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Anomalous variations of *Nm*F2 over the Argentine Islands: a statistical study

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Abstract. We present a statistical study of variations in the F2-layer peak electron density, *Nm*F2, and altitude, *hm*F2, over the Argentine Islands ionosonde. The critical frequencies, *fo*F2, and, *fo*E, of the F2 and E-layers, and the propagation factor, $M(3000)$F2, measured by the ionosonde during the 1957–1959 and 1962–1995 time periods were used in the statistical analysis to determine the values of *Nm*F2 and *hm*F2. The probabilities to observe maximum and minimum values of *Nm*F2 and *hm*F2 in a diurnal variation of the electron density are calculated. Our study shows that the main part of the maximum diurnal values of *Nm*F2 is observed in a time sector close to midnight in November, December, January, and February exhibiting the anomalous diurnal variations of *Nm*F2. Another anomalous feature of the diurnal variations of *Nm*F2 exhibited during November, December, and January when the minimum diurnal value of *Nm*F2 is mainly located close to the noon sector. These anomalous diurnal variations of *Nm*F2 are found to be during both geomagnetically quiet and disturbed conditions. Anomalous features are not found in the diurnal variations of *hm*F2. The statistical study of the *Nm*F2 winter anomaly phenomena over the Argentine Islands ionosonde was carried out. The variations in a maximum daytime value, R, of a ratio of a geomagnetically quiet daytime winter *Nm*F2 to a geomagnetically quiet daytime summer *Nm*F2 taken at a given UT and for approximately the same level of solar activity were studied. The conditional probability of the occurrence of R in an interval of R, the most frequent value of R, the mean expected value of R, and the conditional probability to observe the F2-region winter anomaly during a daytime period were calculated for low, moderate, and high solar activity. The calculations show that the mean expected value of R and the occurrence frequency of the F2-region winter anomaly increase with increasing solar activity.

Keywords. Ionosphere (Mid-latitude ionosphere; Modeling and forecasting)

1 Introduction

The Argentine Islands ionosonde station (65.2° S, 295.7° E) has a high geographic latitude, but due to the offset of the geographic and geomagnetic poles and the difference between the geomagnetic field center and the Earth's center, it is a geomagnetically mid-latitude station in terms of its geomagnetic coordinates (see Wrenn et al., 1987, and Sect. 2 of this paper). As a result, the ionosphere over the Argentine Islands ionosonde station exhibits certain high-latitude characteristics (near 24 h daylight during local summer months) and certain mid-latitude characteristics (Sojka et al., 1988; Pavlov et al., 2008a, b). This creates an extreme set of physical conditions and resulting anomalous diurnal variations of the F2-layer peak electron density, *Nm*F2, when a maximum value of *Nm*F2 is displaced from the expected mid-latitude noon sector to a sector close to midnight (Wrenn et al., 1987; Sojka et al., 1988; Pavlov et al., 2008a, b). It should be noted that such anomalous diurnal variations of *Nm*F2 are observed not only by the Argentine Islands ionosonde station. This unusual phenomenon observed in the Southern Hemisphere is known as the Weddell Sea Anomaly in *Nm*F2 (see Horvath, 2007, and references therein).

As far as the authors know, there are no published studies of statistical relationships of these anomalous diurnal variations of *Nm*F2 with season and geomagnetic activity levels. The first purpose of this work is to study, for the first

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time, these statistical relationships in terms of occurrence probabilities using the critical frequency, *fo*F2, of the F2-layer measured by the Argentine Islands ionosonde station and provided by the Ionospheric Digital Database of the National Geophysical Data Center in Boulder, Colorado. Such a study presented in our work is important to identify potential mechanisms for these anomalous diurnal variations of *Nm*F2.

The F2-region winter anomaly is a well-known phenomenon when the F2-layer peak electron density is greater in winter than that in summer at the same point in time over the same Earth's surface point for geomagnetically quiet daytime conditions, despite the reduced solar insolation in winter in comparison with that in summer (e.g. Croom et al., 1960; King, 1961; Torr and Torr, 1973; Millward et al., 1996; Zou et al., 2000; Rishbeth et al., 2000; Tao Yu et al., 2000; Pavlov and Pavlova, 2005, 2008a, b). The winter/summer variations in the *fo*F2 monthly noon medians were studied by Torr and Torr (1973) using the data of 140 ionosondes in 1958, 1964, and 1969. It follows from this study that the winter anomaly phenomenon in the *fo*F2 monthly noon medians is more pronounced in the Northern Hemisphere than in the Southern Hemisphere and the region of existence and magnitude of the winter anomaly decrease with decreasing solar activity. The mechanisms of formation of the winter-summer variations in *Nm*F2 over the Millstone Hill radar and Argentine Island ionosonde, whose locations are approximately magnetically conjugate, were studied for the geomagnetically quiet daytime conditions of 2–3 June 1979 and 5–6 January 1980 at high solar activity, and 15–17 January 1985 and 10–13 July 1986 at low solar activity (Pavlov and Pavlova, 2005a, b). They found that the phenomenon of *Nm*F2 winter anomaly is observed by the Millstone Hill radar, whereas this event is not observed by the Argentine Islands ionosonde, except of one instant of time (close to noon) in the comparison of the 2 June 1979 and 5 January 1980 diurnal variations of *fo*F2 measured by the Argentine Islands ionosonde. The second purpose of this work is to carry out the first statistical study of the *Nm*F2 winter anomaly over Argentine Islands using the Argentine Islands ionosonde measurements of *fo*F2 to find, for the first time, a probability to observe the winter anomaly in *Nm*F2 and an average amplitude of the *Nm*F2 winter anomaly at solar minimum, at moderate solar activity, and at solar maximum.

2 Data

Our analysis is based on hourly *fo*F2 data measured by the Argentine Islands station (65.2° S, 295.7° E) during the 1957–1959 and 1962–1995 time periods (month median *fo*F2 are not used in this work). The *fo*F2 data are available by Internet from the Ionospheric Digital Database of the National Geophysical Data Center, Boulder, Colorado. It should be noted that the value of *Nm*F2 is related to *fo*F2 as

$$NmF2 = 1.24 \times 10^{10} foF2^2, \qquad (1)$$

where the unit of *Nm*F2 is m^{-3}, the unit of *fo*F2 is MHz.

To determine the ionosonde value of the F2-layer peak altitude, *hm*F2, the relation between *hm*F2 and the values of *fo*F2, the dimensionless ionospheric propagation factor, $M(3000)$F2, and the critical frequency, *fo*E, of the E-layer recommended by Dudeney (1983) is used as

$$hmF2 = 1490/[M(3000)F2 + \Delta M] - 176, \qquad (2)$$

where ΔM=0.253/(*fo*F2/*fo*E−1.215)−0.012, the unit of *hm*F2 is km, and the units of *fo*F2 and *fo*E are the same.

If there are no *fo*E data then it is suggested that ΔM=0, i.e. the *hm*F2 formula of Shimazaki (1955) is used.

When the thermosphere is disturbed, the time it takes to relax back to its initial state, this thermosphere relaxation determines the time for the disturbed ionosphere to relax back to the quiet state, and the values of *Nm*F2 and *hm*F2 at given UT with 3-h geomagnetic index, $K_p \leq 3$, cannot always be considered as geomagnetically quiet *Nm*F2 and *hm*F2. The characteristic time of the neutral composition recovery after a storm impulse event ranges from 7 to 12 h on average (Hedin, 1987), while it may need days for all altitudes down to 120 km in the atmosphere to recover completely back to the undisturbed state of the atmosphere (Richmond and Lu, 2000). Therefore, we believe that the values of *Nm*F2 and *hm*F2 at given UT are the geomagnetically quiet ionospheric parameters if $K_p \leq 3$ at UT under consideration and for 24-h time period prior to given UT.

We use an eccentric tilted dipole approximation for the geomagnetic field (Fraser-Smith, 1987; Deminov and Fishchuk, 2000) to calculate the geomagnetic latitude and longitude of the ionosonde station which values depend on a year. The limits of the geomagnetic latitude and longitude year changes are calculated to be (−51.70±0.27)° and (7.76±0.83)°, respectively, and the McIlwain parameter, L, is changed from 2.677 to 2.786.

3 Statistical study of *Nm*F2 and *hm*F2 diurnal variations: results and discussion

The value of *Nm*F2 reaches its minimum, $NmF2_{min}$, and maximum, $NmF2_{max}$, values, and the F2-layer peak altitude is changed between its minimum, $hmF2_{min}$, and maximum, $hmF2_{max}$, values for each time period from 00:00 UT to 24:00 UT where UT is the universal time. The solar local time is related with UT as

$$SLT = UT + \lambda/15, \qquad (3)$$

where λ is the geographic longitude, the unit of measurements of λ is degree, SLT and UT come in units of hours. The differences of locations in SLT of the maximum and minimum values of *Nm*F2 and *hm*F2 determine differences between mid-latitude diurnal variations of *Nm*F2 and *hm*F2. We calculate a probability to observe each value of Y=$NmF2_{min}$, $NmF2_{max}$, $hmF2_{min}$, $hmF2_{max}$ in 2 intervals of a maximum 3-h geomagnetic index K_p for 24-h time period prior to and including SLT where the value of Y under study is observed: $K_p^{\max}\leq 3$ (it is labeled as "geomagnatically quiet conditions") and $K_p^{\max}>3$ (it is labeled as "geomagnetically disturbed conditions"). Each value of $Nm\mathrm{F2}_{\min}$, $Nm\mathrm{F2}_{\max}$, $hm\mathrm{F2}_{\min}$, and $hm\mathrm{F2}_{\max}$ is tested individually for each time period from 00:00 UT to 24:00 UT to label it as a geomagnetically quiet or geomagnetically disturbed value.

For each specified values of $K_p^{\max}$ and SLT, we determine a number, $N_{\min}$ (M, $K_p^{\max}$, SLT), of the $Nm\mathrm{F2}_{\min}$ observations and a number, $N_{\max}$ (M, $K_p^{\max}$, SLT), of $Nm\mathrm{F2}_{\max}$ observations in a given month of M provided the value of $K_p^{\max}$ was located within the interval specified ($K_p^{\max}>3$ or $K_p^{\max}\leq 3$). The probability, Ψ_N, to observe $Nm\mathrm{F2}_{\max}$ and the probability, P_N, to observe $Nm\mathrm{F2}_{\min}$ at given SLT during a diurnal time period (from 00:00 UT to 24:00 UT) in a chosen month of M during geomagnetically quiet or geomagnetically disturbed conditions, are determined as

$$\Psi_N(M, K_p^{\max}, \mathrm{SLT}) = N_{\max}(M, K_p^{\max}, \mathrm{SLT})/N(M, K_p^{\max}),$$
$$P_N(M, K_p^{\max}, \mathrm{SLT}) = N_{\min}(M, K_p^{\max}, \mathrm{SLT})/N(M, K_p^{\max}), \tag{4}$$

where $N(M, K_p^{\max})$ is a number of days in a chosen month of M when the ionosonde measurements of *Nm*F2 were carried out provided the value of $K_p^{\max}$ is located within the interval specified ($K_p^{\max}>3$ or $K_p^{\max}\leq 3$).

The F2-layer peak altitude is changed between its minimum, $hm\mathrm{F2}_{\min}$, and maximum, $hm\mathrm{F2}_{\max}$, values for each time period from 00:00 UT to 24:00 UT. For a given month in a year, we calculate a number, $H_{\min}(M, K_p^{\max}$,SLT), of the $hm\mathrm{F2}_{\min}$ observations and a number, $H_{\max}(M, K_p^{\max}$,SLT), of the $hm\mathrm{F2}_{\max}$ observations in a given month of M provided the value of $K_p^{\max}$ is located within the interval specified ($K_p^{\max}>3$ or $K_p^{\max}\leq 3$). The probability, Ψ_h, to observe $hm\mathrm{F2}_{\max}$ and the probability, P_h, to observe $hm\mathrm{F2}_{\min}$ at given SLT during a diurnal time period (from 00:00 UT to 24:00 UT) in a chosen month of M during geomagnetically quiet or geomagnetically disturbed conditions, are determined as

$$\Psi_h(M, K_p^{\max}, \mathrm{SLT}) = H_{\max}(M, K_p^{\max}, \mathrm{SLT})/H(M, K),$$
$$P_h(M, K_p^{\max}, \mathrm{SLT}) = H_{\min}(M, K_p^{\max}, \mathrm{SLT})/H(M, K_p^{\max}), \tag{5}$$

where $H(M, K_p^{\max})$ is a number of days in a chosen month of M when the ionosonde measurements of $M(3000)$F2 were carried out provided the value of $K_p^{\max}$ was located within the interval specified ($K_p^{\max}\leq 3$ or $K_p^{\max}>3$).

The results of calculations of Ψ_N and P_N are shown in Figs. 1 and 2, respectively, for each month in a year. In each panel of Figs. 1–2, solid and dashed lines correspond to quiet ($K_p^{\max}\leq 3$) and disturbed ($K_p^{\max}>3$) conditions, respectively. We consider that mid-latitude diurnal variations of *Nm*F2 are anomalous for a month in a year if the F2-layer peak electron density reaches its minimum value close to the noon sector, or the F2-layer peak electron density maximum is located in a time sector close to midnight. On the bases of these features, we conclude from Figs. 1 and 2 that, in the main, *Nm*F2 does not exhibit anomalous diurnal variations in April, May, June, July, August, and September. As the model calculations show, during these months the maximum value of *Nm*F2 is mainly located in the sector close to the minimum value of the solar zenith angle, χ, and a main peak of P_N is displaced from a peak of Ψ_N to larger solar zenith angles (to calculate the solar zenith angle we use the Fortran subroutine soco taken from the IRI2007 model at ftp://nssdcftp.gsfc.nasa.gov/models/ionospheric/iri/iri2007/). In November, December, January, and February, the maximum value of *Nm*F2 is not primarily observed in a time sector close to noon. Furthermore, the minimum value of the F2-layer peak electron density is observed mainly close to the noon sector during November, December, and January (see Fig. 2). We conclude that the diurnal variations of *Nm*F2 are anomalous in November, December and January and these diurnal variations are partially anomalous in February. The changeover from the November and February diurnal variations of *Nm*F2 to those in April and September occurs in March and October, respectively. The difference between the quiet and disturbed values of Ψ_N (see solid and dashed lines in Fig. 1) and the difference between P_N for $K_p^{\max}\leq 3$ and that for $K_p^{\max}>3$ (see solid and dashed lines in Fig. 2) can be produced by the difference in the wind-induced plasma drift and neutral densities between quiet and disturbed conditions.

Figure 3 shows the calculated values of P_h (solid lines and squares) and Ψ_h (dashed and dotted lines) at SLT for $K_p^{\max}\leq 3$ (solid lines and squares) and $K_p^{\max}>3$ (dashed and dotted lines) for each month in a year. As Fig. 3 shows, the diurnal variations of *hm*F2 over the Argentine Islands correspond to the normal diurnal variations of *hm*F2 observed at middle latitudes. The F2-layer peak altitude is mainly lowest close to midday because the thermospheric wind blows poleward and forces ions and electrons down the field lines. Conversely, close to midnight the thermospheric wind blows away from the pole to the equator forcing the ionospheric plasma up the field lines and consequently increasing *hm*F2.

It follows from Fig. 1 that the maximum in the diurnal variations of *Nm*F2 were observed primarily close to midday in June, July, August, and September. Let $\Delta t_d=\mathrm{SLT}_2-\mathrm{SLT}_1$ is a daytime duration from a sunrise solar local time, SLT_1, to a sunset solar local time, SLT_2, when $\chi<90°$. The value of Δt_d changes from day to day during a month within limits which are calculated. We found that Δt_d=07:17–10:42 (April), 03:57–06:49 (May), 02:44–03:52 (June), 03:05–06:00 (July), 06:07–09:24 (August), 09:31–12:53 (September). It follows from our calculations that Δt_d=20:02–21:19 in December and Δt_d=17:37–20:53 in January, i.e. the Argentine Islands can be sunlit almost all day during some days of these months. Hence, diurnal variations of *Nm*F2 have only a weak solar zenith dependence by Chapman function

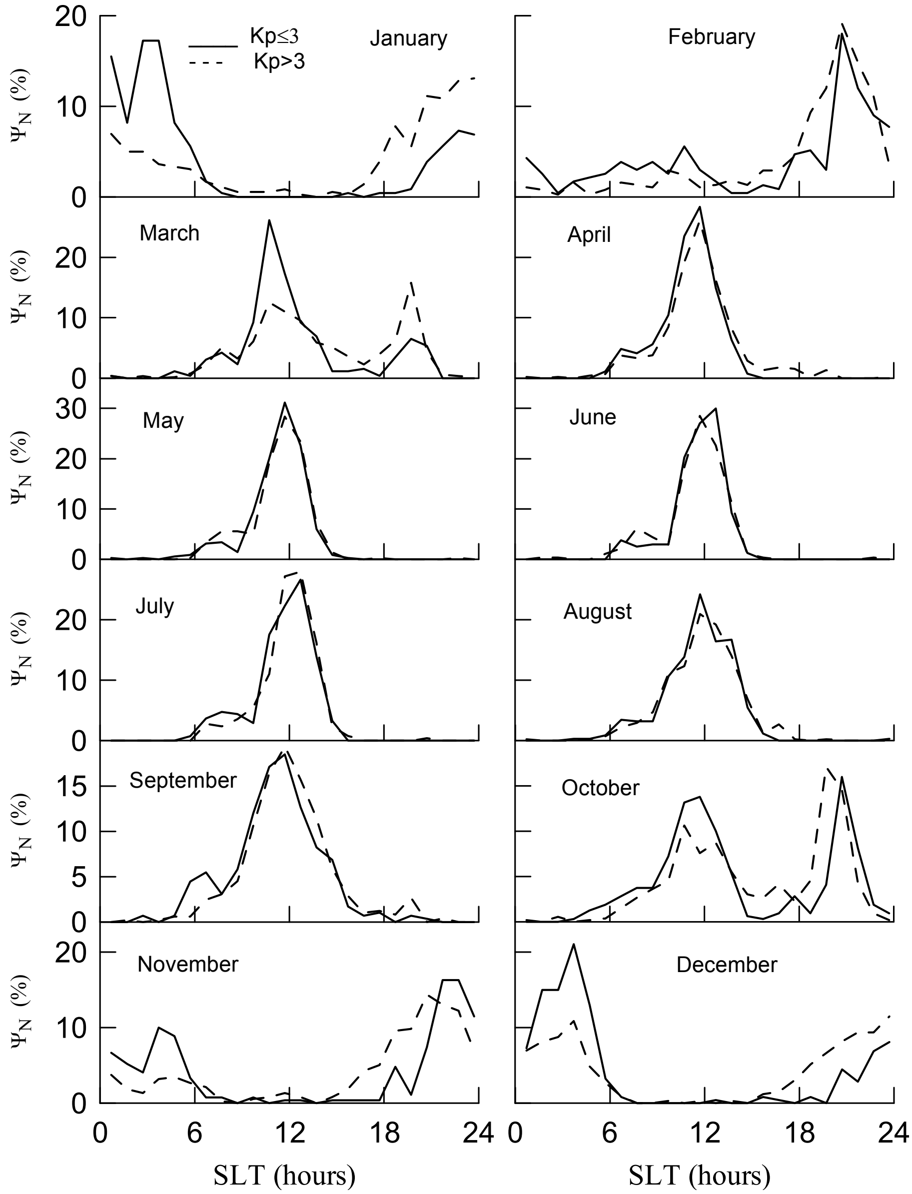

Fig. 1. A probability, Ψ_N, of the maximum *Nm*F2 value occurrence at SLT for $K_p^{\max}\leq 3$ (solid lines) and $K_p^{\max}>3$ (dashed lines) in diurnal variations of *Nm*F2 measured at the Argentine Islands ionosonde station for January, February, and March, April, May, June, July, September, October, November, and December.

variations in the production rates of O^+ ions during the main part of a daytime period, and the main part of these diurnal variations of *Nm*F2 is caused by changes in the neutral wind-induced plasma drift along magnetic field lines and by neutral densities variations. A poleward neutral wind causes a lowering of the F2-region height and a resulting reduction of *Nm*F2 due to an increase in the loss rate of $O^+(^4S)$ ions in the chemical reactions of these ions with unexcited and vibrationally excited N_2 and O_2, whereas a wind, which is equatorwards, tends to increase the value of *Nm*F2 by transporting the plasma up along field lines to regions of lower chemical loss of $O^+(^4S)$ ions. It follows from Fig. 3 that, close to the noon sector, the F2-layer is lowered into an altitude region of higher recombination rates of $O^+(^4S)$ ions leading to lower *Nm*F2 values. Close to the midnight sector, the F2-layer is raised and maintained by this plasma drift. As the ionosphere is sunlit during the long summer day in January and December, the value of *Nm*F2 is increased leading to the observed higher anomalous *Nm*F2 values close to midnight. This mechanism of the formation of the anomalous diurnal variations of *Nm*F2 over the Argentine Islands is supported by the model simulations of the monthly diurnal

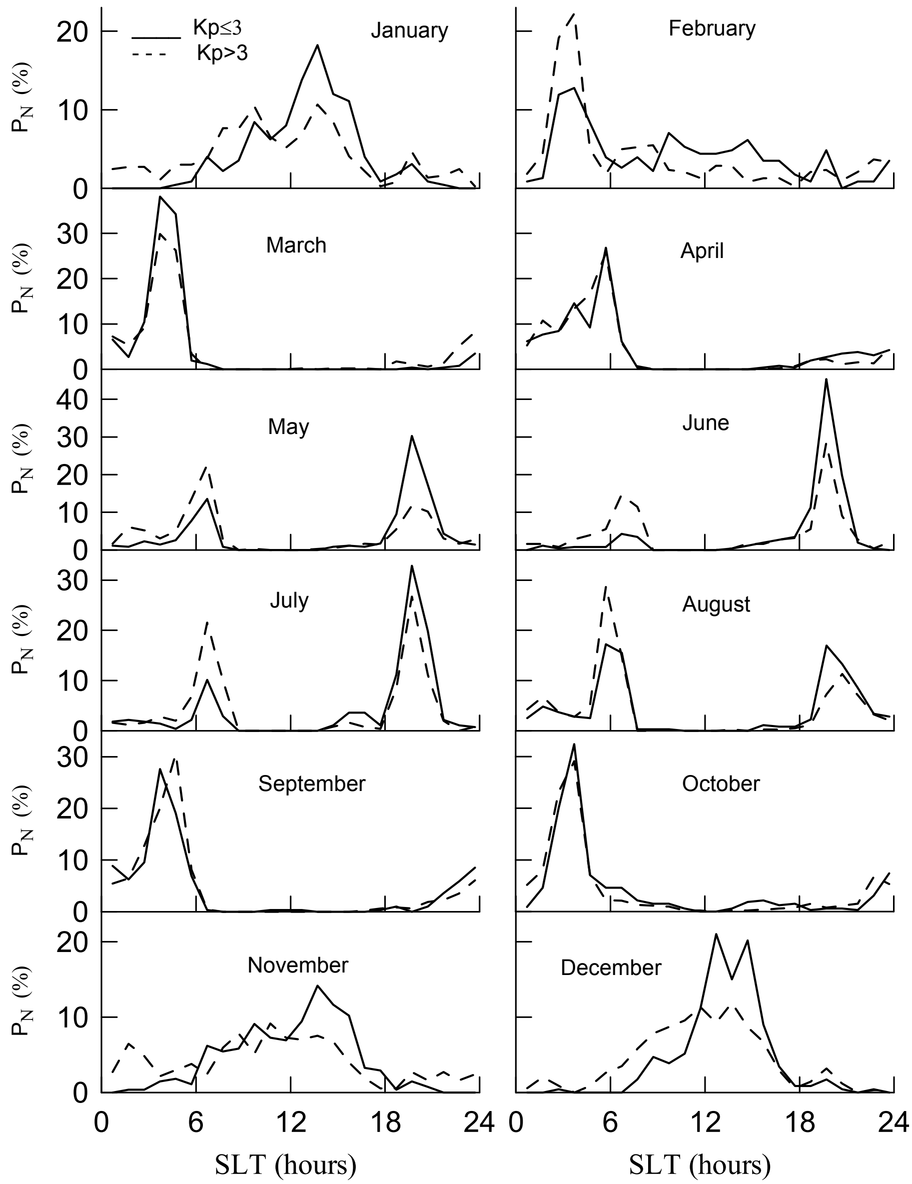

Fig. 2. A probability, P_N, of the minimum *Nm*F2 value occurrence at SLT for $K_p^{\max}\leq 3$ (solid lines) and $K_p^{\max}>3$ (dashed lines) in diurnal variations of *Nm*F2 measured at the Argentine Islands ionosonde station for January, February, and March, April, May, June, July, September, October, November, and December.

variations for the geomagnetically quiet conditions at several levels of solar cycle (Sojka et al., 1988) and by the comparison between the measured and modeled *Nm*F2 during the 5–6 January 1980 and 15–17 January1985 geomagnetically quiet time periods at solar maximum and minimum (Pavlov et al., 2008a, b).

The maximum value of Ψ_N is located close to midnight in February and in November while Δt_d=14:16–17:30 in February and Δt_d=16:28–19:57 in November. It appears reasonable to assume that this daytime duration is large enough to provide the mechanism of the February and November anomalous diurnal variations of *Nm*F2 described above for January and December. It should be noted that, contrary to January, November, and December, the majority of the minimum values of P_N is not observed close to the noon sector in February (see Fig. 2). The difference between the February and November diurnal variations of Ψ_N and P_N is an evidence in favour of a difference between February and November thermospheric circulations during geomagnetically quiet conditions.

Month averages of $Nm\mathrm{F2}_{\min}$, $hm\mathrm{F2}_{\min}$, $Nm\mathrm{F2}_{\max}$, and $hm\mathrm{F2}_{\max}$ are the observed characteristic of the anomalous diurnal variations of *Nm*F2. These ionospheric parameters were calculated for geomagnetically quiet and disturbed

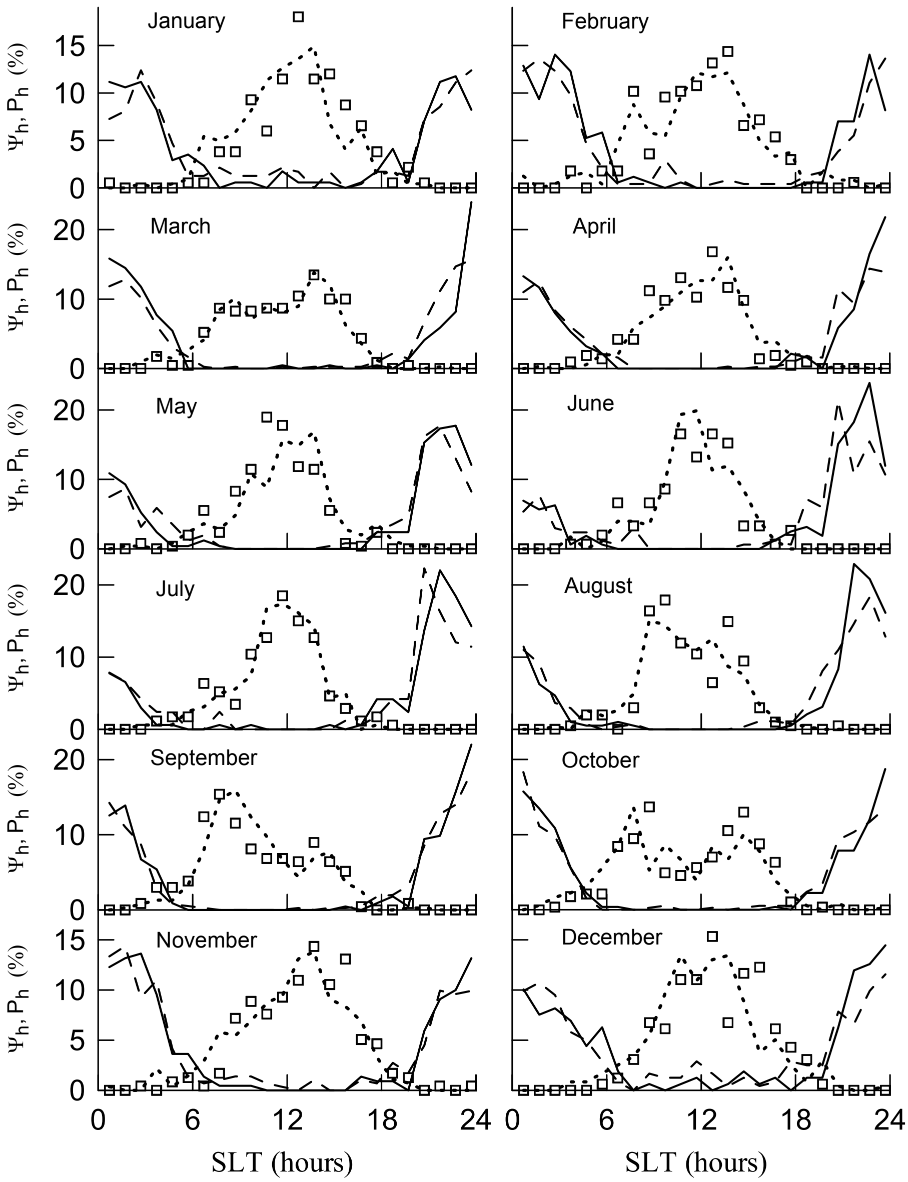

Fig. 3. A probability, P_h, of the minimum *hm*F2 value occurrence (solid lines and squares) and a probability, Ψ_h, of the maximum *hm*F2 value occurrence (dashed and dotted lines) at SLT for $K_p^{\max} \leq 3$ (solid lines and squares) and $K_p^{\max} > 3$ (dashed and dotted lines) in diurnal variations of *hm*F2 measured at the Argentine Islands ionosonde station for January, February, and March, April, May, June, July, September, October, November, and December.

conditions taking into consideration three different F10.7 solar activity index relative labels: "low, moderate, and high solar activity", for which we use F10.7<100, 100≤F10.7≤170, and F10.7>170, respectively. Average values of $NmF2_{\min}$ and $NmF2_{\max}$ for a given value of M, quiet and disturbed conditions, and low, moderate, and high solar activity levels are determines as

$$<NmF2_{\min}>=SN_{\min}(M,\, K_p^{\max},\, F10.7)/N(M,\, K_p^{\max},\, F10.7),$$
$$<NmF2_{\max}>=SN_{\max}(M,\, K_p^{\max},\, F10.7)/N(M,\, K_p^{\max},\, F10.7), \quad (6)$$

where $N(M, K_p^{\max}$,F10.7) is a number of days in a chosen month in a year when the ionosonde measurements of *Nm*F2 were carried out provided the values of $K_p^{\max}$ and F10.7 were located within the intervals specified, $SN_{\min}(M, K_p^{\max}$,F10.7) and $SN_{\max}(M, K_p^{\max}$,F10.7) are sums of $NmF2_{\min}$ and $NmF2_{\max}$, respectively, for chosen values of M, $K_p^{\max}$, and F10.7.

We determine average values of $hmF2_{\min}$ and $hmF2_{\max}$ for a given month in a year, 2 intervals of $K_p^{\max}$, and 3 intervals of F10.7 as

Table 1. The month averages of $Nm\mathrm{F2}_{\mathrm{min}}$, $hm\mathrm{F2}_{\mathrm{min}}$ (first numbers), and $Nm\mathrm{F2}_{\mathrm{max}}$, $hm\mathrm{F2}_{\mathrm{max}}$ (second numbers) found from the measurements of the Argentine Island ionosonde station during the geomagnetically quiet and disturbed conditions for low, moderate, and high solar activity in January, February, November, and December.

	$<Nm\mathrm{F2}_{\mathrm{min}}>$, $<Nm\mathrm{F2}_{\mathrm{max}}>$, 10^5 cm^{-3}						$<hm\mathrm{F2}_{\mathrm{min}}>$, $<hm\mathrm{F2}_{\mathrm{max}}>$, km					
	F10.7<100		$100\leq$F10.7≤170		F10.7>170		F10.7<100		$100\leq$F10.7≤170		F10.7>170	
	$K_p^{\max}\leq3$	$K_p^{\max}>3$	$K_p^{\max}\leq3$	$K_p^{\max}>3$	$K_p^{\max}\leq3$	$K_p^{\max}>3$	$K_p^{\max}\leq3$	$K_p^{\max}>3$	$K_p^{\max}\leq3$	$K_p^{\max}>3$	$K_p^{\max}\leq3$	$K_p^{\max}>3$
January	2.9, 8.3	2.4, 7.2	5.1, 13.8	4.1, 13.0	5.6, 15.3	4.9, 12.0	219, 352	220, 387	280, 413	262, 421	300, 438	288, 455
February	2.6, 6.1	1.9, 6.9	4.8, 9.9	3.4, 10.7	7.0, 12.7	4.3, 10.9	214, 348	216, 372	248, 395	249, 423	297, 439	288, 468
November	3.3, 8.4	2.6, 9.2	5.8, 13.2	4.9, 11.8	7.6, 16.2	6.6, 14.0	223, 361	228, 384	275, 401	279, 432	323, 442	315, 471
December	3.2, 10.0	2.8, 8.4	5.1, 15.4	4.8, 13.5	6.3, 17.8	5.1, 13.6	231, 359	229, 379	285, 407	282, 429	325, 457	308, 462

$$<hm\mathrm{F2}_{\mathrm{min}}>=\mathrm{SH}_{\mathrm{min}}(M,\,K_p^{\max},\,\mathrm{F10.7})/H(M,\,K_p^{\max},\,\mathrm{F10.7}),$$
$$<hm\mathrm{F2}_{\mathrm{max}}>=\mathrm{SH}_{\mathrm{max}}(M,\,K_p^{\max},\,\mathrm{F10.7})/H(M,\,K_p^{\max},\,\mathrm{F10.7}), \quad (7)$$

where $H(M,\,K_p^{\max},\mathrm{F10.7})$ is a number of days in a chosen month in a year when the ionosonde measurements of $M(3000)$F2 were carried out provided the values of $K_p^{\max}$ and F10.7 were located within the intervals specified, $\mathrm{SH}_{\mathrm{min}}(M,\,K_p^{\max},\mathrm{F10.7})$ and $\mathrm{SH}_{\mathrm{max}}(M,\,K_p^{\max},\mathrm{F10.7})$ are sums of $hm\mathrm{F2}_{\mathrm{min}}$ and $hm\mathrm{F2}_{\mathrm{max}}$, respectively, for chosen values of M, $K_p^{\max}$, and F10.7.

Table 1 shows the calculated values of $<Nm\mathrm{F2}_{\mathrm{min}}>$, $<Nm\mathrm{F2}_{\mathrm{max}}>$, $<hm\mathrm{F2}_{\mathrm{min}}>$, $<hm\mathrm{F2}_{\mathrm{max}}>$, for January, February, November, and December when the anomalous diurnal variations of *Nm*F2 are observed. As Table 1 shows, during the geomagnetically quiet conditions the $<Nm\mathrm{F2}_{\mathrm{max}}>/<Nm\mathrm{F2}_{\mathrm{min}}>$ ratio is equal to 2.7–2.9, 1.8–2.3, 2.1–2.5, 2.8–3.1 in January, February, November, and December, respectively, and an increase in solar activity leads only to a weak decrease in the $<Nm\mathrm{F2}_{\mathrm{max}}>/<Nm\mathrm{F2}_{\mathrm{min}}>$ ratio in February, November, and December, while this ratio is approximately the same in January for moderate and high solar activity. It is seen from Table 1 that the average geomagnetic storm and substorm response is negative in $<Nm\mathrm{F2}_{\mathrm{min}}>$ and $<Nm\mathrm{F2}_{\mathrm{max}}>$, except of February and November for low solar activity and February for moderate solar activity when a change of the geomagnetic activity level from $K_p^{\max}\geq3$ to $K_p^{\max}<3$ causes a reduction in $<Nm\mathrm{F2}_{\mathrm{max}}>$. The differences in the wind-induced plasma drift and neutral densities between quiet and disturbed conditions are responsible for the difference between the quiet and disturbed values of $<Nm\mathrm{F2}_{\mathrm{min}}>$ and $<Nm\mathrm{F2}_{\mathrm{max}}>$. As it was shown above, the diurnal variations of *hm*F2 are not anomalous. It is only worth noting that the value of $<hm\mathrm{F2}_{\mathrm{max}}>$ for $K_p^{\max}\geq3$ is greater than that for $K_p^{\max}<3$. This increase in $<hm\mathrm{F2}_{\mathrm{max}}>$ can be interpreted as a result of an increase in the strength of the average wind-induced plasma drift.

Soft particle precipitation can be suggested as a mechanism in changing the diurnal variations of *Nm*F2 under investigation. The bombardment of the atmosphere by low energy electrons causes diffuse aurora which is located in the region near the equatorward edge of the auroral oval (Feldstein and Galperin, 1985; Horwitz et al., 1986). However, only a part of the low energy electrons with energies less than or equal to about 2–5 eV is mainly effective for producing ionization at F-region altitudes (Rees, 1964). Nevertheless, it is possible to suggest that this low energy electron participation produces additional ionization in the F2-region over the Argentine Islands and a part of the studied diurnal variations of Ψ_N and P_N.

Soft electrons, with energy greater than 1.97 eV, excite the atomic oxygen to the D level by collisional impact at F2-region altitudes (where atomic oxygen is the dominant neutral gas constituent) leading to an increase in the intensity of the 630 nm atomic oxygen emission. As far as the authors know, there are no published papers where this optical manifestation of such bombardment of the atmosphere at the F2-region altitudes for geomagnetically quiet conditions would discussed. Therefore, an argument against ionization of neutral species by soft electrons as a part of a source of the geomagnetically quiet diurnal variations of Ψ_N and P_N is that such ionization would be accompanied by strong airglow emissions at 630 nm.

It follows from the DE 1 and 2 spacecraft measurements that the most probable equatorial boundary location of low energy electrons (100 eV) of diffuse aurora corresponds to the McIlwain parameter $L=L_{eq}$=8.02, 7.18, 6.34, 5.50 for K_p=0, 1, 2, 3, respectively, in the 15:00–24:00 MLT sector (Horwitz et al., 1986). The value of $L_{eq}>3.16$ for $K_p\leq3.75$ during all the DE 1 and 2 spacecraft measurements, and, $L_{eq}\geq3.34$ for $K_p\leq4.75$, except of only two measurements with $L_{eq}\approx3.16$ (see Fig. 6 of Horwitz et al., 1986). Thus, the Argentine Islands ionosonde cannot be located in a region of low energy electron precipitation during geomagnetically quiet conditions for $K_p\leq3$. The electron bombardment of the atmosphere cannot be invoked to account for the studied diurnal variations of Ψ_N and P_N for $K_p^{\max}\leq3$.

Precipitation of low energy electrons (∼1–2 keV) was recorded by instruments on board the Aureol-1, 2 satellites. The empirical model produces the equatorward boundary of this precipitation region at L=3.78–9.90 for K_p=00:00–03:00 and 00:00–07:00 MLT, and these results agree with the data from the DMSP satellites (Galperin et al., 1997). It should be noted that low energy electron fluxes measured by the instruments on board the Aureol-1, 2 satellites in the region of the main ionospheric trough of the subauroral ionosphere in the sector of 18:00–24:00 MLT were very weak, and, there were no significant resulting additional ionization of the F2-region (Lissakov et al., 1985). Therefore, not all low energy electron precipitations can produce noticeable variations of the F2-region electron density even if these low energy electron precipitations exist. If there are measurements of soft electron precipitations or increases in the 630 nm emission caused by these precipitations during geomagnetically disturbed conditions at middle geomagnetic latitudes, then it is necessary to study the relative role of these electrons as a possible source of variations in *Nm*F2 in each case.

4 Statistical study of the *Nm*F2 winter anomaly: results and discussion

In the Southern Hemisphere, the December and June solstices are usually considered to be centre points of the local summer and winter seasons, respectively. Therefore, we compare *Nm*F2 measured during December and June while January *Nm*F2 measurements are compared with those measured during July to reach 6 month difference between summer and winter months. The study of the F2-region winter anomaly carried out in this work, is based on the comparison of geomagnetically quiet daytime values of *Nm*F2 (see Sect. 2) at given UT when $\chi<90°$. To reach approximately the same level of the solar activity for summer and winter days, the difference between the winter and summer daily F10.7 solar activity indexes is taken to be less or equal to 20 in the statistical analysis. On the other hand, the value of *Nm*F2 is a function of production and loss rate of unexcited and electronically excited O^+ ions (see, e.g., Pavlov and Pavlova, 2005). As a result, the F2-layer peak electron density depends on the neutral temperature and densities whose values are functions of F10.7 solar activity index for a previous day (Hedin, 1987). Hence, we find a difference between F10.7 solar activity indexes for days preceding the winter and summer days examined. If this difference is less or equal to 20, then these winter and summer days are taken into consideration.

The F2-region winter anomaly is determined by the ratio

$$r = Nm\mathrm{F2}(W, \mathrm{UT}, \mathrm{F10.7})/Nm\mathrm{F2}(S, \mathrm{UT}, \mathrm{F10.7}), \quad (8)$$

where *Nm*F2(W,UT,F10.7) and *Nm*F2(S,UT,F10.7) are geomagnetically quiet daytime winter and summer values of *Nm*F2, respectively, described above.

If there are several values of *Nm*F2(S,UT,F10.7) arranged in order of increasing a number of a day in a month for a given value of *Nm*F2(W,UT,F10.7), then only the first one is used in the statistical analysis.

It should be noted that the mid-latitude ionosphere exhibits considerable day-to-day variability in *Nm*F2 during geomagnetically quiet conditions under similar solar activity conditions at all local times for each month (Forbes et al., 2000; Rishbeth and Mendillo, 2001). The origins of this ionospheric variability are discussed in detail by Forbes et al. (2000) and Rishbeth and Mendillo (2001). This day-to-day variability of *Nm*F2 results in a variability of r, and the statistical methods are required to be used in the study of the *Nm*F2 winter anomaly.

A dependence of r on UT has a maximum value R=$r_{\max}$ during each daytime period under consideration at some value of UT. The F2-region winter anomaly occurs during a daytime period for given F10.7 and chosen winter and summer months if $R>1$. The statistical study of this phenomena is carried out taking into consideration three different daily F10.7 solar activity index relative labels: "low, moderate, and high solar activity", for which we use F10.7<100, 100≤F10.7≤170, and F10.7>170, respectively. To determine these solar activity intervals, we employ F10.7 index corresponding to a winter day. A difference between F10.7 indexes for summer and winter days used in each calculation of r is taken to be less or equal to 20.

To study the distribution of R in amplitude, we split the range of R into intervals of the same length, ΔR=0.2. The conditional probability, $Q(R)$, of the occurrence of R in an interval of R is determined as a ration of a number of R with amplitudes in a given range to a number of R including all amplitudes of R provided the value of F10.7 was located within the interval specified. Figure 4 shows the calculated value of $Q(R)$ for high (solid lines), moderate (dashed lines), and low (dotted lines) solar activity on the base of the December and June *fo*F2 data set (left panel) and the January and July *fo*F2 data set (right panel). It is seen from Fig. 4 that the solid, dashed, and dotted lines of each panel do not differ greatly in appearance. The most frequent value, R_{MF}, of R is an amplitude where the maximum of $Q(R)$ is achieved. As Fig. 4 shows this maximum of $Q(R)$ is sharply pronounced. The value of R_{MF} is the same for low, moderate, and high solar activity if the December and June *fo*F2 data set is used (see Fig. 4 and Table 2). The use of the January and July *fo*F2 data set leads us to conclude that the most frequent value of R at low solar activity coincides with that at high solar activity and is slightly less than that at middle solar activity (see Fig. 4 and Table 2).

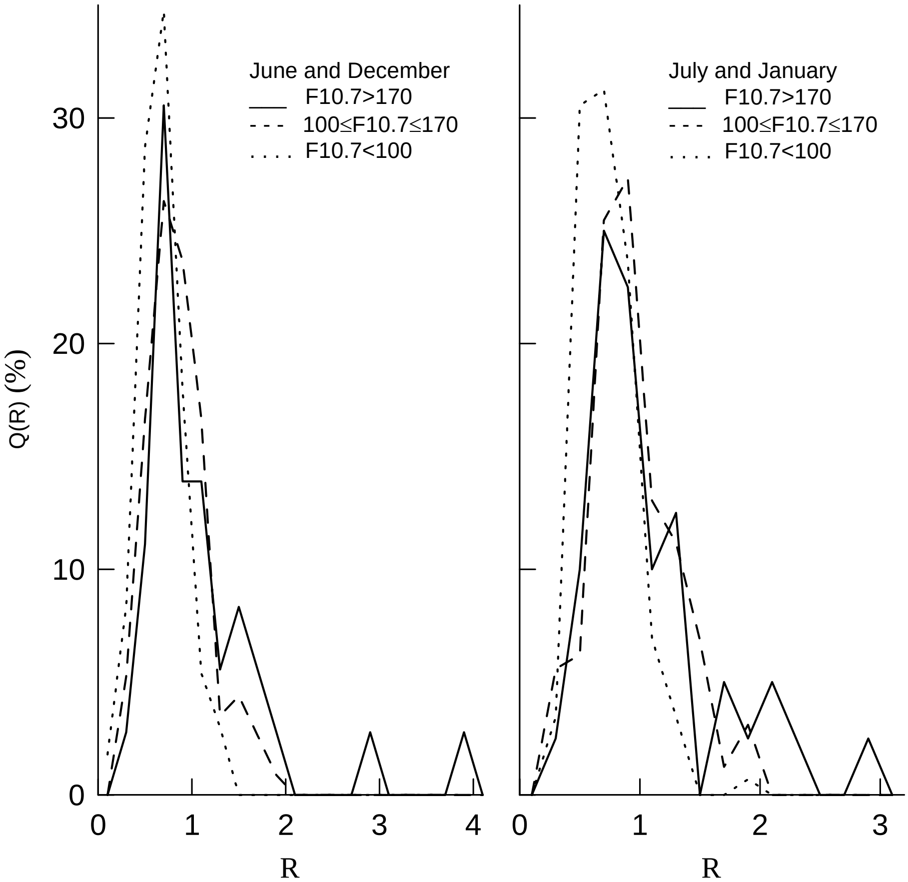

Fig. 4. The conditional probability, $Q(R)$, of the occurrence of R in an interval of R for high (solid lines), moderate (dashed lines), and low (dotted lines) solar activity calculated by the use of the December and June *fo*F2 data set (left panel) and the January and July *fo*F2 data set (right panel).

The mean value of expectation of R (the average) is defined by

$$< R >= \sum_{k\geq 1} R_k Q(R_k), \tag{9}$$

where R_k=$(k-0.5)\Delta R$.

The results of calculations presented in Table 2 show that the magnitude of $<R>$ decreases with decreasing solar activity. It follows from Table 2 that the value of $<R>$ exceeds the value of R_{MF}. Nevertheless, this difference is not very large because the conditional probability distribution $Q(R)$ is not strongly skewed (see Fig. 4). It follows from Table 2 that the value of $<R>$ is less than 1 for low and moderate solar activity when the probability to observe the *Nm*F2 winter anomaly is changed between 8.4% and 35.4%. We conclude that a comparison of the winter/summer values of $<R>$ cannot be a criterion of the absence of the *Nm*F2 winter anomaly.

The conditional probability, $Q(R>1)$, to observe the F2-region winter anomaly during a daytime period can be determined as a ratio of the number of $R>1$ to the number of R including all amplitudes of R provided the value of F10.7 was located within the interval specified. The calculated values of $Q(R>1)$ are presented in Table 2. It is seen from this table that the occurrence frequency of the F2-region winter anomaly increases with increasing solar activity.

Table 2. The conditional probability, $Q(R>1)$, to observe the F2-region winter anomaly during a daytime period, the most frequent value, R_{MF}, of R, and the expected value, $<R>$, of R found from the measurements of the Argentine Island ionosonde station during the geomagnetically quiet conditions for low, moderate, and high solar activity.

	December and June			January and July		
	$Q(R>1)$ %	R_{MF}	$<R>$	$Q(R>1)$ %	R_{MF}	$<R>$
F10.7<100	8.4	0.70	0.67	11.1	0.70	0.73
100≤F10.7≤170	28.1	0.70	0.85	35.4	0.90	0.94
F10.7>170	41.7	0.70	1.09	40.0	0.70	1.08

We use the hourly *fo*F2 data measured by the Argentine Islands station during the 1957–1959 and 1962–1995 time periods, and we consider that the seasonal anomaly in *Nm*F2 exists in the ionosphere if the ratio r given by Eq. (8) exceeds 1. We calculate a number, S, of daytime periods when the seasonal anomaly in *Nm*F2 is observed for given solar activity if the December and June *fo*F2 or January and July data set is used. Among these anomalous events, we find numbers, S_1 and S_2, of the seasonal anomaly events when $r>1$ only at one instant of time for S_1 and only at two instants of time for S_2 during a daytime period under consideration. We determine $G_1=S_1/S$ and $G_2=S_2/S$ and express these calculated values in percentage terms. It follows from the calculations that G_1=86, 53, and 40% and G_2=14, 24, and 28% at low, moderate, and high solar activity, respectively, if the December and June *fo*F2 data are used. The calculated values of G_1=85, 53, and 56% and G_2=15, 24, and 25% correspond to the low, moderate, and high solar activity levels if the January and July measurements of *fo*F2 are used. We conclude that the hourly *fo*F2 measured by the Argentine Islands inosonde exhibit the winter anomaly mainly at one instant of time by day at low solar activity. On average, the winter anomaly duration is less at low solar activity than that at moderate solar activity or at high solar activity.

The *Nm*F2 winter anomaly is often explained by the winter/summer changes in the [O]/[N_2] ratio (e.g. Millward et al., 1996; Zou et al., 2000; Rishbeth et al., 2000; Tao Yu et al., 2000). On the other hand, Zou et al. (2000) compared the coupled thermosphere-ionosphere-plasmasphere model (CTIP) results with ionosonde data from mid-latitudes for geomagnetically quiet conditions. Observed variations of the mid-latitude winter anomaly of *Nm*F2 at solar maximum and the fact of the matter that the winter anomaly of *Nm*F2 is stronger at solar maximum than at solar minimum are not successfully explained by the CTIP model (see pages 927 and 942 of Zou et al., 2000). Zou et al. (2000) concluded that these disagreements may be a consequence of the increase of F2-layer loss rate in summer in comparison with that in winter by vibrationally excited N_2 which is not included in the CTIP model.

Unexcited $O^+(^4S)$ ions that predominate at F2-region altitudes are lost in the reactions of $O^+(^4S)$ ions with vibrationally unexcited and vibrationally excited N_2 and O_2. The fundamental laboratory measurements (Schmeltekopf et al., 1968; Hierl et al., 1997) show that vibrationally excited N_2 and O_2 react much more strongly with $O^+(^4S)$ ions than vibrationally unexcited N_2 and O_2. The daytime mid-latitude electron density of the F2-region is decreased up to a factor of 2–3 due to vibrationally excited N_2 and O_2 (Pavlov, 1998; Pavlov et al., 1999; Pavlov and Foster, 2001; Prolss and Werner, 2002). As a result, a part of the mid-latitude F2-layer winter anomaly can be attributed to the seasonal difference of the increase in the loss rate of $O^+(^4S)$ ions due to vibrationally excited N_2 and O_2 (Torr et al., 1980; Pavlov and Pavlova, 2005; Pavlov et al., 2008a, b).

Using the photoionization cross-section for atomic oxygen compiled by Richards et al. (1994) and the EUVAC solar flux model (Richards et al., 1994), we conclude that, during atomic oxygen photoionization, a part of oxygen ions, which is created in electronically excited states, is larger than that forming electronically unexcited $O^+(^4S)$ ions with the production rate, P_{EUV}. These electronically excited oxygen ions are converted to N_2^+ and O_2^+ ions, and $O^+(^4S)$ ions in chemical reactions constituting a large daytime source, P_{ex}, of $O^+(^4S)$ ions through chemical reactions (see, e.g., Pavlov and Pavlova, 2005). Neglect of electronically excited oxygen ions in model simulations, leads to inaccurate values of *Nm*F2 while a difference between seasonal variations of $P_{EUV}+P_{ex}$ and P_{EUV} can lead to disagreements between values of r (see Eq. 8) found from ionosonde observations and model simulations.

The model simulations (Torr et al., 1980; Pavlov and Pavlova, 2005; Pavlov et al., 2008a, b) provide evidence that the mid-latitude winter/summer anomalous difference in *Nm*F2 is produced, not only by seasonal changes in the [O]/[N_2] and [O]/[O_2] ratios, but also by seasonal variations in the N_2 and O_2 vibrational temperatures, and by an increase in the production rate of $O^+(^4S)$ ions in winter in comparison with that in summer due to chemical reactions of electronically excited O^+ ions as a source of $O^+(^4S)$ ions. A part of the mid-latitude F2-layer winter anomaly which can be attributed to seasonal variations of the vibrationally excited N_2 and O_2 temperatures and the production rate of $O^+(^4S)$ ions from electronically excited O^+ ions is decreased with declining solar activity from solar maximum to solar minimum (Pavlov et al., 2008a, b). This decrease in the relative role of these two sources of the *Nm*F2 winter anomaly can be responsible for the decrease of $Q(R>1)$ with decreasing solar activity over the Argentine Islands (see Table 2). At solar minimum, the mid-latitude winter anomaly of *Nm*F2 is practically not produced by seasonal variations of the vibrationally excited N_2 and O_2 temperatures, and the role of electronically excited oxygen ions in producing the mid-latitude winter/summer anomalous difference in *Nm*F2 is less than that caused by seasonal variations of neutral number densities (Pavlov et al., 2008b). We conclude that seasonal neutral composition variations are mainly responsible for the very low probability to observe the winter anomaly of *Nm*F2 over the Argentine Islands at solar minimum shown in Table 2.

A statistical median of a set of numbers is one of statistical parameters used in statistical studies (e.g. Johnson and Leone, 1977). As a particular case of a general definition of a statistical median, a definition of a monthly median value, *fo*F2(med), of *fo*F2 at given UT measured by an ionosonde is presented by the URSI handbook of ionogram interpretation and reduction (1978). The values of *fo*F2 measured during a month at given UT are sorted in such a way that their magnitude is increased from lowest value to highest value. An odd number of *fo*F2 values under investigation leads us to determine *fo*F2(med) as the middle value. The average of the

Table 3. The arithmetical mean, <*fo*F2(med)>, of the median values of *fo*F2 at 16:00 UT (11:43 SLT) and the percentage, P_q(med), of the geomagnetically quiet median values of *fo*F2 at 16:00 UT for January, June, July, and December calculated from the Argentine Island ionosonde *fo*F2 data for low, moderate, and high solar activity.

	<*fo*F2(med)>, MHz				P_q(med), %			
	January	June	July	December	January	June	July	December
F10.7<100	5.07	4.28	4.31	5.17	67	46	33	42
100≤F10.7≤170	6.58	6.40	5.83	6.79	64	70	14	64
F10.7>170	6.84	6.41	6.76	6.69	17	25	29	17

two middle values of *fo*F2 is taken as *fo*F2(med) if the number of days in a month when these values were measured is even. This definition of *fo*F2(med) is not related to geomagnetic activity, and it is necessary to examine if *fo*F2(med) correspond to geomagnetically quiet conditions or geomagnetically disturbed conditions. The use of *fo*F2(med) which correspond to geomagnetically disturbed conditions can be a potential source of incorrect results and conclusions in ionospheric studies where geomagnetically quiet values of *fo*F2 are employed (for example, *fo*F2(med) measured by ionosondes close to noon were used to study the winter anomaly of *Nm*F2 by Torr and Torr, 1973, and Zou et al., 2000).

Table 3 shows the arithmetical mean, <*fo*F2(med)>, of the median values of *fo*F2 at 16:00 UT (11:43 SLT) for January, June, July, and December calculated from the Argentine Island ionosonde *fo*F2 data for low, moderate, and high solar activity during the 1957–1959 and 1962–1995 time periods. It follows from Table 3 that the winter anomaly of *Nm*F2 is not observed over the Argentine Islands from the point of view of the winter/summer arithmetical mean median comparison. This wrong conclusion, which is in contradiction with our statistical study, shows the shortcomings of the median approach. As was pointed out above, even the winter/summer comparison of $<R>$ cannot be used to prove the absence of the *Nm*F2 winter anomaly. The statistical analysis carried out in this work leads us to find find the conditional probability to observe the F2-region winter anomaly during a daytime period.

The percentage, P_q(med), of the geomagnetically quiet median values of *fo*F2 at 16:00 UT presented in Table 3 is determined as a ratio of a sum of *fo*F2(med) corresponding to geomagnetically quiet conditions to a sum of *fo*F2(med) corresponding to geomagnetically quiet and disturbed conditions in a month for given solar activity. In agreement with our definition of a geomagnetically quiet value of an ionospheric parameter given in Sect. 2, a value of *fo*F2(med) determined as the middle value is considered as a geomagnetically quiet value if $K_p \leq 3$ for 24-h time period prior to and including UT (16:00 UT for the results of Table 3) where *fo*F2(med) is taken. A value of *fo*F2(med) calculated as the average of the two middle value is taken into consideration as a geomagnetically quiet value if $K_p \leq 3$ for each 24-h time period prior to and including UT for two middle values of *fo*F2 used in calculations of *fo*F2(med). The results of the calculations presented in Table 3 show that only a part of *fo*F2(med) corresponds to geomagnetically quiet conditions, and the percentage of *fo*F2(med) which does not correspond to geomagnetically quiet conditions is large enough. It is an argument against the use of *fo*F2(med) in ionospheric studies instead of geomagnetically quiet *fo*F2 without an examination if *fo*F2(med) could be considered as a geomagnetically quiet value.

5 Conclusions

A statistical study of the diurnal variations of *Nm*F2 and *hm*F2 over the Argentine Islands was carried out to reveal anomalous features in these variations and to study statistical relationships of the found anomalous diurnal variations with season and geomagnetic activity levels. The ionosonde measurements of *fo*F2, M(3000), and *fo*E during the 1957–1959 and 1962–1995 time periods were used in the statistical analysis. Probabilities to observe maximum and minimum values of *Nm*F2 and *hm*F2 in a diurnal variation of the electron density are calculated. Diurnal variations of *Nm*F2 are considered to be anomalous for a month in a year if the F2-layer peak electron density reaches its minimum value close to the noon sector, or the maximum in diurnal variations of *Nm*F2 is located in a time sector close to midnight. It is found that, in the main, *Nm*F2 do not exhibit anomalous diurnal variations in April, May, June, July, August, and September. Our calculations do not show anomalous features in the diurnal variations of *hm*F2 during each month in a year.

It is shown that, in November, December, January, and February, the main part of the maximum diurnal values of *Nm*F2 is observed in a time sector close to midnight, while the minimum diurnal values of *Nm*F2 are observed mainly close to the noon sector only during November, December, and January. It follows from the statistical study that these anomalous diurnal variations of *Nm*F2 are observed during both geomagnetically quiet and disturbed conditions. Geomagnetic disturbance effects in the month averages of $Nm\mathrm{F2}_{\mathrm{max}}$ and $Nm\mathrm{F2}_{\mathrm{min}}$ are found to be negative in November, December, January, and February, except for February and November for low solar activity and February for moderate solar activity when these effects are positive.

Statistical data processing has been performed to study statistical characteristics of the F2-region winter anomaly phenomena over the Argentine Islands inosonde. We compare *Nm*F2 measured during January (local summer) and July (local winter), and December *Nm*F2 measurements (local summer) with those during June (local winter). Changes in a maximum daytime value R of a ratio of a geomagnetically quiet daytime winter *Nm*F2 to a geomagnetically quiet daytime summer *Nm*F2 taken at a given UT and for approximately the same level of solar activity were studied. The conditional probability of the occurrence of R in an interval of R, the most frequent value R_{MF} of R, the mean expected value $<R>$ of R, and the conditional probability $Q(R>1)$ to observe the F2-region winter anomaly during a daytime period were calculated for low, moderate, and high solar activity. The calculations show that R_{MF}=0.7–0.9, $<R>$=0.67–1.09, and $Q(R>1)$=8.4–41.7%. The data sets provide evidence that the mean expected value of R and the occurrence frequency of the F2-region winter anomaly increase with increasing solar activity. We found that the hourly *fo*F2 measured by the Argentine Islands ionosonde exhibit the *Nm*F2 winter anomaly mainly at one instant of time by day at low solar activity, and the probability to observe this anomaly at two moments in time by day is found to be negligible at low solar activity. The hourly Argentine Islands ionosonde measurements of *fo*F2 show that there is only a relatively small chance to observe this phenomenon at two moments in time by day at moderate solar activity.

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