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Global morphology of night-time *Nm*F2 enhancements

A. F. Farelo[1], **M. Herraiz**[1], **and A. V. Mikhailov**[2]

[1]Department of Geophysics and Meteorology, Faculty of Physics, Complutense University, E-28040 Madrid, Spain
[2]Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Russian Academy of Sciences, Troitsk, Moscow Region, Russia

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Abstract. An overall statistical study of night-time enhancements of *Nm*F2 has been carried out. All available *fo*F2 observations since 1955 at 53 ionosonde stations distributed worldwide in the latitude range $\phi_{\text{geom}} = 15° - 60°$ were used in the analysis. More than 200 000 station-nights of data were analysed. This large data base allowed us to study seasonal, solar cycle and spatial variations of the *Nm*F2 night-time enhancements. Both pre-midnight and post-midnight *Nm*F2 peaks demonstrate distinct variations with geophysical conditions, indicating different physical mechanisms responsible for their formation.

Key words. Ionosphere (mid-latitude ionosphere, ionosphere-magnetosphere interactions) Radio science (ionospheric physics)

1 Introduction

Night-time enhancements of electron concentration are typical phenomena of the F2-layer in middle latitudes that can be observed both in the maximum of electron concentration in the F2-layer (*Nm*F2) and total electron content (TEC) (Arendt and Soicher, 1964; Evans, 1965; Da Rosa and Smith, 1967; Bertin and Papet-Lepine, 1970; Young et al., 1970; Titheridge, 1973; Tyagi, 1974; Davies et al., 1979; Ivanov-Kholodny and Mikhailov, 1986; Balan and Rao, 1987; Joshi and Iyer, 1990; Lois et al., 1990; Jakowski et al., 1991; Jakowski and Förster, 1995; Mikhailov and Förster, 1999; Mikhailov et al., 2000a, b). Although *Nm*F2 and TEC variations usually exhibit similar behaviour in the night-time ionosphere, there are some differences in the occurrence of these variations and in the treatment that has been applied to their analysis (Tyagi, 1974; Lois et al., 1990). Two peaks (pre- and post-midnight) in the *Nm*F2 and TEC daily variations are considered here, analysing such characteristic parameters as: occurrence probability, time of occurrence and amplitude, together with their geographic, seasonal and solar activity dependences.

Different mechanisms have been proposed to explain the observed variations. However, the results of previous analyses have often been contradictory. While Rao et al. (1982) found that for stations in Asia the amplitudes of both enhancements are higher during solar maximum; according to Titheridge (1973) and Tyagi (1974), the opposite tendency is observed. Jakowski et al. (1991) pointed out a higher occurrence probability of night-time enhancements of electron concentration during winter and solar minimum for observations in Havana, and a reversal of this behaviour during solar maximum with higher probabilities in summer, which agrees with Rao et al. (1982) but contradicts Titheridge (1973) and Tyagi (1974). Different conclusions are also reached when the local time of occurrence and the duration of *Nm*F2 enhancements are studied.

It should be stressed that in previous publications devoted to this problem the authors considered either one or two increases of electron concentration at night but in quite different ways. In some papers no distinction was made between pre- and post-midnight enhancements and only one peak (the one with the higher amplitude) was considered, even though the presence of both was mentioned (Young et al., 1970; Titheridge, 1973; Tyagi, 1974; Balan and Rao, 1987; Joshi and Iyer, 1990). Other researchers treated these increases separately in their statistical studies, but only one was considered for each night (Jakowski et al., 1991; Jakowski and Förster, 1995). In our study both increases are considered separately, following a method of data analysis similar to one used previously by Mikhailov et al. (2000a, b). Comparisons with results of previous studies based on other methods should be made with caution.

Another important point to be considered is that previous analyses are quite limited either geographically or temporally, lacking complete seasonal and solar activity coverage or being restricted to a single station. Only Mikhailov et al. (2000a) made an extensive study over four solar cycles for four stations in the Eurasian region.

Correspondence to: M. Herraiz (mherraiz@fis.ucm.es)

Table 1. List of stations and data samples used in alphabetical order

Station	Station Code	Latitude (°)	Longitude (°)	Geomagnetic Latitude (°)	Geomagnetic Longitude (°)	Year range		Number of Data
Akita	AK	39.70	140.10	29.83	207.00	1957	1988	4169
Alma Ata	AA	43.20	76.90	33.46	152.00	1957	1989	5219
Arenosillo	EA	37.10	353.20	41.32	72.40	1975	1997	993
Ashkhabad	AS	37.90	58.30	30.37	134.70	1957	1995	3419
Bekescsaba	BH	46.70	21.20	45.19	103.40	1964	1989	2111
Boulder	BC	40.00	254.70	48.89	318.50	1958	1997	5993
Brisbane	BR	−27.50	152.90	−35.33	228.50	1955	1986	4719
Camden	CN	−34.00	150.70	−42.06	227.50	1980	1995	1190
Canberra	CB	−35.30	149.10	−43.57	226.10	1955	1994	5960
Cape Kennedy	CC	28.40	279.40	39.46	348.70	1958	1989	634
Christchurch	GH	−43.60	172.80	−47.69	254.20	1957	1994	3745
Concepcion	CP	−36.60	287.00	−25.35	357.90	1957	1979	2638
Dourbes	DB	50.10	4.60	51.65	89.00	1957	1997	6455
Gorki	GK	56.10	44.30	50.18	127.80	1958	1989	3840
Grahamstown	GR	−33.30	26.50	−33.97	89.70	1973	1997	2883
Graz	GZ	47.10	15.50	46.67	98.20	1958	1981	1762
Hobart	HO	−42.90	147.30	−51.29	226.10	1955	1997	5550
Irkutsk	IR	52.50	104.00	41.88	175.70	1957	1997	5702
Johannesburg	JO	−26.10	28.10	−27.42	94.40	1957	1991	4290
Juliusruh/Rügen	JR	54.60	13.40	54.21	99.90	1957	1998	6013
Kaliningrad	KL	54.70	20.60	52.94	106.60	1964	1994	5182
Karaganda	KR	49.80	73.10	40.35	149.90	1964	1989	3552
Kerguelen	KG	−49.40	70.30	−57.49	130.30	1965	1988	1501
Khabarovsk	KB	48.50	135.10	38.17	201.50	1959	1993	2810
Kiev	KV	50.50	30.50	47.12	113.50	1964	1992	4347
Lannion	LN	48.80	356.60	51.97	80.40	1971	1998	3407
Leningrad	LD	59.90	30.70	56.02	118.40	1957	1998	5098
Lisbonne	LE	38.70	350.70	43.33	70.30	1987	1992	776
Magadan	MG	60.00	151.00	50.94	211.80	1968	1997	3879
Maui	MA	20.80	203.50	21.19	269.80	1957	1994	7150
Miedzeszyn	MZ	52.20	21.20	50.45	105.80	1958	1975	2072
Moscow	MO	55.50	37.30	50.73	121.60	1957	1998	7710
Mundaring	MU	−32.00	116.40	−43.16	188.20	1959	1994	5109
Norfolk	NI	−29.00	168.00	−34.35	244.80	1964	1994	4687
Novokazalinsk	NK	45.50	62.10	37.35	139.70	1964	1989	3289
Observatori de L'Ebr	EB	40.80	0.30	43.56	80.90	1956	1998	1785
Ottawa	OT	45.31	284.01	56.60	353.30	1955	1993	4891
Point Arguello	PA	35.60	239.40	42.30	302.70	1969	1997	4724
Rome	RO	41.80	12.50	42.15	93.30	1958	1997	4846
Rostov	RV	47.20	39.70	42.34	120.50	1957	1998	2747
Slough	SL	51.50	359.40	54.00	84.60	1957	1995	6384
Sofia	SQ	42.70	23.40	40.92	104.40	1964	1998	4334
St Johns	SJ	47.60	307.30	58.15	23.20	1957	1980	1916
Sverdlovsk	SV	56.40	58.60	48.46	139.70	1957	1995	6347
Tahiti	TT	−17.70	210.70	−15.16	284.60	1971	1989	2259
Tashkent	TQ	41.30	69.60	32.31	145.40	1961	1998	4411
Tokio	TO	35.70	139.50	25.80	206.90	1957	1991	5196
Tomsk	TK	56.50	84.90	46.04	160.80	1957	1997	6479
Townsville	TV	−19.70	146.90	−28.44	220.70	1955	1997	3864
Uppsala	UP	59.80	17.60	58.28	107.00	1957	1998	4265
Wakkanai	WK	45.40	141.70	35.63	207.50	1957	1988	4147
Wallops Is.	WP	37.80	284.50	49.01	354.20	1967	1997	3429
Yamagawa	YG	31.20	130.60	20.64	199.40	1957	1988	4389

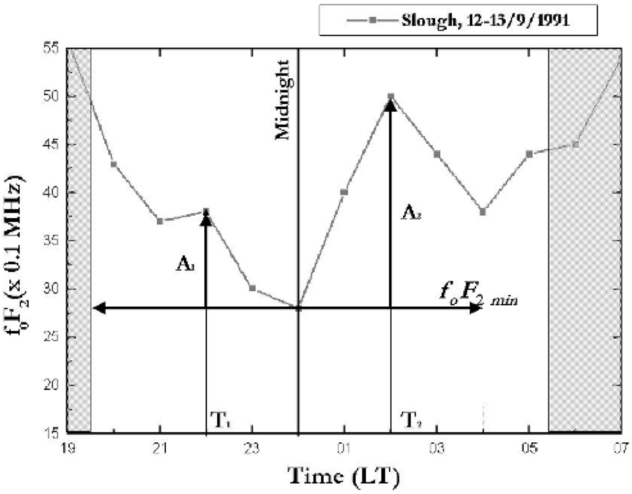

Fig. 1. Definition of each of the two peaks and their characteristic parameters from the original *fo*F2 data. Shadowed rectangles show sunlit time.

Consequently, the contradictions between the results of previous analyses may be due to geographical variations in the morphology of enhancements and to the different methods of data treatment used by the different authors. These contradictions point to the necessity for a broader investigation of the phenomenon that considers a wide range of seasonal and solar conditions and mid- to low-latitudes.

Various physical processes have been suggested to explain the formation of night-time electron concentration enhancements. The most important are: (1) plasma fluxes from the plasmasphere (Hanson and Ortenburger, 1961; Evans, 1965, 1975; Titheridge, 1968; Jain and Williams, 1984; Förster and Jakowski, 1988; Jakowski et al., 1991; Jakowski and Förster, 1995; Mikhailov and Förster, 1999); (2) raising of the F2-layer to higher altitudes (where the recombination rate is smaller) by electric fields and thermospheric winds (Young et al., 1970; Standley and Williams, 1984; Hedin et al., 1991; Titheridge, 1995; Mikhailov et al., 2000a, b). Other less important processes are plasma transfer from conjugate points (Wickwar, 1974; Balan et al., 1994) and night-time ionization at the top of the ionosphere at high latitudes (Titheridge, 1968; Leitinger et al., 1982). All of these physical processes are also among the main mechanisms that generate the night-time F2-layer. Therefore, a proper understanding of the night-time F2 enhancements can make a significant contribution to knowledge of how the night-time F2-layer is formed.

The main goal of this paper can be defined as a morphological study of the night-time *Nm*F2 enhancements using all available worldwide, ground-based ionosonde observations for the last 3–4 solar cycles in both hemispheres. No detailed physical interpretation of the morphological features revealed is attempted here. This will be done elsewhere.

2 Data analysis

The method used to select and specify each of the two night-time peaks is similar to the one described by Mikhailov et al. (2000a, b). All hourly values of the F2-layer critical frequency (*fo*F2) available at the World Data Center for STP at Chilton (WDC) from 53 ionosonde stations for the period since 1955 were analysed. This covers four solar cycles at many of the stations used. The locations of the ionosonde stations selected cover the 15° to 60° range of geomagnetic latitude in both hemispheres, and all longitudinal sectors. Coordinates of the stations used are listed in Table 1. Night-time observations were selected according to solar zenith angle. Each *Nm*F2 enhancement was identified by the presence of a relative maximum in hourly *fo*F2 values, as shown in Fig. 1. Maximum electron concentration, *Nm*F2, is known to be related to the critical frequency, *fo*F2, by the expression

$$NmF2 = 1.24 \cdot 10^4 \cdot (foF2)^2\,\text{cm}^{-3}. \quad (1)$$

Each *Nm*F2 peak revealed in this way was specified by three parameters: occurrence probability, amplitude (relative to the minimum electron concentration for the particular night) and local time of occurrence. Amplitude of the enhancement was defined as

$$\text{Amplitude}_{1,2} = [foF2_{\max 1,2}/foF2_{\min}]^2, \quad (2)$$

where $foF2_{\max 1,2}$ are the critical frequencies at the two possible peaks: pre-midnight ($foF2_{\max 1}$) and post-midnight ($foF2_{\max 2}$), and $foF2_{\min}$ is the minimum critical frequency through the time between sunset, defined by solar angle $> 95°$, and 04:00 LT.

One-hour gaps in the data were filled in using neighbouring values. Nights with gaps lasting two or more hours were rejected. To avoid the effects of solar illumination during summer nights, only periods when the solar zenith angle was greater than 95° were considered. Only magnetically quiet days ($A_p < 12$) were analysed, though night-time enhancements have also been observed during disturbed periods (Mikhailov and Förster, 1999). These filtering processes reduced the number of available observations (nights) to those shown in Table 1.

For statistical analysis, all available data were binned according to season and solar activity level: summer (May–August), equinox (March, April, September and October) and winter (November–February) for the Northern Hemisphere, changing summer for winter months for Southern Hemisphere stations; and three levels of solar activity: high (1957–1959; 1968–1970; 1979–1981; 1989–1991; 1999–2001), medium (1955; 1956; 1960–1963; 1966; 1967; 1971–1974; 1977; 1978; 1982–1984; 1987; 1988; 1992–1995; 1998) and low (1964; 1965; 1975; 1976; 1985; 1986; 1996; 1997). This classification gives nine gradations (3 seasons × 3 solar activity levels), which were applied to each station.

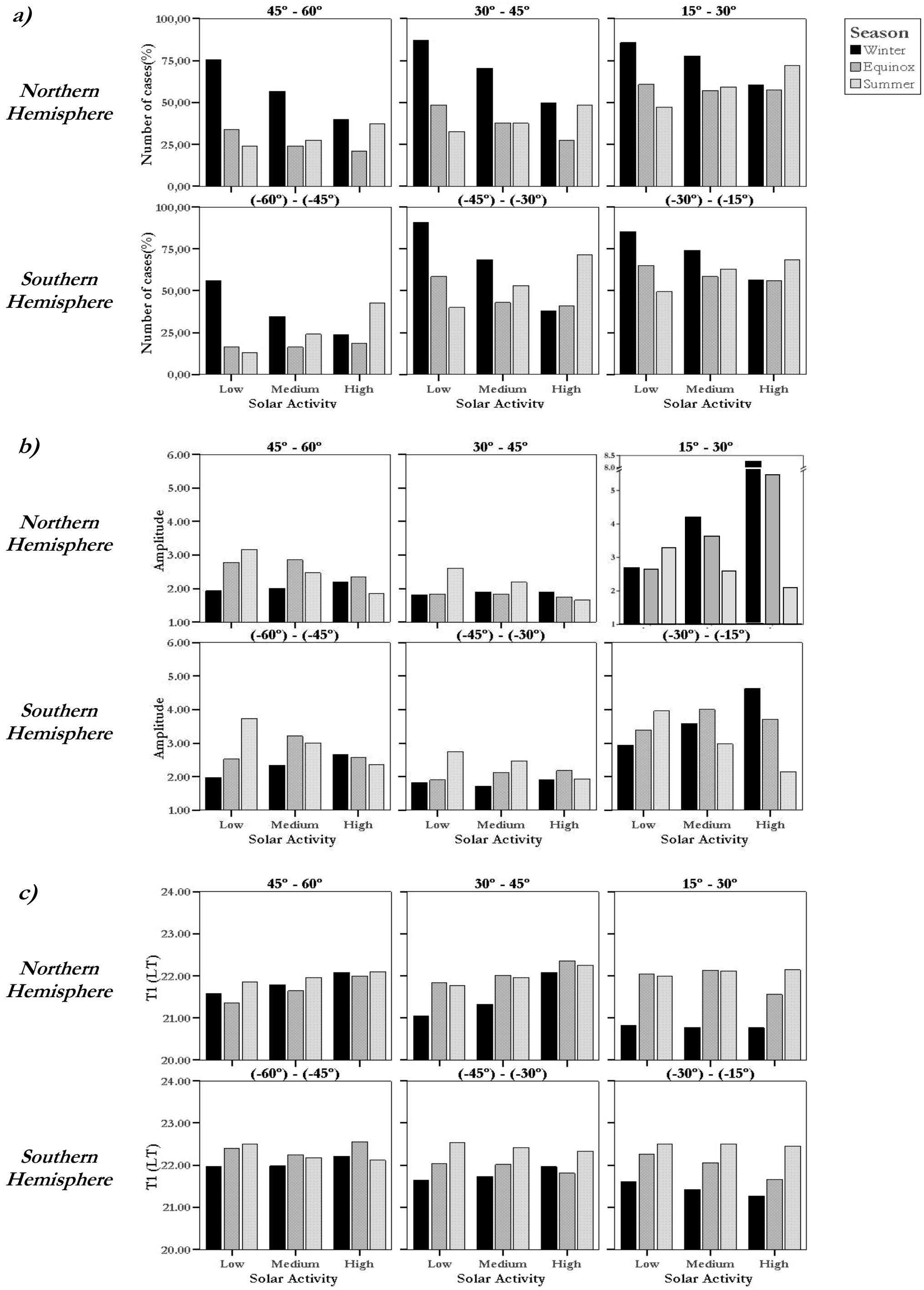

Fig. 2. Seasonal and solar variations of characteristic parameters of the first (pre-midnight) peak. Solar activity is classified in three levels: high solar activity (High), medium solar activity (Medium) and low solar activity (Low). Seasonal variability is arranged in three categories: winter, summer and equinox. See the text for details. **(a)** Probability of occurrence, **(b)** relative amplitude, **(c)** local time of occurrence; for 6 geomagnetic latitude ranges. Bars represent means. Negative latitudes represent Southern Hemisphere positions.

3 Results

Two different kinds of analysis were carried out for the selected stations. First, seasonal and solar variability were studied in different bands of geomagnetic latitude. Second, spatial variations of selected features were analysed. It should be stressed that only by using a sufficient amount of data for each of the conditions considered is it possible to obtain reliable results. This was achieved by using 53 stations, most of which cover a wide temporal range. Even after filtering for disturbed days and data gaps, the total amount of data is over 200 000 station-nights. This gives an indication of the reliability of the results obtained. The main results are summarized in Tables 2 and 3.

3.1 Solar cycle and seasonal variation

To analyse the seasonal and solar cycle variations of the six parameters selected (occurrence probability, relative amplitude and local time of occurrence of each of the two peaks), nights were classified according to their season and solar activity level. Average values of the parameters for each of the gradations considered are shown for the first (pre-midnight) enhancement (Figs. 2a–c) and for the second (post-midnight) enhancement (Figs. 3a–c) for all 53 stations grouped into six geomagnetic latitude ranges. The corresponding numerical values are listed in Table 2. Data being grouped by latitude allows us to study the latitudinal dependence of seasonal and solar cycle variations.

3.1.1 First peak (pre-midnight)

The occurrence probability of the first peak (Fig. 2a) shows a clear seasonal dependence, tending to be higher in winter than in summer. There is also a clear dependence on solar activity level, with a higher probability during the years around solar minimum. However, in summer the peaks are more frequent during solar maximum. This is related to an upsurge in the occurrence probability associated with the months around the summer solstice (June–July in the Northern Hemisphere, December–January in the Southern). This was noted earlier by Mikhailov et al. (2000a) for the Northern Hemisphere. The effect is especially pronounced at high latitude stations. A latitudinal variation can be seen in Fig. 2a, with maximum occurrence probability at lower geomagnetic latitudes.

The variation of the relative amplitude ($N_{\mathrm{peak}}/N_{\mathrm{min}}$) for the first peak (Fig. 2b) does not show such a clear pattern as does that of the occurrence probability. The graphs show a complicated pattern; the amplitude of winter peaks increases along with solar activity, whereas in summer the behaviour is the reverse. The largest peaks occur at low latitudes, especially in winter and near solar maximum. Large amplitudes are also observed during equinox at lower latitudes. It should be noted that relative amplitudes usually do not exceed 3.5, except for lower geomagnetic latitudes (see later).

The third characteristic parameter studied (Fig. 2c) is the local time of occurrence of the peak. At all latitudes, the time of occurrence tends to be later in summer than in winter. At middle latitudes, the enhancements occur later in the evening as solar activity increases, but no clear seasonal variation can be noted. The opposite behaviour is found at low latitudes, with later enhancements during solar minimum. At high latitudes the variability is more complicated, with different behaviour depending on the season. In winter the enhancements occur later at low solar activity level, while in summer the same happens during solar maximum. Early enhancements are found at high latitudes during equinoxes.

The time of occurrence shows small changes with geomagnetic latitude. Very small variations of this parameter are found for different seasons and solar activity levels, the time being always close to 21:50 LT. As it will be shown later, the occurrence time of both peaks mainly reflects its dependence on longitude.

3.1.2 Second peak (post-midnight)

Night-time enhancements of electron concentration are more common after midnight than before midnight, as is clearly shown in Fig. 3a. Post-midnight enhancements occur on about 80% of all the nights, while the pre-midnight occurrence probability is about 50%. The occurrence probability shows a clear seasonal dependence at all latitudes, with more enhancements in winter than in summer. Variations with solar activity are less clear, though in general a higher occurrence probability is observed during solar minimum.

In general, at middle latitudes the amplitude of the post-midnight peaks (Fig. 3b) is slightly smaller than that of the pre-midnight ones, with values being less than three. At higher and lower latitudes we don't see any extreme behaviour of these amplitudes (see later).

In general, the highest relative amplitudes are found in winter and during solar minimum. A physical mechanism to explain this behaviour was proposed by Mikhailov et al. (2000b). This pronounced seasonal and solar variability occurs at high and middle geomagnetic latitudes only.

Post-midnight enhancements usually occur between 01:50–03:50 LT and are later in winter than in summer. No clear dependence of any parameter on solar activity is apparent, except for a small decay of amplitude during solar maximum, which was explained in detail by Mikhailov et al. (2000b). A small variation of these parameters with geographic location occurs and is described later.

3.2 Geographical morphology of night-time $NmF2$ enhancements

A similar analysis was applied to each of the 53 ionosonde stations (Table 1) to determine spatial variations of the F2-layer night-time electron concentration enhancements. The variations were analysed and presented in geomagnetic coordinates.

Figures 4a–c and 5a–c show the spatial variations of each of the previously defined parameters in panels displaying changes with season and solar activity level. Numerical values are listed in Table 2. In general, latitudinal variations are the most important and longitudinal variations are negligible. Only the time of the peak's occurrence shows a small longitudinal dependence displayed in Figs. 4c and 5c. No latitudinal variation of time of occurrence is apparent, and there is no significant difference between hemispheres for any of the parameters studied. Only cases with more than 100 valid nights for a station under a particular solar activity condition and season were used for the graphs in order to provide statistical reliability.

Table 2. Numerical results: mean, standard deviation and number of valid cases for each variable and condition

			PERCENTAGE OF OCCURRENCE OF FIRST PEAK (%)		PERCENTAGE OF OCCURRENCE OF SECOND PEAK (%)		AMPLITUDE OF FIRST PEAK			AMPLITUDE OF SECOND PEAK			T1 (LT)			T2 (LT)		
Geomagnetic latitude Range(°):	Solar Activity	Season	Mean	N	Mean	N	Mean	Std. dev.	N	Mean	Std. dev.	N	Mean	Std. dev.	N	Mean	Std. dev.	N
(-30°) - (-15°)	Low	Winter	85,27	713	93,13	713	2,94	2,57	608	2,04	1,1	664	21,6	1,36	608	2,94	1,24	664
		Equinox	65,15	726	78,65	726	3,39	2,49	473	2,65	2,31	571	22,26	1,27	473	2,41	1,15	571
		Summer	49,47	566	55,3	566	3,96	2,59	280	2,05	1,59	313	22,5	1,25	280	2,31	1,35	313
	Medium	Winter	74,15	2476	90,02	2476	3,59	4,07	1836	1,91	1,04	2229	21,42	1,49	1836	2,84	1,17	2229
		Equinox	58,46	2364	66,5	2364	4,01	3,69	1382	2,23	1,67	1572	22,06	1,37	1382	2,47	1,16	1572
		Summer	62,94	2175	53,24	2175	2,98	2,3	1369	1,79	1,23	1158	22,5	1,15	1369	2,34	1,38	1158
	High	Winter	56,5	1462	81,94	1462	4,63	4,95	826	1,76	1,07	1198	21,27	1,45	826	2,83	1,19	1198
		Equinox	56,15	1163	47,72	1163	3,72	2,51	653	2,02	1,42	555	21,66	1,29	653	2,45	1,23	555
		Summer	68,42	1406	47,44	1406	2,14	0,83	962	1,48	0,44	667	22,45	1,07	962	2,25	1,27	667
(-45°) - (-30°)	Low	Winter	90,65	1690	98,82	1690	1,82	0,51	1532	2,02	0,67	1670	21,63	1,21	1532	3,27	1,28	1670
		Equinox	58,49	1614	85,69	1614	1,9	0,83	944	1,67	0,53	1383	22,03	1,14	944	2,52	1,18	1383
		Summer	40,07	1218	56,08	1218	2,74	1,22	488	1,77	0,88	683	22,53	1,14	488	1,97	1,19	683
	Medium	Winter	68,58	4608	98	4608	1,72	0,59	3160	1,84	0,6	4516	21,73	1,3	3160	3,35	1,15	4516
		Equinox	42,91	4123	69,61	4123	2,12	0,76	1769	1,62	0,54	2870	22,01	1,18	1769	2,41	1,18	2870
		Summer	53,08	3945	47,43	3945	2,47	1,01	2094	1,65	0,62	1871	22,41	1,1	2094	2,15	1,35	1871
	High	Winter	37,75	2580	94,34	2580	1,9	0,74	974	1,6	0,48	2434	21,96	1,34	974	3,19	1,16	2434
		Equinox	40,85	2191	52,3	2191	2,18	0,76	895	1,47	0,43	1146	21,81	1,15	895	2,26	1,2	1146
		Summer	71,42	2579	42,5	2579	1,94	0,49	1842	1,36	0,34	1096	22,33	0,95	1842	2,51	1,36	1096
(-60°) - (-45°)	Low	Winter	56,09	640	92,81	640	1,97	0,81	359	1,97	1,16	594	21,97	1,46	359	2,96	1,45	594
		Equinox	16,62	716	70,53	716	2,52	1,36	119	1,65	0,54	505	22,39	1,43	119	2,43	1,32	505
		Summer	12,83	538	22,3	538	3,74	1,62	69	1,8	0,82	120	22,51	1,04	69	1,87	1,17	120
	Medium	Winter	34,52	1776	90,65	1776	2,34	2,04	613	1,87	0,98	1610	21,98	1,6	613	3,23	1,5	1610
		Equinox	16,27	1862	50,75	1862	3,21	1,73	303	1,78	0,78	945	22,24	1,53	303	2,27	1,36	945
		Summer	24,02	1957	23,71	1957	3	1,29	470	1,67	0,62	464	22,17	0,98	470	1,89	1,26	464
	High	Winter	23,69	1030	89,32	1030	2,67	2,33	244	1,61	0,43	920	22,21	1,7	244	3,22	1,35	920
		Equinox	18,52	999	44,94	999	2,57	1,21	185	1,59	0,49	449	22,55	1,16	185	2,18	1,3	449
		Summer	42,88	1278	24,96	1278	2,36	0,59	548	1,4	0,33	319	22,12	0,82	548	2,1	1,3	319
15° - 30°	Low	Winter	85,75	1439	94,51	1439	2,67	1,55	1234	2,31	1,27	1360	20,82	1,47	1234	2,76	1,37	1360
		Equinox	60,72	1497	80,16	1497	2,64	1,47	909	2,21	1,33	1200	22,05	1,32	909	2,24	1,24	1200
		Summer	47,33	748	59,89	748	3,29	1,91	354	2,01	1,13	448	21,99	1,33	354	1,8	1,2	448
	Medium	Winter	77,82	4067	89,45	4067	4,17	4,39	3165	2,18	1,44	3638	20,78	1,55	3165	2,73	1,35	3638
		Equinox	56,99	3890	70,57	3890	3,62	4,18	2217	2,04	1,45	2745	22,13	1,28	2217	2,2	1,19	2745
		Summer	59,17	2687	56,61	2687	2,64	1,57	1590	1,81	1,06	1521	22,12	1,26	1590	1,9	1,22	1521
	High	Winter	60,42	2850	69,12	2850	8,24	7,75	1722	2,07	1,62	1970	20,77	1,63	1722	2,62	1,33	1970
		Equinox	57,34	2398	48,25	2398	5,5	6,44	1375	1,84	1,16	1157	21,56	1,46	1375	2,13	1,07	1157
		Summer	72,15	2219	53,49	2219	2,13	1,18	1601	1,57	0,71	1187	22,14	1,26	1601	1,94	1,21	1187
30° - 45°	Low	Winter	87,16	4150	98,22	4150	1,81	0,56	3617	2,07	1,06	4076	21,05	1,77	3617	3,32	1,81	4076
		Equinox	48,5	4177	81,25	4177	1,83	0,95	2026	1,42	0,5	3394	21,84	1,45	2026	2,48	1,44	3394
		Summer	32,73	3132	46,23	3132	2,6	1,2	1025	1,34	0,34	1448	21,77	1,15	1025	1,94	1,22	1448
	Medium	Winter	70,49	9986	97,82	9986	1,89	1,08	7039	2,02	1,23	9768	21,33	1,79	7039	3,39	1,68	9768
		Equinox	37,72	9131	80,05	9131	1,83	0,98	3444	1,37	0,45	7309	22,01	1,42	3444	2,39	1,38	7309
		Summer	37,53	8010	49,94	8010	2,19	0,91	3006	1,34	0,32	4000	21,96	1,08	3006	1,97	1,18	4000
	High	Winter	49,66	5797	94,5	5797	1,88	1,49	2879	1,76	1,22	5478	22,08	1,6	2879	3,19	1,54	5478
		Equinox	27,18	4426	72,73	4426	1,75	0,89	1203	1,34	0,59	3219	22,36	1,29	1203	2,27	1,28	3219
		Summer	48,31	4579	50,99	4579	1,65	0,51	2212	1,29	0,47	2335	22,25	1	2212	1,88	1,18	2335
45° - 60°	Low	Winter	75,46	5367	94,17	5367	1,93	0,74	4050	2,28	1,19	5054	21,58	1,73	4050	2,48	1,61	5054
		Equinox	33,67	6318	68,68	6318	2,78	2,55	2127	1,47	0,74	4339	21,35	1,63	2127	2,15	1,3	4339
		Summer	24,1	6311	20,65	6311	3,16	1,71	1521	1,35	0,74	1303	21,86	0,99	1521	1,66	1,09	1303
	Medium	Winter	56,71	14608	91,08	14608	2,01	1,42	8284	2,05	1,44	13305	21,79	1,74	8284	2,59	1,61	13305
		Equinox	24,12	15284	56,84	15284	2,85	2,06	3687	1,48	0,75	8687	21,64	1,59	3687	2,01	1,28	8687
		Summer	27,33	17267	22,52	17267	2,46	1,23	4719	1,33	0,52	3889	21,96	0,98	4719	1,61	1,11	3889
	High	Winter	39,97	9238	86,48	9238	2,19	2,84	3692	1,72	1,4	7989	22,08	1,57	3692	2,75	1,71	7989
		Equinox	20,86	8072	48,1	8072	2,34	1,79	1684	1,47	0,7	3883	22	1,4	1684	1,89	1,26	3883
		Summer	37,25	9115	28,22	9115	1,84	0,87	3395	1,3	0,62	2572	22,1	1,05	3395	1,58	1,04	2572
Total	Low	Winter	81,43	13999	95,85	13999	2,01	1,04	11400	2,16	1,11	13418	21,35	1,66	11400	2,9	1,64	13418
		Equinox	43,85	15048	75,7	15048	2,38	1,87	6598	1,62	0,95	11392	21,78	1,48	6598	2,33	1,33	11392
		Summer	29,86	12513	34,48	12513	3,03	1,68	3737	1,54	0,86	4315	22	1,15	3737	1,87	1,2	4315
	Medium	Winter	64,22	37521	93,46	37521	2,35	2,38	24097	2,01	1,26	35066	21,49	1,69	24097	2,97	1,57	35066
		Equinox	34,93	36654	65,83	36654	2,74	2,59	12802	1,59	0,9	24128	21,94	1,43	12802	2,24	1,3	24128

Table 3. Summary of results

Latitude	**First Peak**			**Second Peak**		
	Occurrence Probability	**Relative Amplitude**	**Time of occurrence (LT)**	**Occurrence Probability**	**Relative Amplitude**	**Time of occurrence (LT)**
High	Highest in winter and solar minimum (50%). Occurrence in summer increases with solar activity during solstice months (40%).	Highest amplitudes during equinoxes (5-7)	Latest peaks in summer, and high solar activity (22:00). In winter later peaks happen during solar minimum.	Clear seasonal dependence. More peaks in winter (80-95%). In summer, more peaks happen during solar maximum.	Seasonal and solar dependence. Higher peaks in winter and solar minimum (1.5-2)	Latest peaks in winter and high solar activity (04:00). No solar variation in summer and equinox.
Medium	Highest in winter and solar minimum (75%). Occurrence in summer increases with solar activity during solstice months (20%).	In winter, highest amplitudes under high solar activity (1.5-2). In summer higher peaks happen with low solar activity	Similar to high latitudes, though peaks happen later (22:00-22:50)	Clear seasonal dependence. More peaks in winter (80-95%).	Seasonal and solar dependence. Higher peaks in winter and solar minimum (1.5-2)	Clear seasonal variability. Later peaks in winter (04:00). Than in summer (02:00-02:50)
Low	Very high occurrence for all conditions (50-90%). More peaks in winter and solar minimum.	Very high amplitude peaks (up to 15 in winter and solar maximum). In winter, amplitude is maximum in solar maximum. In summer, opposite tendency.	Latest peaks in summer and solar minimum (21:50)	Seasonal and solar dependence. More peaks in winter and solar minimum (80%)	Higher amplitudes. No clear seasonal and solar behaviour	Peaks happen earlier than at other latitudes (01:00-01:50).

3.2.1 First peak (pre-midnight)

Figures 4a–c show the geographic morphology of the first enhancement of electron concentration. The occurrence probability (Fig. 4a) shows a maximum around $\phi_{\text{geomag}} = 35°$ and a noticeable latitudinal variation. The lowest occurrence probabilities take place at high latitudes. This behaviour is most pronounced in winter, while in summer, and especially under solar maximum conditions, it distorts at high latitudes due to the influence of the summer solstice feature mentioned earlier.

The amplitude (Fig. 4b) shows quite a different type of morphology, with a relative minimum around 40° and very high values in lower latitudes. The minimum in latitudinal variation shifts equatorward in summer and poleward in winter. Not much can be said about the latitudinal variation of the local time of the first peak's occurrence. However, though smaller and less clear than in the case of the second peak, an irregular longitudinal variation is apparent (Fig. 4c).

3.2.2 Second peak (post-midnight)

The geographic morphology of the second peak of electron concentration is displayed in Figs. 5a–c. The occurrence probability (Fig. 5a) shows a clear maximum around $\phi_{\text{geom}} = 40°$ for all solar activity conditions, with values very close to 100% in winter. For other seasons, occurrence probability is higher around solar minimum. A great reduction in occurrence probability is seen around $\phi_{\text{geom}} = 25°$. As in the case of the first peak, the amplitude of the post-midnight enhancement shows the reverse behaviour, with a minimum in amplitude around $\phi_{\text{geom}} = 40°$ and the greatest amplitudes at latitudes $< 25°$. This is not surprising, since the occurrence probability depends only on the existence of relative increases in electron concentration, while the amplitude is strongly related to the minimum electron concentration during the particular night.

Finally, the time of occurrence shows both a latitudinal and longitudinal dependence. Latitudinally (see Fig. 3c), the variation of the occurrence time of the second enhancement is almost constant, while longitudinally (Fig. 5c) it shows a sinusoidal type of variation with period 360°. Stations at low latitudes ($\phi_{\text{geom}} < 25°$) show quite a different behaviour for both enhancements, indicating a different mechanism of formation at these latitudes.

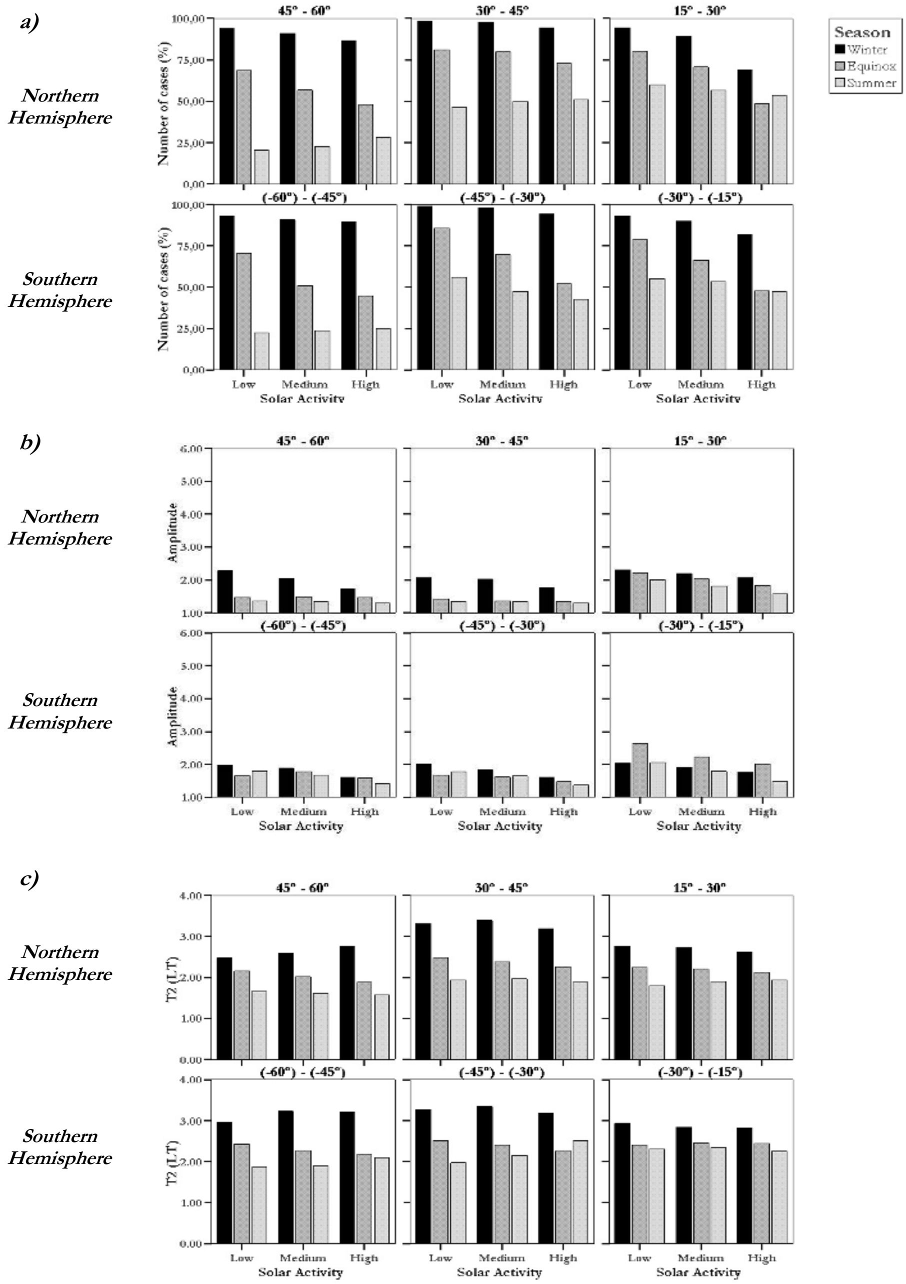

Fig. 3. (a)–(c) Same as Fig. 2 for second (post-midnight) peak.

4 Discussion

The method of data analysis used here allows one to investigate the *Nm*F2 night-time enhancements morphology, revealing that the two peaks have different behaviours and indicating different formation mechanisms. From this perspective it follows that previous studies analysing only one peak omitted the characteristics of the "weaker" peak, which will be pre- or post-midnight, depending on season, solar activity and geographical location. This is believed to be the main reason for the differences between our results and those of other authors. Balan and Rao (1987) found that for low latitudes and winter solar minimum two peaks are common, while only a post-midnight peak is present at middle and high latitudes. This contradicts our results. However, they only considered one peak each night, missing the presence of pre-midnight peaks at low latitudes, whose amplitude is small under these conditions. The difference in methods of analysis does not allow us to make a comparison with their results for geographical variation.

Jakowski et al. (1991) found for observations at Havana a higher occurrence probability in winter during solar minimum and in summer during solar maximum. The joint consideration of the occurrence probabilities of both peaks in our graphs (Figs. 2a and 3a) explains this change, which is due to the increased occurrence of the first peak at high

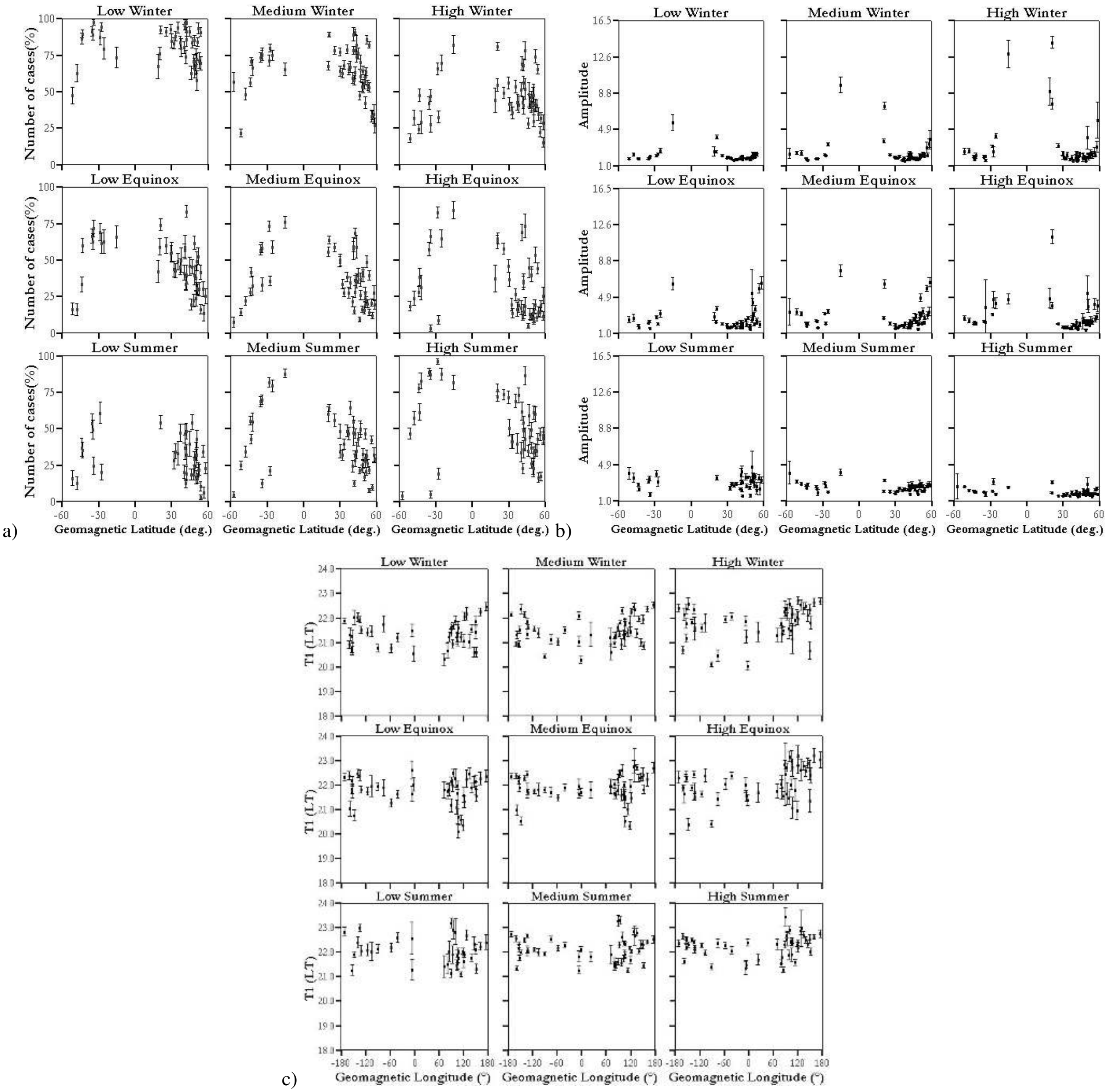

Fig. 4. Geographic variation with of characteristic parameters for the first peak **(a)** probability of occurrence, **(b)** relative amplitude, and **(c)** local time of occurrence with geomagnetic longitude, under different seasonal and solar conditions. Categories are the same as in Figs. 2 and 3. For example, "Low winter" refers to winter data under low solar activity conditions. Points indicate means. Bars indicate 95% confidence limits.

solar activity during summer solstice. They also found that the occurrence of two peaks on the same night occurs only during winter and solar maximum. This can be explained by the fact that the amplitude of both peaks is similar under solar maximum conditions for middle latitude stations like Havana, which makes both enhancements "visible" to their method of data analysis, while under other conditions only the (larger) second peak is found. Other authors also miss one of the peaks for similar reasons.

The distinct and systematic behaviour of each of the two enhancements indicates that different physical mechanisms lead to their formation. For the first (pre-midnight) peak several mechanisms appear to act, depending on season and solar activity. At middle latitudes the highest amplitudes are found during summer and low solar activity. This has been attributed to a collapse in the F2-region as electron temperature decreases after sunset, producing large downward ion fluxes. This, along with the contribution of equatorward meridional thermospheric winds uplifting the F2-layer to regions with low recombination rates, causes the *Nm*F2

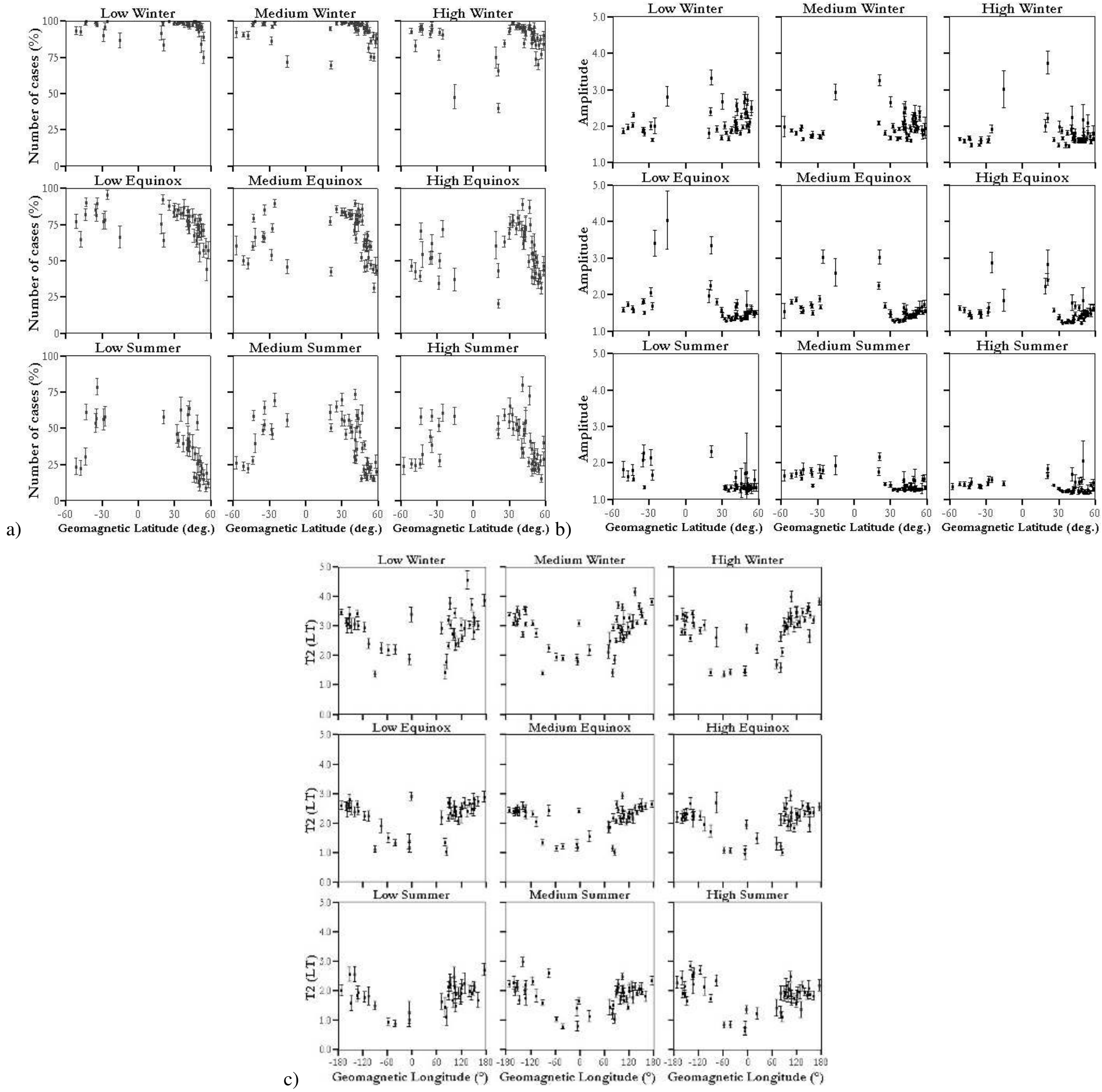

Fig. 5. (a)–(c) Same as Fig. 4 for the second peak.

increase.

During solar maximum, however, the amplitude of the summer peak decreases. The occurrence probability increases during summer solstice months, especially during solar maximum. This effect was attributed by Mikhailov et al. (2000a) to a direct solar photoionization as the night-time ionosphere rises to higher sunlit altitudes. This effect is especially apparent at high latitudes. The time of occurrence of these summer solstice peaks shifts to later hours as solar activity increases. This is consistent with the hypothesis of a photoionization origin. It should be noted that higher amplitudes are often associated with low occurrence probability, while the highest amplitudes are always observed at lower latitudes. This may indicate that the relative amplitude of night-time peaks is controlled mainly by the value of minimum electron concentration used for a scale ($N_{\min}$), which determines the background level above which the enhancements are counted. This was checked by studying the dependence of amplitude on $N_{\min}$. The importance of this background level specification was pointed out by Joshi and Iyer (1990). It may also be the cause of high amplitudes found at lower latitudes for both peaks.

The formation of pre-midnight peaks in winter is due mainly to a strong equatorward thermospheric wind raising the F2-layer to heights with a lower recombination rate (Young et al., 1970; Standley and Williams, 1984; Mikhailov et al., 2000a, b).

Large amplitudes at high-latitudes during equinox can be associated with the highest efficiency in the interaction between the Earth and the solar wind that occurs during these periods (Hargreaves, 1992). The behaviour found at lower latitudes is opposite to that commonly found at middle latitudes and may explain the contradiction between our results and those by Lois et al. (1990) and Jakowski et al. (1991) at Havana, Cuba.

The season-dependent behaviour of the first peak's amplitude that can be seen clearly in Fig. 2b, has a different and unknown physical mechanism. The second enhancement shows a clear seasonal variation, being much more likely to occur in winter than in summer, both around solar maximum and solar minimum. The highest amplitudes also occur in winter, being higher during solar minimum. As with the first peak, the highest amplitudes occur at lower latitudes, which also demonstrate different behaviour compared with middle and high latitudes.

The physical mechanism proposed to explain the formation of the second enhancement is again electron fluxes from the plasmasphere. However, observed fluxes are smaller than those required to explain the peaks (see Mikhailov et al. (2000b) and references therein). This problem was solved by Mikhailov and Förster (1999) and Mikhailov et al. (2000b), who proposed that the observed night-time *Nm*F2 variations were due to the uplifting of the F2-layer by the equatorward thermospheric winds, along with the observed night-time plasmaspheric fluxes into the F2-region. The increase in the night-time height of the maximum electron concentration in the F2-layer, *hm*F2, and the corresponding decrease in the recombination rate is then sufficient to explain the night-time *Nm*F2 increases with the observed relatively small plasma fluxes from the protonosphere.

The critical role played by thermospheric winds in the development of night-time peaks of *Nm*F2 is evident from the geographic variation of the parameters studied, which show relative extremes (maximum in occurrence probability, minimum in amplitude) around $\phi_{\text{geom}} \approx 40°$. Vertical drift of plasma (W) due to the meridional component (V_{nx}) of the neutral winds depends on magnetic inclination (I) as

$$W = V_{nx} \sin\ I\ \cos\ I\ , \tag{3}$$

which is a maximum when $I = 45°$. Additionally, the flux tube content is proportional to L^4, which gives a maximum of electron content in the tube at $\phi_{\text{geom}} \approx 60°$ (Carpenter and Park, 1973) due to the partial filling of tubes with $L > 3$. Tubes at lower latitudes are filled, but their volume is insufficient to produce the necessary plasma influx to the F2-layer. The action of meridional thermospheric winds at the equator may be another cause for the different behaviours, especially for the high amplitudes observed (Titheridge, 1995). A better knowledge of the global pattern of thermospheric winds is desirable in order to improve the understanding of the mechanism of *Nm*F2 peak formation.

5 Conclusions

A detailed study of the morphology of *Nm*F2 night-time enhancements was carried out at 53 ionosonde stations worldwide for different seasons and different levels of solar activity. The main results of our analysis are the following:

1. There are two distinct (pre- and post-midnight) *Nm*F2 peaks, which can occur for any season and solar activity level.

2. All the characteristics of the night-time enhancements that were analysed demonstrate a pronounced dependence on geomagnetic latitude, with distinctive behaviour at lower ($\phi_{\text{geom}} < 25°$) latitudes, indicating different formation mechanisms.

3. In general, the occurrence probability is higher for the second (post-midnight) peak.

4. The occurrence probability of the first peak shows a clear seasonal dependence, with a maximum in winter solar minimum. The greatest occurrence probability is at $\phi_{\text{geom}} \approx 35°$, and the least is at high latitudes (except for summer and high solar activity, due to the summer solstice occurrence upsurge).

5. The occurrence probability of the second peak shows a similar seasonal pattern, but without a dependence on solar activity. The greatest occurrence probability is observed at $\phi_{\text{geom}} \approx 40°$, and the least at high latitudes.

6. In general the amplitude $N_{\text{peak}}/N_{\text{min}}$ of the first peak is higher than for the second peak. The largest enhancements are observed at low latitudes in winter during solar minimum. Appreciable enhancements also take place at high latitudes during equinoxes. At middle latitudes peaks show various patterns depending on the season.

7. The amplitude of the post-midnight peak shows a clear seasonal and solar activity dependence, being larger in winter and during solar minimum. In general, post-midnight enhancements of electron concentration are smaller than the pre-midnight ones. The geographical morphology of the *Nm*F2 enhancements shows a relative minimum around $\phi_{\text{geom}} \approx 35°$, with a large upsurge at lower latitudes.

8. The time of occurrence of the first peak is between 20:00 and 22:50 LT and shows a clear dependence on solar activity. Enhancements occur later at middle latitudes during solar maximum. The dependence of the time of occurrence on solar activity is different at different geomagnetic latitudes. A small longitudinal effect is also present.

9. The time of occurrence of the second peak is between 01:50 and 03:00 LT. Enhancements occur later in winter than in summer. There is a small but distinct longitudinal variation.

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