Proxy for the ionospheric peak plasma density reduced by the solar zenith angle

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The F_2 layer peak plasma density N_mF_2 is reduced by the factor constructed from the relative changes in the Sun's zenith angle χ for a particular local time and the local noon value χ_0. Proposed transformation yields a proxy for the peak plasma density which coincides with the source observation at noon but apart from the latter is gradually reduced towards the night. Hourly observations at 8 ground based ionosondes for the solar maximum (2000) and minimum (2006) are analyzed for inter-stations and inter-seasonal correlation of the peak plasma density and the proxy values. The proxy values show improved correlation between the data at different locations and improved inter-seasonal correlations for a particular location due to greater homogeneity of results throughout the year contributing to improved evaluation of the ionospheric weather indices.

Key words: Ionosphere, plasma density, solar zenith angle.

1. Introduction

Diurnal and seasonal changes of the plasma density and temperature in the ionosphere depend directly on the illumination of the upper atmosphere by the Sun. The features of the peak plasma density, N_mF_2, m^{-3}, proportional to square of the ionospheric critical frequency f_oF_2 can be made more uniform if the effect of the solar grazing incidence on the plasma density in the F region could be reduced with a proper transformation.

Earlier, the relevant relations of the noon F_2 layer critical frequency have been investigated for the magnetic conjugate locations at the ends of the magnetic line of force assuming that daytime temperature of the neutral gas is proportional to the cosine of the Sun's zenith angle at local noon (Rotwell, 1962). The correction factor deduced for such relation, so called "M-factor" has been used for constructing the global model of the noon f_oF_2 critical frequency from the data of global network of ionosondes (Besprozvannaja, 1970, 1987) and the monthly ionospheric index MF_2 (Mikhailov and Mikhailov, 1995). However, this approach is valid only for the local noon while relevant transformation for all times throughout the day is required.

The solar zenith angle determines proportions of daytime and nighttime conditions in the ionosphere at different altitudes over the Earth (Gulyaev and Gulyaeva, 1984) with relevant plasma density and temperature controlled by the energy transmitted from the Sun in the form of an electromagnetic wave radiation in the UV/EUV ranges to the upper atmosphere (Chapman, 1931). The solar zenith angle dependence as predicted by the Chapman ionization theory cannot thoroughly explain spatial and temporal variations of the ion density by the factors such as plasma production due to UV/EUV alone, differential loss due to varying recombination rate, transport, neutral winds, atmospheric composition. The energy input from the magnetosphere in the form of electric fields and charged particle precipitation due to the solar wind also contributes significantly to the changes of the peak plasma density (Lal, 1997). If the dominant effect of the solar zenith angle on the ionospheric plasma density could be reduced by a proper transformation, an improved metric of the solar-controlled behaviour of the plasma around the peak of the F_2 layer can be obtained.

In the present paper, the variations in the Sun's zenith angle are used to produce a proxy for the peak plasma density, N_pF_2, by multiplying the observed peak plasma density N_mF_2 by a factor related with the solar zenith angle χ at a particular time and the local noon value χ_0. This process is evaluated with the data of eight ground based ionosondes at solar minimum (2006) and maximum (2000) to illustrate the advantages of the reduced peak plasma density as compared with the source observations that will be useful for applications in the ionosphere modeling and forecasting.

2. Technique of Inversion of the F_2 Layer Critical Frequency by the Solar Zenith Angle

The solar zenith angle χ reaches peak at the local midnight tending to a minimum at the local noon. Impact of the local conditions of the Sun's illumination can be excluded by normalizing the peak plasma density N_mF_2 by the solar zenith angle χ in radians. Change of the normalizing factor $1/\chi$ from day to night is shown by the dashed line with triangles in Fig. 1.

The multiplier $1/\chi$ is larger when the solar zenith angle gets smaller and in the limit of noon between the north and south tropics as χ approaches zero, $1/\chi$ tends to infinity.

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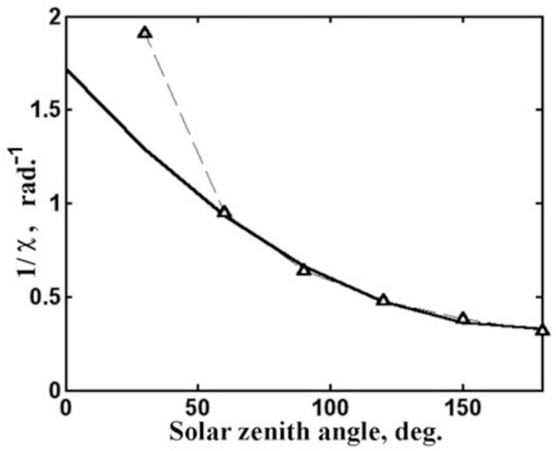

Fig. 1. Correction factor deduced from the solar zenith angle.

To avoid this singularity, we introduce the second order polynomial approximation of the best least square fit to $1/\chi$ for the angles of $\chi > 1$ rad. as follows:

$$z(\chi) = \gamma(x^2 - \beta x + \alpha) \tag{1}$$

where $x = \chi^\circ/100$, $\alpha = 3.8749$, $\beta = 3.5402$, and $\gamma = 0.4444$ and $z(\chi)$ is given in solid line in Fig. 1.

Multiplying $N_\mathrm{m}F_2$ by the coefficient $z(\chi)$ yields reduced nighttime and sunrise/sunset values but tends to increase the daytime values, particularly in summer towards the equator when $z \gg 1$. To equilibrate such opposite effects for day and night we replace multiplier in Eq. (1) by the normalizing factor $C(\chi, \chi_0)$ equal to the ratio of the coefficient of Eq. (1) for given local time to the value for local noon:

$$C(\chi, \chi_0) = z(\chi)/z(\chi_0). \tag{2}$$

With the normalizing factor defined in terms of coefficients α and β we obtain the proxy $N_\mathrm{p}F_2$ for the peak plasma density $N_\mathrm{m}F_2$ by multiplying the latter by $C(\chi, \chi_0)$:

$$N_\mathrm{p}F_2 = C(\chi, \chi_0) \times N_\mathrm{m}F_2. \tag{3}$$

The resultant $N_\mathrm{p}F_2$ coincides with the source value $N_\mathrm{m}F_2$ at noon ($C_0 = 1$) but it is essentially reduced towards the night when coefficient $C(\chi, \chi_0)$ tends to zero depicting a reduced maintenance of nighttime ionization compared with its noon value. Thus, all regularities of the noon peak plasma density $N_\mathrm{m}F_2$ (Besprozvannaja, 1987; Williscroft and Poole, 1996) are valid for $N_\mathrm{p}F_2$. However the reduced values of $N_\mathrm{p}F_2$ at other times are significantly changed.

3. Validation of the Proxy for the Peak Plasma Density with Ground Based Ionosonde Data

The above transformation is applied to daily-hourly observations at 8 ionospheric stations listed in Table 1 for the solar maximum (2000) and minimum (2006). The solar zenith angle was calculated for given day of year, geodetic coordinates of ionosonde site and local time with the standard subroutine SOCO (McNamara, 1986) of the International Reference Ionosphere code (Bilitza, 2001).

Figure 2 shows the monthly median at Chilton for the source $N_\mathrm{m}F_2$ and reduced $N_\mathrm{p}F_2$ for 4 seasons during the solar minimum: spring (March), summer (June), autumn (September) and winter (December) 2006. The source median and the proxy median coincide at noon. The diurnal curve of $N_\mathrm{p}F_2$ become rather uniform throughout the year gradually reduced from day to night which corresponds to reduced income of the ionizing radiation from the Sun (Gulyaev and Gulyaeva, 1984). The sunrise minimum of $N_\mathrm{m}F_2$ is smoothed in the diurnal change of $N_\mathrm{p}F_2$. The diurnal variation is particularly improved at summer when it became similar to $N_\mathrm{p}F_2$ variation for other seasons.

Table 1. Geodetic and geomagnetic coordinates (latitude and longitude) of the ionosonde stations providing data used in the present paper.

Station	Geodetic		Magnetic	
	Lat °N	Lon °E	Lat °N	Lon °E
Sodankyla	67.4	026.6	63.6	120.8
Julius-Rugen	54.6	013.4	54.3	099.7
Chilton	51.6	358.7	54.1	083.2
Moscow	55.5	037.3	50.4	123.2
Tortosa	40.4	000.3	43.6	080.9
Rome	41.8	012.5	42.3	093.2
El Arenosillo	37.1	353.3	41.4	072.3
Wakkanai	45.4	141.7	35.5	207.3

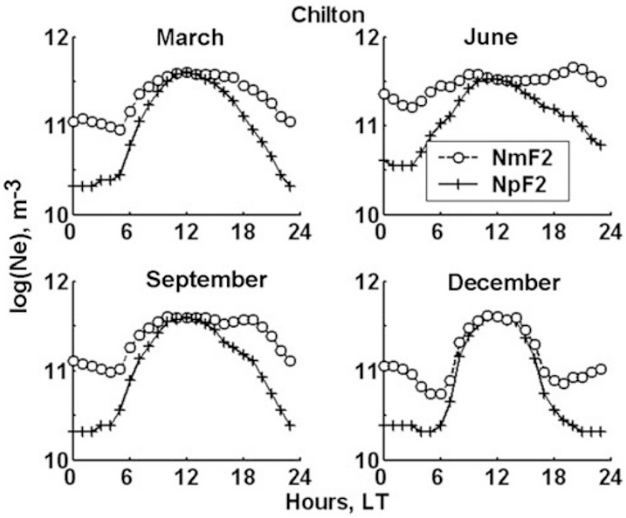

Fig. 2. Monthly median of observed peak plasma density $N_\mathrm{m}F_2$ at Chilton and proxy $N_\mathrm{p}F_2$ reduced by the solar zenith angle for four seasons at the solar minimum 2006.

The hourly values of $N_\mathrm{m}F_2$ and $N_\mathrm{p}F_2$ for four seasons are used for each pair of stations of Table 1 and the mean of all correlation coefficients are computed. In Table 2, the inter-location correlation coefficient r_2 is presented for selected months at solar maximum (2000) and minimum (2006). Improved correlation between the stations data is obtained with the proxy values in all cases. The most appreciable improvement of r_2 is obtained for the summer solstice when the dominant is daytime process of the ion production due to solar illumination during the day.

While the improvement in the correlation of the data from different stations has been the primary goal of implementation of Eq. (3), the results reveal also an improved the inter-seasonal correlation coefficient r_1 for each station in Ta-

Table 2. Mean inter-station correlation coefficient for observed N_mF_2 and proxy N_pF_2 for the peak plasma density at solar maximum and minimum for four seasons/months.

Year	2000		2006	
Month	N_mF_2	N_pF_2	N_mF_2	N_pF_2
03	0.841	0.906	0.801	0.888
06	0.521	0.834	0.478	0.802
09	0.653	0.814	0.771	0.883
12	0.827	0.881	0.756	0.856

Table 3. Inter-seasonal correlation coefficient averaged for all stations for N_mF_2 and N_pF_2 at solar maximum (2000) and solar minimum (2006) for two pairs of months.

Year	2000		2006	
Months	N_mF_2	N_pF_2	N_mF_2	N_pF_2
03∼12	0.824	0.938	0.641	0.880
06∼09	0.298	0.858	0.528	0.885

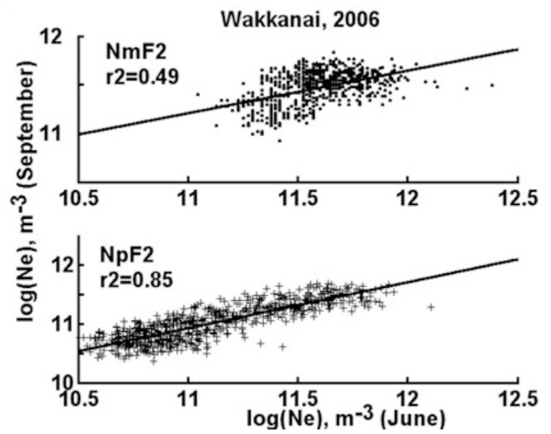

Fig. 3. Inter-seasonal relation for September versus June 2006 for observed peak plasma density N_mF_2 (upper panel) and for proxy N_pF_2 (lower panel) at Wakkanai.

ble 1. The averages of the correlation coefficients r_1 are provided in Table 3 for all stations referring to selected months of March–December and June–September at the solar maximum and minimum. The proposed technique brings improved inter-seasonal correlations for N_pF_2 as compared with N_mF_2, particularly, for the June–September pair of months due to the most appreciable changes in N_pF_2 for the summer solstice.

Figure 3 illustrates inter-seasonal relation for June–September at Wakkanai between the hourly values of N_mF_2 (upper panel) and N_pF_2 (lower panel) at solar minimum, 2006. It is evident that regression between the data for 2 different seasons (summer and equinox) is improved in the proxy data set as compared with the observed N_mF_2. It is expected that proposed transformation of the F_2 layer peak density depicting more uniform daily/seasonal variation as compared with the observations would be helpful for the modelling and forecasting purposes than the more sophisticated day-to-day and hour-to-hour changes of the source N_mF_2 data.

The advantages of the proposed approach proved to be useful for reconstruction of missed ionosonde observations of the critical frequency f_oF_2 with the data of another station using the cloning technique discussed in (Gulyaeva *et al.*, 2008) so that the complete daily/hourly data sets for selected location/season/month are available for derivation of the ionospheric weather indices.

4. Conclusion

In this study, a new technique for obtaining a proxy for the ionospheric peak plasma density is proposed. The correction factor depends on ratio of the solar zenith angle at the time of observation to its local noon value. The noon values of the normalized peak plasma density coincide with observations of N_mF_2 but N_pF_2 is gradually reduced from day to night throughout the year for all observations analyzed at eight ionospheric stations for the maximum and minimum of solar activity. The normalization of the peak plasma density improves not only the correlation coefficient between the data of different stations but also the inter-seasonal correlation for the data of a particular station.

The proposed technique of inversion of the peak plasma density by the solar zenith angle presents physically justified replacement of the variable by a proxy value of significantly improved characteristics. The proposed proxy parameter exhibits diurnal/seasonal homogeneity of the peak electron density which is one of the key parameters of modern ionospheric models.

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