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A comparison of f_0E and *hmE* model calculations with El Arenosillo digisonde observations. Seasonal variations

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Abstract
Seasonal variations of *hmE* and f_0F_2 are analyzed using El Arenosillo digisonde observations during solar minimum (1995-1996). Unlike some widely used empirical models daytime *hmE* show seasonal variations with winter *hmE* being higher than summer ones and seasonal differences increase with solar zenith angle. Model calculations enable us to reproduce the observed *hmE* seasonal variations but the calculated daytime f_0E values are too low if conventional EUV fluxes and dissociative recombination rate constants are used. A reduction of $\alpha(NO^+)$ by taking into account $T_e > T_n$ in the *E*-region as it follows from probe measurements seems to be a plausible solution. The *E*-region ion composition corresponding to rocket observations may be obtained in model calculations using an appropriate [NO] height distribution. Calculated summer concentrations of [NO] are by a factor of 3-4 larger than winter ones at the *hmE*-heights.

Key words *ionospheric E-layer-theoretical modeling – solar EUV – nitric oxide*

1. Introduction

The ionospheric *E*-layer has been studied for some decades and existing empirical f_0E models like IRI (Bilitza, 1990) reproduce regular f_0E variations with high accuracy. The situation with *hmE* is not that straightforward due to the problems with *hmE* determination from the ionogram reduction procedure. The $Ne(h)$ profile is very irregular at the *E*-region heights as rocket observations show (*e.g.*, Andreyeva *et al.*, 1971), so there is an uncertainty with *hmE* identification. This results in different seasonal, solar cycle and daily *hmE* variations given by various empirical models. The IRI-90 (Bilitza, 1990) and DGR (Di Giovanni and Radicella, 1990) models give neither seasonal nor daily variations of *hmE*. But daily *hmE* variations should be present in empirical models as the *E*-layer mostly follows Chapman's theory and *hmE* may be expected to vary with solar zenith angle, χ as

$$hm = hm_0 + H \ln(\sec\chi) \tag{1.1}$$

where H is the scale height of neutral atmosphere. A pronounced *hmE* seasonal variation with winter *hmE* higher than summer ones follows from incoherent scatter observations (Taran, 1979). Similar seasonal *hmE* changes predict the SMI model (Chasovitin *et al.*, 1987, 1988), while opposite *hmE* seasonal behaviour may be found in the model by Ivanov-Kholodny and Nusinov (1979) and Nusinov (1988) based on ionosonde observations.

There is one more serious problem concerning theoretical *E*-layer modeling. The use of conventional EUV solar flux models and disso-

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ciative recombination reaction rate constants for NO^+ and O_2^+ ions gives calculated $NmE = 1.24 \times 10^4 f_0E^2$ which are 30-40% less compared to the observations (Buonsanto *et al.*, 1995; Titheridge, 1997). Because of the square-law loss process, this 40% deficit in *NmE* implies a 100% increase in the total ionization rate at the *E*-layer maximum. Some approaches have been proposed to overcome this problem. Ivanov-Kholodny and Nusinov (1979) used low α^+_{NO} and α^+_{O2} values by Mul and McGowan (1979) along with $[O_2]$ scale height seasonal variations in the 100-110 km height range. Later Antonova *et al.* (1996) took into account vibrationally excited NO^+ and O_2^+ ions which allowed them to explain *NmE* and *hmE* seasonal variations. Titheridge (1996, 1997), using a full allowance for secondary ionization with *X*-ray radiation down to 25 A and a 33% additional increase in the $\lambda < 150$ A fluxes in the EUVAC model (Richards *et al.*, 1994), reproduced the observed daytime *NmE* values in his model calculations. Although there is large uncertainty with EUV fluxes in this spectrum range, such an increase in the fluxes in the 50-150 A range (already been tripled in the EUVAC model) seems unjustified.

The aim of the paper is to compare *E*-region model calculations with f_0F_2 and *hmE* El Arenosillo digisonde observations and discuss the problems encountered.

2. Data selection

The El Arenosillo digisonde routine ionogram reduction hourly data produced with THTABLE and NHPC (version 3.04, 1996) codes were used in the analysis. All available f_0E and *hmE* observations for winter (December-January) and summer (June-August) periods of 1995-1996 were considered. As *Es* is very often on iono-

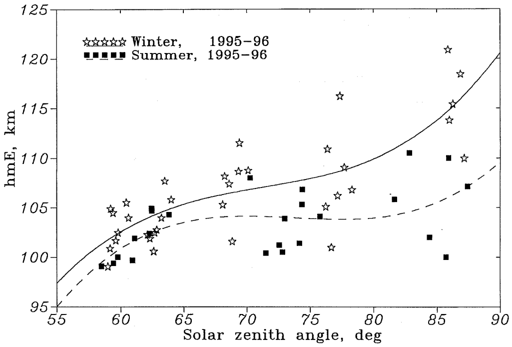


Fig. 1. Observed at El Arenosillo *hmE* variations for winter and summer months. Curves – least squares approximation.

grams only quiet days with well read f_0E and *hmE* daily variations were used in our analysis. Even in this case *hmE* values are very variable and we put together all winter and all summer months for 1995-1996 to increase statistics. It is possible to do this as both years belong to the solar minimum with a three month average $F_{10.7} = 70\text{-}74$.

Observed winter and summer *hmE* variations are shown in fig. 1 for one and the same solar zenith angle range. Curves are the least-squares approximation of the observations. Winter *hmE* values are seen to be higher on average than summer ones and the difference increases with solar zenith angle. Similar seasonal *hmE* variations with winter *hmE* higher than summer ones may be found in the SMI model by Chasovitin *et al.* (1987) and in the incoherent scatter observations at the Kharkov (49.43N; 36.92E) given in the monograph by Antonova *et al.* (1996). These *hmE* seasonal variations at solar minimum are given in table I for two solar zenith angles.

Table I. Seasonal variations of *hmE* (in km) for solar minimum.

Solar zenith angle	72°		82°	
Season	Winter	Summer	Winter	Summer
IS observations	118	113	121	117
SMI model	112	110	118	110

3. Model calculations

Midlatitude regular ionospheric *E*-region is known to be controlled by photochemical processes and may be with some reservations described by Chapman's theory (Ivanov-Kholodny and Nusinov, 1979). Neutral atmosphere at the *E*-layer heights is mostly ionized by two UV lines in the solar spectrum with λ = 97.7 nm (CIII) and λ = 102.57 nm (*HLyβ*). Some contribution (around 20% with non-flare Sun) provides *X*-ray radiation with λ = 0.1-10.0 nm. Two mentioned UV lines can ionize only molecular oxygen and absorption by molecular nitrogen is relatively small. Ion composition is mostly presented by two molecular ions O_2^+ and NO^+, produced from primary O^+, O_2^+ and N_2^+ ions through the chain of chemical reactions. This simplifies the qualitative analysis of the model calculations.

Although such a simple approach helps us to understand many features of the *E*-layer (Ivanov-Kholodny and Nusinov, 1979), here we are using a two-component model of solar EUV from Nusinov (1992) to calculate the photo-ionization rates in 48 wavelength intervals with $\lambda \leq 105$ nm. The photo-ionization and photo-absorption cross-sections are obtained mostly from Torr *et al.* (1979) with allowance for secondary ionization for λ < 25 nm in accordance with Ivanov-Kholodny and Nikoljsky (1969). Our model takes into account photo-chemical processes for $O^+(^2D)$, $O^+(^2P)$, $O_2^+(X^2\Pi)$, N^+, N_2^+ and NO^+ ions. The list of chemical reactions given in table II is mostly the same as we used in Förster *et al.* (1995).

Neutral composition (O, O_2, N_2, N) and temperature T_n are used from MSIS-86 thermospheric model (Hedin, 1987). Nitric oxide, NO is very important for *E*-region chemistry. It was found by fitting the calculated NO^+/N_e and O_2^+/N_e ratios to the model values given by the Danilov and Smirnova model (1995), which is based on rocket measurements. This model is supposed to be used in a new version of IRI.

Calculated and observed f_0E and *hmE* variations are given in fig. 2 for winter and in fig. 3 for summer conditions for one and the same solar zenith angle range. Empirical IRI-90 (Bilitza, 1990) model variations are given for a comparison. Observed f_0E and *hmE* variations are seen to be reproduced fairly well with our model calculations keeping in mind a pretty large scatter in the observed values. The IRI-90 f_0E variations practically coincide with the calculated f_0E. There is a small difference between pre-noon and post-noon f_0E and *hmE* values resulted from neutral atmosphere parameter daily variations, so both branches are given in the figures. Calculated *hmE* clearly show a pronounced increase with solar zenith angle in accordance with observations and Chapman's theory prediction.

4. Discussion

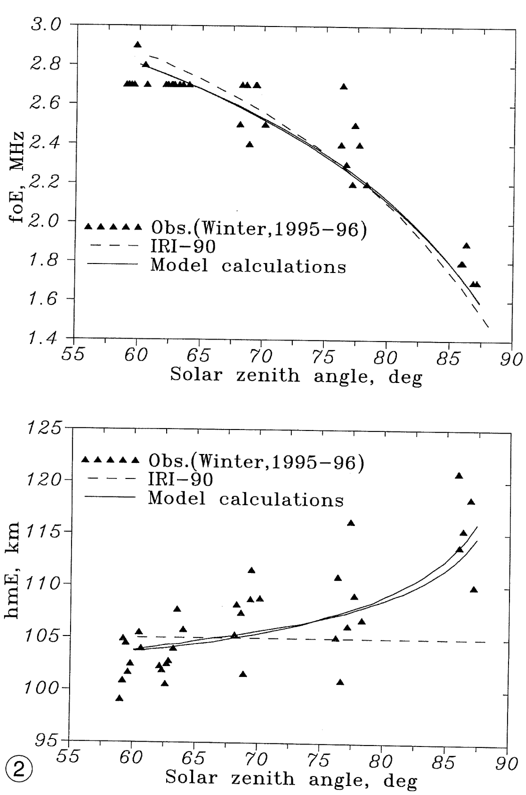
In accordance with observations (fig. 1) calculated winter *hmE* are a slightly higher than summer ones for one and the same solar zenith angles and this difference increases with solar zenith angle. This results from MSIS-86 [O_2] winter concentration being 40% larger than summer in the *E*-region (the 105 km height is considered). A similar 40% increase takes place for [N_2] as well, but N_2 only slightly absorbs two UV lines responsible for the *E*-layer formation. An even larger (73%) winter increase takes place for [O], but atomic oxygen does not absorb these UV lines at all. The enhanced absorption of UV radiation in winter results in a general elevation of the *E*-layer (hm_0 in expression (1.1)). On the other hand, this increase is partly compensated by lower winter neutral temperature (200 K compared to 218 K in summer) as lower T_n gives less neutral scale height *H* in expression (1.1). In accordance with Chapman's theory our model calculations provide the *hmE* increase with solar zenith angle, while the IRI-90 model gives a constant *hmE* = 105 km value throughout the day (figs. 2 and 3). A constant *hmE* = = 120 km is accepted in the DGR (Di Giovanni and Radicella, 1990) model which is circulating within the European COST 251 project.

Observed *hmE* are rather low compared to IS and SMI model values (table I). To reproduce such low *hmE* values a factor of two reduction of MSIS-86 [O_2] concentration was required. This is not a principle correction as the accuracy of [O_2] observations is not very high (Torr *et al.*, 1982; Krankowsky *et al.*, 1979).

Table II. Chemical reactions used in the model.

Reaction	Rate coefficient, cm^{-3} s^{-1}, or rate, s^{-1}
$O^+(^4S) + N_2 \rightarrow NO^+ + N$	$1.2 \times 10^{-12}(300/T_{eff})$ $T_{eff} < 740$ K $8.0 \times 10^{-14}(300/T_{eff})^{-2}$ $T_{eff} > 740$ K
$O^+(^4S) + O_2 \rightarrow O_2^+ + O$	$1.0 \times 10^{-9}/T_n^{0.7}$
$O^+(^4S) + NO \rightarrow NO^+ + O$	8.0×10^{-13}
$O^+(^2D) + O \rightarrow O^+(^4S) + O$	1.0×10^{-10}
$O^+(^2D) + N_2 \rightarrow N_2^+ + O$	1.0×10^{-9}
$O^+(^2D) + O_2 \rightarrow O_2^+(a^4\Pi) + O$	8.0×10^{-10}
$O^+(^2D) + e \rightarrow O^+(^4S) + e$	$6.6 \times 10^{-8}(300/T_e)^{0.5}$
$O^+(^2P) + O \rightarrow O^+(^4S) + O$	1.8×10^{-10}
$O^+(^2P) + N_2 \rightarrow N_2^+ + O$	5.0×10^{-11}
$O^+(^2P) + N_2 \rightarrow O^+(^4S) + N_2$	4.0×10^{-10}
$O^+(^2P) + e \rightarrow O^+(^2D) + e$	$1.5 \times 10^{-7}(300/T_e)^{0.5}$
$O^+(^2P) + e \rightarrow O^+(^4S) + e$	$3.2 \times 10^{-8}(300/T_e)^{0.5}$
$O^+(^2P) \rightarrow O^+(^2D) + h\nu$	$A = 0.173\ s^{-1}$
$O^+(^2P) \rightarrow O^+(^4S) + h\nu$	$A = 0.048\ s^{-1}$
$O_2^+(X^2\Pi) + N \rightarrow NO^+ + O$	1.8×10^{-10}
$O_2^+(X^2\Pi) + N \rightarrow N^+ + O_2$	4.0×10^{-10}
$O_2^+(X^2\Pi) + N_2 \rightarrow NO^+ + NO$	1.0×10^{-15}
$O_2^+(X^2\Pi) + NO \rightarrow NO^+ + O_2$	4.4×10^{-10}
$O_2^+(X^2\Pi) + e \rightarrow O + O$	$1.95 \times 10^{-7}(300/T_e)^{0.7}$
$N_2^+ + O \rightarrow O^+(^4S) + N_2$	$1.0 \times 10^{-11}(300/T_n)^{0.23}$
$N_2^+ + O \rightarrow NO^+ + N$	$1.4 \times 10^{-10}(300/T_n)^{0.44}$ $(\times 1.3)$
$N_2^+ + O_2 \rightarrow O_2^+ + N_2$	$5.0 \times 10^{-11}(300/T_n)$
$N_2^+ + NO \rightarrow NO^+ + N_2$	4.8×10^{-10}
$N_2^+ + N \rightarrow N^+ + N_2$	1.0×10^{-11}
$N_2^+ + e \rightarrow N + N$	$3.5 \times 10^{-7}(300/T_e)^{0.5}$
$N^+ + O_2 \rightarrow O^+(^4S) + NO$	3.6×10^{-11}
$N^+ + O_2 \rightarrow NO^+ + O$	2.6×10^{-10}
$N^+ + NO \rightarrow NO^+ + N$	2.0×10^{-11}
$N^+ + O_2 \rightarrow O_2^+ + N$	3.1×10^{-10}
$N^+ + O \rightarrow O^+(^4S) + N$	2.2×10^{-12}
$NO^+ + e \rightarrow N + O$	$4.5 \times 10^{-7}(300/T_e)^{0.83}$

$T_{eff} = (m_i T_n + m_n T_i)/(m_n + m_i)$; T_n, T_e, T_i -neutral, electron and ion temperatures.



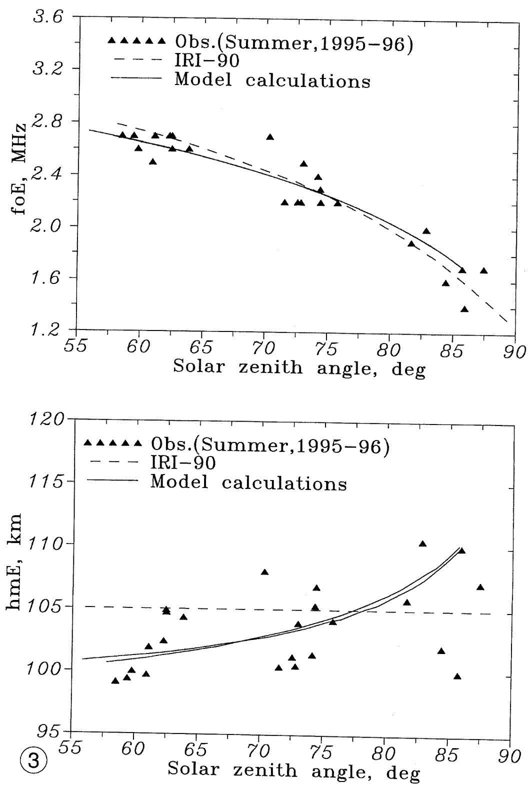


Fig. 2. Observed and calculated f_0E and hmE variations for winter months of 1995-1996. Model IRI-90 values are given for a comparison.

Fig. 3. Same as fig. 2 but for summer months.

A much more serious problem is with the calculated NmE. Using conventional O_2^+ and NO^+ dissociative recombination rate constants (table II) and EUV solar radiation from the Nusinov model (1992), the calculated NmE is 40% lower than observations – this is a well-known problem (see Introduction). Our model calculations (figs. 2 and 3) were carried out with increased by a factor of two the q/a_{eff} ratio, where q is the photo-ionization rate and a_{eff} is the effective dissociative recombination rate constant

$$\alpha_{eff} = \alpha^+_{NO}[NO^+]/n_e + \alpha^+_{O2}[O_2^+]/n_e. \qquad (4.1)$$

Doubling the fluxes of two UV lines with λ = 97.7 nm (CIII) and λ = 102.57 nm ($Hly\beta$) which provide the major contribution to the total ionization rate is unreasonable as the EUV solar radiation is known with pretty good accuracy in the UV range of spectrum (Woods *et al.*, 1998). The idea of Titheridge (1996, 1997) to increase X-ray emission in the 5-10 nm range distorts the proportion between UV and X-ray contributions to the total photo-ionization rate in favor of X-ray (more than 60%) while normally the X-ray contribution is less than 20% (Ivanov-Kholodny *et al.*, 1976; Ivanov-Kholodny and Nusinov, 1979).

The other possibility is to decrease α_{eff}. If not to consider a hypothesis with vibrationally excited O_2^+ and NO^+ (Antonova *et al.*, 1996), the only way to decrease α^+_{NO} and α^+_{O2} is to accept that $T_e > T_n$ in the *E*-region. Daytime electron temperature around 700 K would be sufficient to solve the problem. This is by a factor of 3.5 larger than neutral temperature which is around 200 K in the *E*-region. According to probe measurements in the 100-170 km height range a sharp peak with T_e/T_n = 3-5 is observed around 110 km (Duhau and Azpiazu, 1985). The Physical mechanism of such heating is not proposed yet, but a possibility that this effect results from the method of probe measurements cannot be excluded either. It should be mentioned that no difference between T_e and T_i which coincides with T_n in the *E* region, is observed by the incoherent scatter method. Nevertheless, a possibility of enhanced T_e over T_n seems very promising in solving the problem of low q/a_{eff} in the daytime *E*-region.

Nitric oxide is a very important species for the *E*-region physics. It controls the NO^+/O_2^+ ratio. As NO^+ and O_2^+ have different dissociative recombination rate constants (see table II), a predominate ion will determine electron concentration in the *E*-region. Varying the [NO] height distribution, we obtain an agreement of calculated ion composition with the empirical model by Danilov and Smirnova (1995). Figure 4 gives calculated and model NO^+ and O_2^+ concentrations in the 95-120 km height range for conditions in question with

$F_{10.7}$ = 74 and solar zenith angle χ = 60°. Figure 4 shows that observed ion composition may be perfectly reproduced in model calculations by varying nitric oxide distribution. Our model describes even such small features as the crossing of NO^+ and O_2^+ curves around the 100 km height.

The calculated [NO] summer and winter height profiles are given in fig. 4 (bottom). Strong seasonal variation with summer [NO] higher that winter by a factor of 3-4 takes place at the *hmE* heights. Similar seasonal variations of [NO] at 110 km during solar minimum where observed by Solar Mesospheric Explorer satellite (Fesen *et al.*, 1990). Such seasonal changes in [NO] are supposed to result from seasonal var-

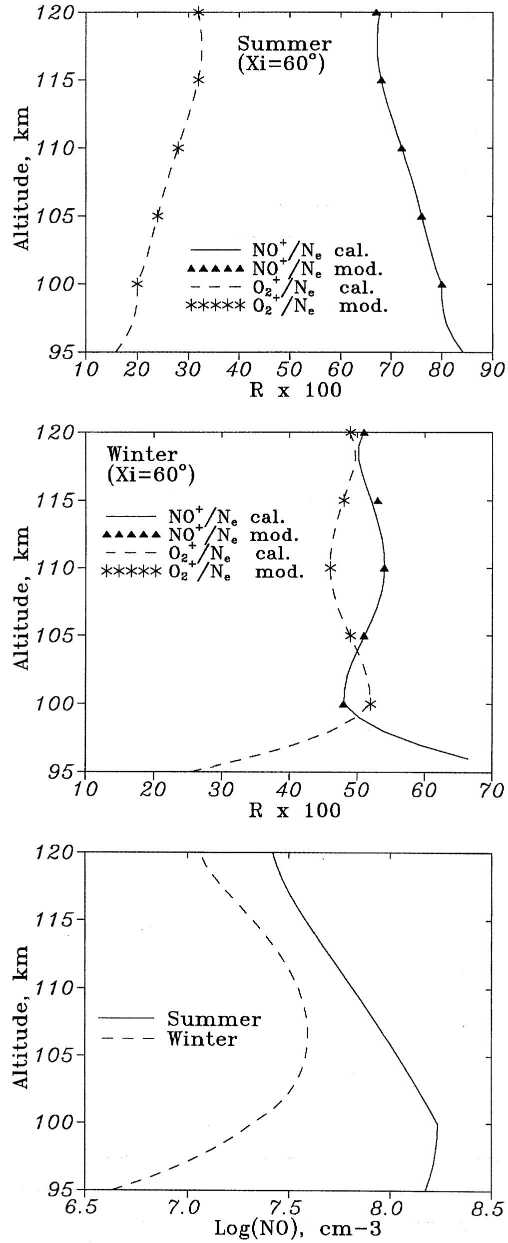


Fig. 4. Model (Danilov and Smirnova, 1995) and calculated relative NO^+/N_e and O_2^+/N_e daytime (χ = 60°) concentrations for summer and winter conditions in question. Corresponding nitric oxide profiles are shown at the bottom. Concentration of NO below 100 km is the result of an extrapolation.

iation of eddy diffusion which is stronger in winter (Ebel, 1980; Danilov, 1984). More intensive eddy diffusion removes [NO] downward from the *E*-region.

5. Summary

The main results of our analysis are the following:

1) El Arenosillo digisonde observations during solar minimum (1995-1996) show seasonal variations of daytime *hmE* values with winter *hmE* being higher than summer ones. Seasonal difference increases with solar zenith angle. These variations are not present in such empirical models as IRI or DGR.

2) Model calculations based on conventional EUV fluxes, neutral composition and chemical reaction rate constants enable us to reproduce the observed *hmE* seasonal variations. On the other hand the calculations underestimate the observed daytime f_0E. An increase in electron temperature with respect to neutral by a factor of 3.5 seems to be a plausible way to solve the problem of low calculated daytime f_0F_2.

3) Seasonal variations of NO^+ and O_2^+ corresponding to rocket observations may be reproduced in model calculations using a proper [NO] height distribution. The calculated summer [NO] are higher than winter ones by a factor of 3-4 at the *hmE* heights, the differences being even larger below *hmE*. Seasonal variations of [NO] may be related to seasonal changes of eddy diffusion at the *E*-layer heights.

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