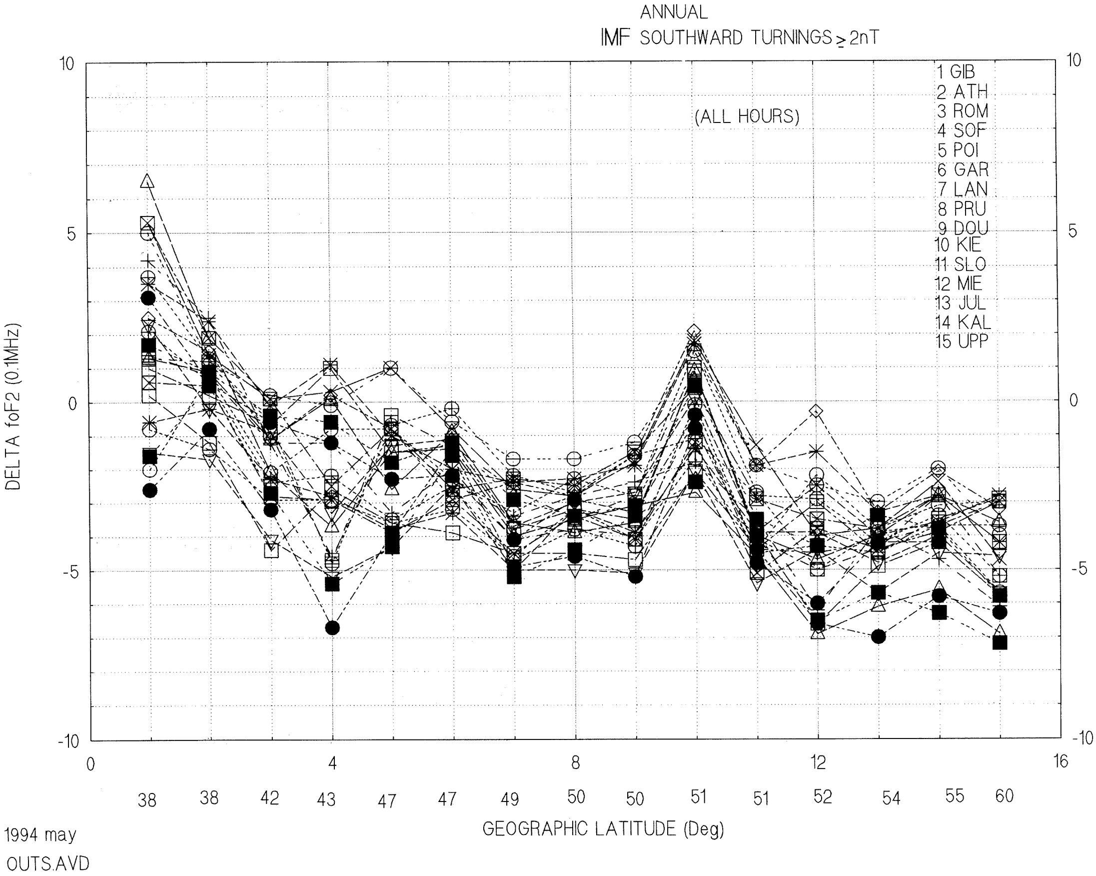


Fig. 3. The latitudinal variation of the $\delta f_0 F_2$ for the 15 PRIME stations of interest during the IMF southward turnings. Each curve is polynomial fits at a fixed Universal Time (UT).

the values of $\delta f_0 F_2$ ranges between -0.7 and $+0.7$ MHz at low latitudes, and at the other extreme, they range -0.7 to -0.2 MHz at the highest latitude, that is at Uppsala. Figure 4 is the diurnal variation of the annual, summer and winter $\delta f_0 F_2$ for all observations in the periods of interest. Largest deviations of the critical frequencies from quiet-time values occur around 10 h UT and the smallest deviations are near dusk. Due to the seasonal anomaly the winter $\delta f_0 F_2$ values are nearer to zero in the winter curve.

Figure 4 is the diurnal variation of the annual, summer and winter $\delta f_0 F_2$ for all observations in the periods of interest. Largest deviations of the critical frequencies from quiet-time values occur around 10 h UT and the smallest deviations are near dusk. Due to the seasonal anomaly the winter $\delta f_0 F_2$ values are nearer to zero in the winter curve.

As seen in table I, for the major southward IMF B_z turnings the distributions of $\delta f_0 F_2$ are skewed with the most common (mode) values between -0.9 and 0.4 during summer, winter, or annually (all seasons) for the PRIME stations of interest. The upper and lower decile values as listed in table I range between 0.7 and 1.5 MHz; -2.1 and 0.9 MHz annually, and

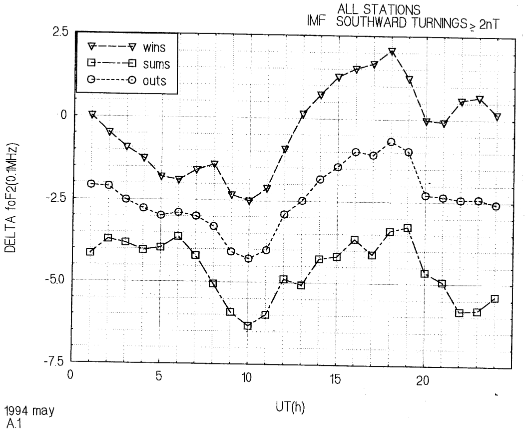


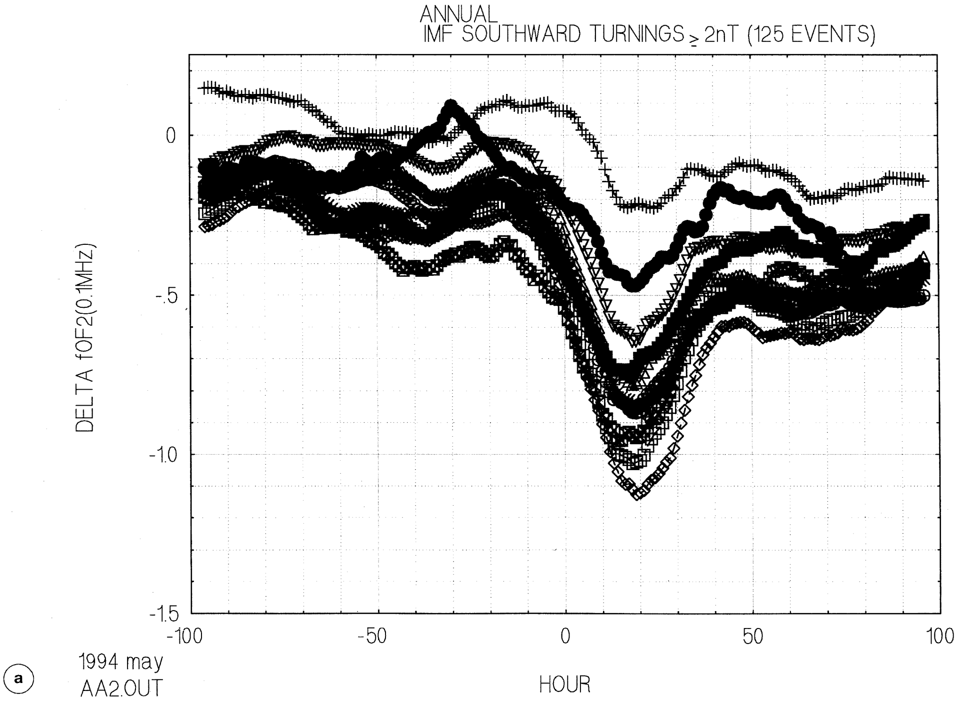
Fig. 4. The diurnal variation of the annual (outs), summer (sums), winter (wins) averaged $\delta f_0 F_2$ during the IMF southward turnings.

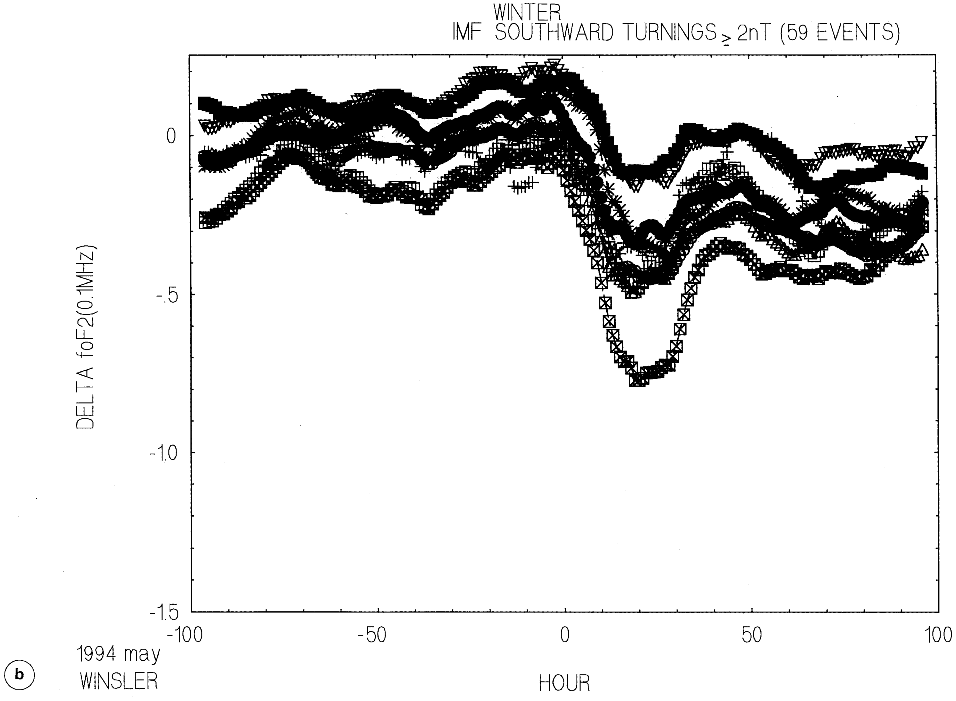
between 0.5 and 1.7 MHz; -2.3 and -1.3 MHz during summer; 0.8 and 1.4 MHz; -1.7 and -0.7 MHz during winter. Hence, the day to day variability, not accounted for by regular quiet-time variations amount to a spread between 1.7 and 3.2 MHz for the data under consideration. 1.7 and 3.2 MHz spread are found when the difference between the upper and the lower decile values are considered for all the stations during winter and summer. 1.7 and 3.1 MHz when compared with the most common values of f_0F_2; *i.e.* around 6.1 MHz, once more, it has become apparent that, the day-to-day variability presents an important problem in practice (Tulunay, 1994).

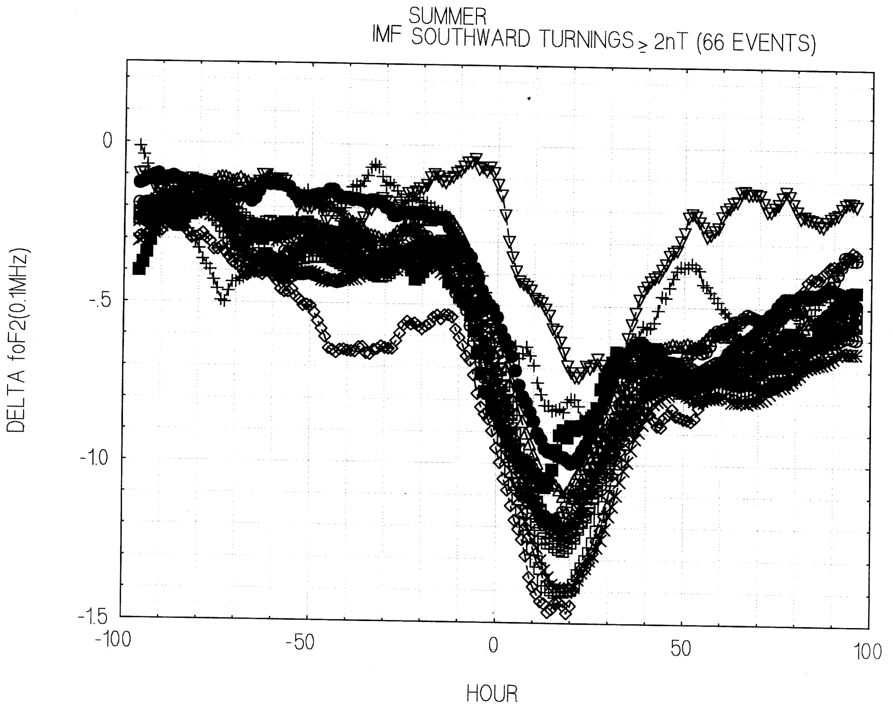
3. Results and conclusions

In order to study the possible effects of the orientation of the IMF on the ionospheric variability, the IMF B_z was required to change polarity towards the south and to change in magnitude by at least 2 nT (Hapgood *et al.*, 1991; Tulunay *et al.*, 1991; Tulunay and Rahman, 1993; Tulunay, 1994). Such a reversal was named an «event» and fig. 5a-c shows the results of the superposed epoch studies for the $|\Delta B_z| \geq 11.5$ nT events. The results of this analysis show that changes in IMF B_z do cause depletions of the mid-latitude ionosphere. The $\delta f_0 F_2$ shows systematic variations for one to three days following southward IMF turnings. The results are in favour of the fact that the IMF controlled flows at high latitudes have some influence on the mid-latitude ionosphere, via the action of the neutral thermosphere the IMF B_y component is known to modulate the flow pattern of convection. It has been predicted that the dayside thermospheric heating will be different for the two B_y polarities, because the afternoon sector response of auroral thermospheric winds is not the same as that in the morning sector (Lockwood, 1995, private communication). Any possible significant effect of polarity changes of both IMF B_z (in GSM) and B_y in the near will be considered.

The effect of the annual southward IMF B_z turnings is represented in fig. 5a annually, in (b) for winter and in (c) for summer. In all plots the IMF change occurred at time zero. The horizontal axis gives the times in hours relative to the IMF B_z polarity change, and the vertical axis shows the mean value of $\delta f_0 F_2$. The best fit curves of the data exhibited in fig. 5a-c show clear minima in the average $\delta f_0 F_2$ during the day after the southward IMF turnings. Table II summarizes the $\delta f_0 F_2$ values in MHz before and after the southward turning of the IMF B_z component. On the average these minima are at $\delta f_0 F_2$ of approximately, -0.72 MHz in the annual, -0.42 in the winter and -1.22 MHz in the summer results. The values before the events, are however, not always zero, indicating that many non quiet-day values are present (Tulunay, 1994). The average $\delta f_0 F_2$ values before the event are -0.15 MHz, -0.04 MHz, -0.29 MHz for the annual winter and summer results respectively. Thus, the peak change in $\delta f_0 F_2$ which can be attributed to the southward IMF B_z turnings are, approximately, 0.60 MHz, 0.39 MHz, 0.93 MHz for the annual, winter and summer results on the average (table II). The peak change is the largest for Kaliningrad with 0.91 MHz and the smallest for Kiev with 0.31 MHz for the annual results; for the winter results the corresponding values are for Uppsala with 0.64 MHz, for Kiev with 0.23 MHz; and for the summer results the


ANNUAL
IMF SOUTHWARD TURNINGS ≥ 2nT (125 EVENTS)
DELTA fOF2(0.1MHZ)
0
-.5
-1.0
-1.5
-100
-50
0
50
100
HOUR
a
1994 may
AA2.OUT


WINTER
IMF SOUTHWARD TURNINGS ≥ 2nT (59 EVENTS)
DELTA foF2(0.1MHz)
0
-.5
-1.0
-1.5
-100
-50
0
50
100
HOUR
b
1994 may
WINSLER



c

Fig. 5a-c. Superimposed epoch plots of mean δf_0F_2 as a function of event time: a) for all seasons: b) for winter; c) for summer during the IMF southward turnings. Event time zero is the time of southward turning events of the IMF B_z. The horizontal axis gives the time (in hours) relative to the IMF B_z polarity change, and vertical axis shows the mean value of δf_0F_2.

corresponding values are for Juliusrud with 1.43 MHz, and for Athens with 0.58 MHz. On the average the percent peak deviation is larger in the winter results than those of the summer results with respect to the values obtained before the events. The magnitude of the changes described here are a large part of the total variability reported before in fig. 2a-c of Tulunay (1994). Thus, the results imply that the southward turning of the IMF B_z can contribute to day-to-day variability of the mid-latitude densities. In particular, the day-to-day variability seems season-dependent and the results reported here show that winter is more favorable for such variabilities. δf_0F_2values before and after the IMF B_z turnings tend to increase towards higher latitudes as depicted from the data exhibited in table II.

Summarizing, this study of critical frequencies from fifteen PRIME stations reveals once more that much of the day-to-day variability of the mid-latitude ionosphere may be related to the orientation of the southward IMF B_z. This variability is quantified as the peak change of δf_0F_2. The peak deviation of the critical frequencies from quiet-time values occurs near dusk, whereas the smallest deviation is near dawn. The winter day time f_0F_2 values in general and the day-to-day variability seems to be larger than those of the summer and annual values exhibiting the ionospheric winter anomaly. A latitudinal variation of δf_0F_2 is also found with larger values at higher latitudes. The duration of the ionospheric effect of the IMF B_z turning was also analyzed by Tulunay (1995b). The median of the duration from

Table II. The $\delta f_0 F_2$ values in MHz before and after the southward IMF B_z turnings (these values are marked as (a) and (b) in fig. 5.

Station name	Annual			Winter			Summer		
	a	b	Ia-bI	a	b	Ia-bI	a	b	Ia-bI
Gibilmanna				−0.42	−0.02	0.4			
Athens							−0.17	−0.75	0.58
Rome	−0.02	−0.47	0.45				−0.2	−1.02	0.82
Sofia	−0.17	−0.57	0.4				−0.31	−1.09	0.78
Poitiers	−0.05	−0.64	0.59	0.11	−0.16	0.27	−0.2	−1.1	0.9
Garchy	−0.1	−0.48	0.38				−0.25	−0.94	0.69
Lannion	−0.17	−0.9	0.73	0.02	−0.43	0.45	−0.31	−1.3	0.99
Pruhonice	−0.23	−0.76	0.53				−0.29	−1.3	1.01
Dourbes	−0.14	−0.8	0.66	−0.02	−0.36	0.34	−0.3	−1.24	0.94
Kiev	0.07	−0.24	0.31	−0.11	−0.12	0.23			
Slough	−0.16	−0.85	0.69	−0.1	−0.52	0.42	−0.3	−1.22	0.92
Miedzyne	−0.32	−0.98	0.66	−0.11	−0.39	0.28	−0.5	−1.52	1.02
Juliusrud	−0.27	−1.04	0.79	−0.16	−0.52	0.36	−0.25	−1.68	1.43
Kaliningrad	−0.19	−1.1	0.91	−0.03	−0.47	0.44	−0.34	−1.26	0.92
Uppsala	−0.2	−0.87	0.67	−0.15	−0.79	0.64	−0.36	−1.4	1.04
Average	−0.15	−0.72	0.6	0.01	−0.38	0.39	−0.29	−1.22	0.93

prestorm conditions to recovery for all seasons is 57.9 h, for winter 44.5 h and for summer 55.8 h.

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REFERENCES

ARAVINDAN, P. and K.N. IYER (1990): Day-to-day variability in ionospheric electron content at low latitudes, *Planet. Space Sci.*, **38**, 743-750.

ARAVINDAN, P. and K.N. IYER (1993): Day-to-day variability in ionospheric electron content, *J. Atmos. Terr. Phys.*, **55** (11/12), 1565-1573.

HAPGOOD, M.A., M. LOCKWOOD, G.A. BOWE, D.M. WILLIS and Y.K. TULUNAY (1991): Variability of the interplanetary medium at 1 a.u. over 24 years: 1963-1986, *Planet. Space Sci.*, **39**, 411-423.

TULUNAY, Y. (1994): Interplanetary magnetic field and its possible effects on the mid-latitude ionosphere II, *Annali di Geofisica*, **37** (2), 193-200.

TULUNAY, Y. (1995a): Variability of mid-latitude ionospheric $f_0 F_2$ compare to IMF Polarity inversions, *Adv. Space Res.* **15** (2), 35-44.

TULUNAY, Y. (1995b): *Final Report (Advanced Issue) of the PRIME*, edited by P.A. BRADLEY, 178-181.

TULUNAY, Y. and S. RAHMAN (1993): IMF and its possible effects on $f_0 F_2$ obtained at two almost conjugate stations Slough and Argentine Island I, in *Proceedings of the PRIME/URSI Joint Workshop on «Data Validation of Ionospheric Models and Maps (VIM)»*, Roquetes, May 1992, *Memoria*, **16**, COST 238 TD (93) 001, 410-419.

TULUNAY, Y., P.M. WILLIS, M. LOCKWOOD and M.A. HAPGOOD (1991): The interplanetary magnetic field and its possible effects on mid latitudes, *Final Report of the Project, NATO 0753/87.*