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Behavior of the equivalent slab thickness over three European stations

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Abstract

The total electron content (TEC) derived from the global positioning system (GPS) and the F2-layer peak electron density obtained from Digisonde data have been used to study the diurnal, seasonal and solar activity variations of the ionospheric equivalent slab thickness (τ) over three European stations located at Pruhonice (50.0°N, 15.0°E), Ebro (40.8°N, 0.5°E) and El Arenosillo (37.1°N, 353.3°E). The diurnal variation of the τ is characterized by daytime values lower than nighttime ones for all seasons at low solar activity while daytime values larger than nighttime characterizes the diurnal variation for summer at high solar activity. A double peak is noticeable at dusk and at dawn, better expressed for winter at low solar activity. The seasonal variations of τ depend on local time and solar activity, the daytime values of τ increases from winter to summer whereas nighttime values of τ show the opposite. The effect of the solar activity on τ depends on local time and season, there being very sensitive for winter nighttime values of τ. The results of this study are compared with those presented by other authors.

Keywords: Ionospheric slab thickness; F2-layer peak; TEC; European stations

1. Introduction

It is well known that the total electron content (TEC) is a key parameter that describes the major impact of the ionized atmosphere on the propagation of radio waves, which is crucial for terrestrial and Earth-space communications including global navigation satellite systems (GNSS). A standard technique to determine TEC is the ground measurements of dual frequency from the constellation of the global positioning system (GPS). The technique measures the electron content along a slant signal path, from which a vertical TEC can be estimated by geometric corrections (e.g. Brunini et al., 2008). Another important parameter that characterizes the ionosphere is the maximum electron density of the F2-region (NmF2) which is proportional to the square of the F2-layer critical frequency (foF2). NmF2 combined with the TEC is used to estimate the equivalent ionospheric slab thickness, τ. τ represents the thickness of the current ionosphere having a uniform density equal to NmF2 peak, i.e., τ is defined as the ratio of the TEC to the NmF2

The τ is greatly influenced by the shape of the ionospheric electron density profile Ne (h). Thus, τ is a convenient parameter representing the electron density profile and it is related to the different physical processes in the ionosphere. Wright (1960) and further Furman and Prasad (1973) showed that τ generally depends upon the scale

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height of the ionosphere. Also Titheridge (1973) has found a relationship between τ and neutral temperature and, for a given electron density profile, it can be related directly to the plasma scale height.

As the orbit altitude of GPS satellites is ~20,000 km, TEC estimated from the GPS corresponds to the total electron content of the ionosphere (bottomside and topside) and plasmasphere. Since the τ is the radio of TEC to NmF2, its variability is quiet complex subject to the combined effect of the variability of both parameters simultaneously, this variability being tied to ionospheric and plasmapheric processes. In the past, a number of studies have been carried out to evaluate the variation of this parameter under different conditions such as seasonal, latitude and solar activity variation (e.g. Bhonsle et al., 1965; Kersley and Hajeb Hosseinieh, 1976; McNamara and Smith, 1982; Huang, 1983; Bhuyan et al., 1986; Davies and Liu, 1991; Minakoshi and Nishimuta, 1994; Gulyaeva, 1997). In addition τ variability was studied with several independent data, such as TEC from satellite, foF2 from the ionosondes (e.g. Belehaki et al., 2003; Jayachandran et al., 2004; Mansilla et al., 2005; Jin et al., 2007) or even with incoherent scatter radar data (Pandey et al., 2001). As each observation technique has its own feature and due to the complex variability of τ, various observations at different conditions are needed to achieve a good understanding of the phenomenon.

In this paper, we contribute to the τ behavior at mid and mid/high-latitudes, during solar maximum and minimum phases, and using GPS and ionosonde independent data. We also compared the results of the study with those presented by other authors. In the following sections, the method, data used and results are addressed. Discussions as well as the conclusion are given in the final section.

2. Method and data used

The diurnal, seasonal and solar activity variations of the equivalent slab thickness (τ) are studied using total electron content (TEC) and F2-layer peak electron density (foF2), data collected simultaneously over two mid-latitude stations, El Arenosillo (37.1°N, 353.3°E) and Ebro (40.8°N, 0.49°E), and over the mid/high-latitude station of Pruhonice (50.0°N, 15.0°E).

Vertical TEC values were estimated using dual-frequency carrier-phase GPS observations using LPIM (La Plata ionospheric model). LPIM estimation is based on the fact that the range-delay that the ionosphere produces in the GPS measurements is proportional to the slant TEC along the satellite–receiver line-of-sight and inversely proportional to the square of the signal frequency. Therefore subtracting simultaneous observations at different frequencies leads to an observable in which all frequency independent effects disappear and only the ionospheric effect and some electronic frequency dependent biases remain. Using a thin-shell atmospheric approximation and a simple mapping function vertical TEC are obtained. Details of the model can bee found in Brunini et al. (2008).

The maximum electron density of the F-region NmF2 is computed using the relation:

$$\mathrm{NmF2} = 1.24 \times 10^{10} \times (\mathrm{foF2})^2 \tag{1}$$

where NmF2 is in m^{-3} and foF2 is in MHz.

Once the TEC and maximum electron density NmF2 are extracted from GPS and Digisonde measurements respectively, the τ in km, is computed from the following relation for each hour:

$$\tau = \mathrm{TEC}/\mathrm{NmF2}. \tag{2}$$

The τ is then obtained as a function of the local time at intervals of 1 h for each day separately. The diurnal medians for January, April/October and July have been considered to represent the winter, equinox and summer seasons, respectively, during the solar maximum (2001) and minimum (2007) years.

It is noted that some days with no or poor observations (TEC or foF2) are not used. Also, to improve the input data set at each time interval, we applied a filtering method around the TEC median (foF2 median) to disregard outliers observation: those TEC values (foF2 median) lower than Q1 – 1.5 * IQR or higher than Q3 + 1.5 * IQR are not used, where Q1, Q3 are the lower and upper quartile, the median is represented by Q2 and IQR is the inter-quartile range of the sample (Q3-Q1). At the end of the filtering process each time interval contains at least 20 daily observations.

In addition, to analyze the diurnal variation of the τ, the daytime from 08:00 to 16:00 LT and the night-time from 20:00 to 04:00 LT are considered. Then, the magnitude of the diurnal variation of slab thickness is computed by using the diurnal ratio, which is defined as the ratio of maximum to the minimum, as well as by the night-to-day ratio, defined as the radio of the night-time to the daytime averages.

3. Results

Fig. 1 shows the median diurnal variation of τ for three seasons (winter, equinox and summer) during the solar maximum occurred in 2001 and the solar minimum in 2007, for the mid- and mid/high-latitude stations under investigation. A considerable oscillating hourly variability is observed. The average diurnal variation of τ shows that the values of τ vary from 200 to 610 km in 2001 (high solar activity) and they change between 160 and 730 km in 2007 (low solar activity). The diurnal variation of τ is generally characterized by larger values at nighttime than at daytime, except for summer. Also noticeable are the peak values at dusk and at dawn, being sharper in winter and subtle in summer. In addition subsidiary pre- and post-noon peaks and pre- and post-midnight peaks are observed. Furthermore as the solar activity increases the curves become smoother.

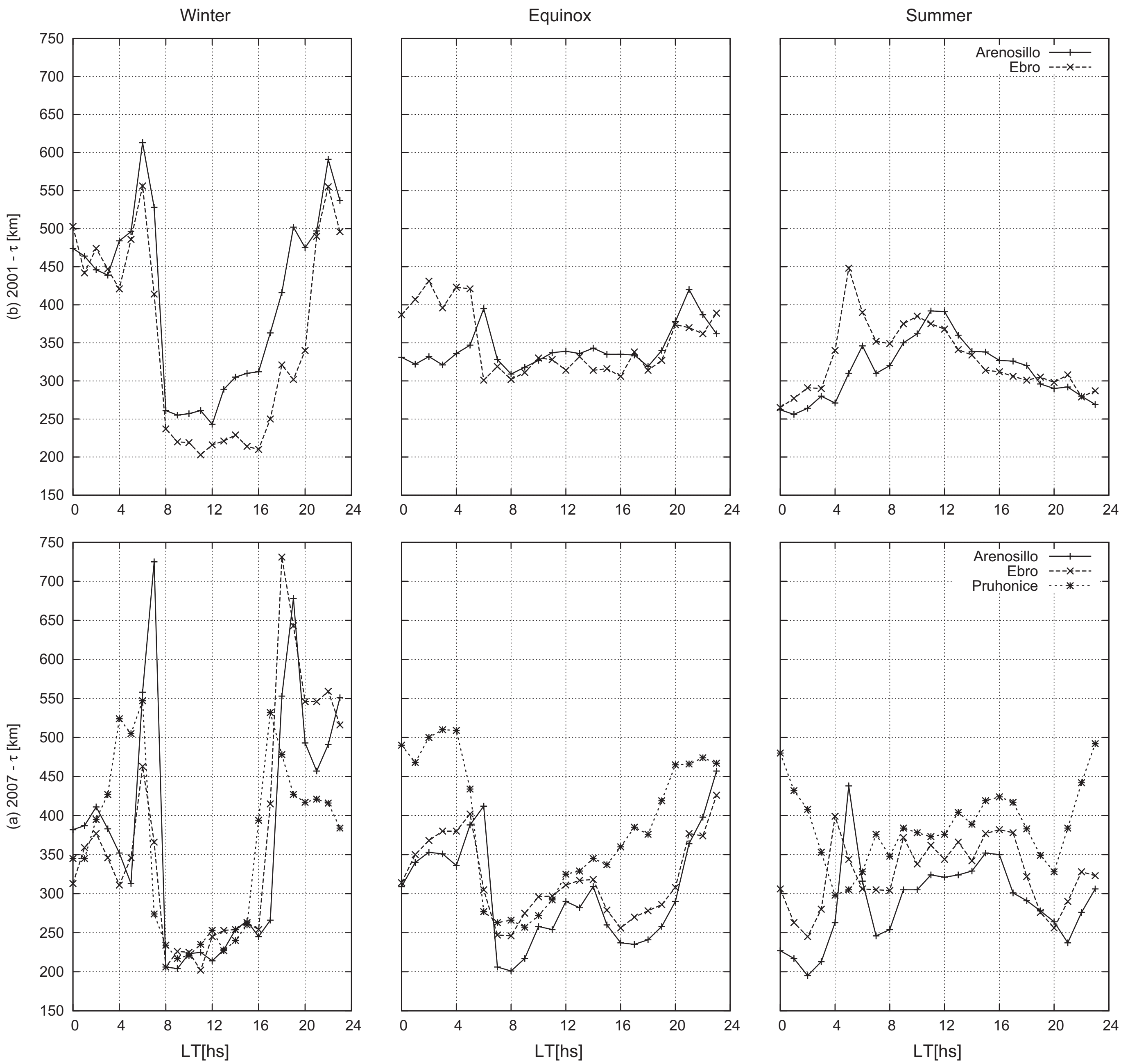

Fig. 1. Median diurnal variation of τ for three seasons (winter, equinox and summer): (a) during the solar minimum in 2007 at Arenosillo, Ebro and Pruhonice and (b) during the solar maximum occurred in 2001 at Arenosillo and Ebro stations.

Fig. 2 shows the seasonal variation of the median daytime (08–16 LT) and night-time (20–04 LT) values of τ for the solar maximum phase in 2001 and the solar minimum in 2007, as measured in the stations of Arenosillo, Ebro and Pruhonice. Both median daytime and median nighttime values of τ show a seasonal, latitude and solar activity variation. The seasonal variation is the most clear, showing that daytime τ increases from winter to summer with intermediate values for equinoxes whereas nighttime τ decreases from winter to summer. The measurements of the mid-high latitude station at Pruhonice behaves a bit different, showing larger nighttime values for equinoxes compared to the solstices. At solar minimum for mid-and mid/high-latitudes, the median night-time values are higher than the median daytime values for the three seasons, except during summer at mid-latitudes where the opposite occurs. There is some trend to observe larger values of the τ for higher latitude stations compared to the lower latitude measurements. In a more detail, the mid/high-latitude τ values for both daytime and night-time are higher compared to corresponding mid-latitudes values for the three seasons. During the solar maximum for mid-latitudes, the median night-time values are again higher than the median daytime values except during the summer. In addition, the

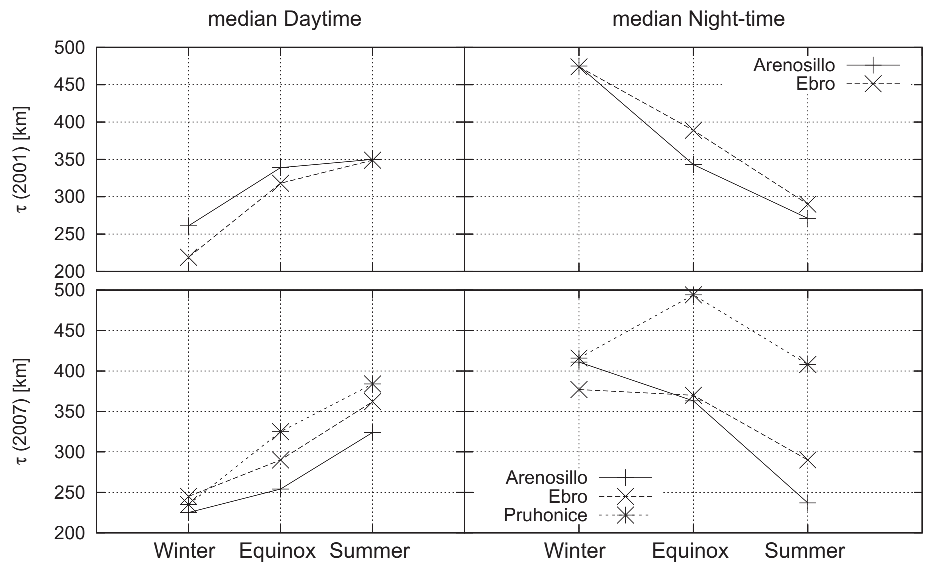

Fig. 2. Median daytime (08–16 LT) and night-time (20–04 LT) values of ionospheric slab thickness during the solar maximum phase in 2001 and the solar minimum in 2007, for the stations of Arenosillo, Ebro and Pruhonice respectively. For a better visualization points are joined with lines at each station.

median daytime value of τ shows higher values during summer and equinox as compared to the winter, whereas the night-time median τ are highest in winter and lowest in summer with intermediate values at the equinox. The relationship of the variations of the τ with the solar activity depends on local time and season. There is a clear direct dependence of the τ during winter and equinoxes for both day- and nighttime, with τ measurements increasing as solar activity increases. The later is more evident for winter conditions. However, the solar activity dependence of the τ measurements is rather marginal for summer conditions.

The magnitude of diurnal variation of τ is computed by the median diurnal maximum-to-minimum (diurnal ratio) and the median night-to-day ratios in Table 1. During the solar minimum and for the three latitudes the diurnal ratios are higher during winter and equinox as compared to the summer, with values around 2.7, 2.5 and 1.7 respectively. During the solar maximum at mid-latitudes, the diurnal ratios are also highest in winter and lowest in summer with intermediate values at the equinox, with values around 2.4 to 2.7, 1.7 to 2.0, and 1.5 respectively. For winter and equinox the ratios decrease with latitude, while in summer they are quite similar. Thus, at solar minimum the seasonal variations of the diurnal ratios are greater than the corresponding at solar maximum.

On the other hand, the median night-to-day ratios of τ, shows a similar pattern as described above. Except for mid-latitude and summer season (values below 1.0), night-time values are higher than daytime. During solar minimum and for the three latitudes, median night-time values increase with respect to those of daytime around 60% and 40% for winter and equinox respectively. On summer, for the mid/high-latitude station Pruhonice, similar median night-time and daytime values are observed, while for the mid-latitudes stations median daytimes values increase with respect to those at night-time around 25%. During solar maximum at mid-latitudes, median night-time values increase with respect to those at daytime around 90–110% and 20–40% for winter and equinox respectively, where values decrease with latitude. Finally, during summer, median daytime values increase around 20% in both stations, with respect of the median night-time values.

4. Discussion and conclusions

The whole phenomenon is mainly due to the electrodynamics of the F-region and of the plasmasphere. It is known that the shape factor is most sensitive to variations of H+/O+ ratio at the F2 peak or equivalent to the transition level at which [O+]=[H+] (Davies et al., 1976). The enhancement in the τ values could be primarily due to the field-aligned plasma flow from the protonosphere to the ionosphere where large downward fluxes of H+ can decrease the O+ to H+ transition levels, thereby increasing the topside electron content and therefore the slab thickness. Evans and Holt (1978) measured such fluxes during winter season. They also report that the field aligned plasma flow is from the protonosphere to the ionosphere particularly during the post midnight hours and the duration of this flow is found to be decreasing with the increase of solar activity; these circumstances agree with the observations reported by our results. Furthermore, the enhancement in the τ values could be likely due to the downward movement of the ionosphere when the neutral winds change (Titheridge, 1973). Therefore, the daily variation of the τ can be regarded as a superposition of a diurnal curve with maximum at noon that corresponds to the thermospheric variation and of a second diurnal curve with a double peak at dusk and at dawn that corresponds to the plasmaspheric variation (e.g. Belehaki et al, 2003) which

Table 1
Diurnal variation of τ for Arenosillo, Ebro and Pruhonice during the winter, equinox and summer season of the solar maximum and solar minimum occurred during the years 2001 and 2007 respectively: (a) by the median diurnal maximum-to-minimum ratio (b) by the median night-to-day radio.

Diurnal variation	2001			2007		
	W	E	S	W	E	S
Arenosillo (a)	2.43	1.69	1.53	2.69	2.53	1.80
N/D (b)	1.82	1.01	0.77	1.83	1.43	0.73
Ebro (a)	2.73	2.05	1.45	2.77	2.54	1.63
N/D (b)	2.17	1.23	0.83	1.54	1.27	0.80
Pruhonice (a)	–	–	–	2.75	2.50	1.65
N/D (b)	–	–	–	1.77	1.52	1.06

is most prominent in winter and it is due to the lowering of the transition height.

The τ behavior has been reported by several authors. Below we compare some previous results, describing differences and similarities with our work. Minakoshi and Nishimuta (1994) report that for a Japanese mid-latitude station, a large pre-sunrise peak in τ shows up during the solar minimum disappearing as the sunspot number increases; this peak starts to reappear during the solar maximum, particularly during the winter season. Our results are in a good agreement with our Japanese colleagues with the difference that pre-sunrise peak in τ does not disappear completely in presence of high solar activity. Our analyses show that it decreases considerably. On the other hand, Jayachandran et al. (2004) report that for Boulder mid/high-latitude, pre-sunrise and pre-midnight peaks appears during solar minimum as we also showed at Pruhonice. They also report that the mean night time τ values are higher compared to the mean daytime values, except during summer of Hawaii low- and Goosebay high-latitude, where the reverse seems to be true. For us the exception occurs during summer at Arenosillo and Ebro mid-latitudes stations. While the mean daytime values of τ, highest in summer and lowest in winter, are in good agreement with our results, the seasonal nighttime mean τ values shows small discrepancies which may be due to different geomagnetic conditions. In addition they report that at Boulder mid/high-latitude the mean τ values for both daytime and nighttime are higher compared to corresponding Hawaii low latitude and Goosebay high-latitude values. Likewise for us Pruhonice values are higher than Arenosillo and Ebro values. Finally, Shuanggen Jin et al (2007) results are quiet in agreement with our study although some differences appear. This is mainly due to the fact that their work is based on median solar activity, whereas our analyses are carried out during solar minima and maxima. This is another element supporting the dependence of τ values upon solar activity.

Moreover, one must be careful when generalizing results from the study of a particular station under certain conditions. Although it is commonly accepted that there is strong latitude dependence, this dependence is schematically divided into three main regions: low-, mid-, and high- latitudes. Our results show that τ values vary in a more complex manner with latitude. In our case, it is clear how Arenosillo and Ebro, two mid-latitude locations, show a similar pattern. However this pattern is slightly different from that of Pruhonice which is mid/high- latitude (mid-latitude according to Jayachandran et al. (2004) who use Boulder located at similar latitude) and clearly even more different from that of Goosebay which is high-latitude.

In conclusion, the most general results in the present study are the following:

- τ shows a seasonal, latitude and solar activity variation. Also a considerable oscillating hourly variability is observed.
- The seasonal variation of τ is generally characterized by pre-sunrise and post-sunset peaks and also subsidiary peaks at pre- and post-noon hours and at pre- and post-midnight hours.
- For mid-latitudes at Ebro and Arenosillo and for both solar minimum and solar maximum phases, the median night-time values are higher than the median daytime values for winter and equinox, during summer the opposite occurs. Thus, while the median daytime value of τ are highest in summer and lowest in winter, the reverse seems to be the case for the median nighttime values. In addition, at solar minimum the seasonal variations of the diurnal ratios are greater than the corresponding at solar maximum.
- For mid/high-latitud at Pruhonice and during solar minimum phase, the median night-time values are higher than the median daytime values for all season. The median daytime value of τ are highest in summer and lowest in winter, while the median nighttime are highest in equinox and registered similar lower values for the solstices. Pruhonice mid/high-latitude median τ values, for both daytime and night-time, are higher compared to corresponding Arenosillo and Ebro mid-latitudes values for the three seasons.

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