Planar Trend Analysis of the Midlatitude Ionosphere for Turkey and the Balkans

(Türkiye ve Balkanlar için Orta Enlem İyonküresinin Düzlemsel Yönseme Analizi)

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ABSTRACT

A locally planar Total Electron Content (TEC) trend model for the midlatitude region encompassing a major part of Turkey and some Balkan countries is investigated by estimating its coefficients in the least square sense for the solar minimum year 2009 and the solar maximum year 2014. The TEC values are obtained from Global Ionospheric Maps (GIM) which have a spatial resolution of 2.5° in latitude and 5° in longitude. The temporal resolution of the maps is two hours. The coefficients, as well as their 7-day and 27-day medians are investigated which in turn reveal the diurnal, seasonal and semiannual periodicities in the midlatitude ionosphere TEC trend. The estimated model coefficients are used to generate model maps and the difference between these and actual GIM are obtained in squared L_2 sense as a performance indicator. Despite the major distinctness in solar activity levels in both years, the differences for both 2009 and 2014 generally remain below 0.1% and the deviation of the model from actual GIM never exceeds 0.9% even on days with severe geomagnetic disturbances. The planar trend model provides a successful representation of TEC for the midlatitude region taken into consideration in both years. Periods with higher levels of solar activity result in estimated model coefficients with both increased values and spread.

***Keywords**: planar trend model, midlatitude ionosphere, coefficient estimation.*

ÖZ

Bu çalışmada, Türkiye'nin büyük bir kısmı ile bazı Balkan ülkelerini kapsayan bir orta enlem bölgesindeki Toplam Elektron İçeriği'ni (TEİ) temsil eden bölgesel düzlemsel bir yönseme modeli, güneş döngüsünün en az ve en çok güneş etkinliği olan yılları 2009 ve 2014 için irdelenmiştir. Model katsayıları, 2.5° enlem, 5° boylam ve 2 saat zaman çözünürlüğüne sahip Global Ionospheric Maps TEİ (GIM-TEC) verileri kullanılarak en küçük kareler yaklaşımı ile kestirilmiştir. Kestirilen model katsayıları ile bu katsayıların 7 günlük ve 27 günlük ortanca değerleri incelenerek, yönsemede günlük, mevsimsel ve 6 aylık dönemlerde tekrarlanan özellikler gözlenmiştir. Her iki yıl için kestirilen model katsayıları kullanılarak elde edilen model haritası ile gerçek GIM-TEC verileri arasındaki farkın L_2 normunun karesi bir başarım göstergesi olarak hesaplanmıştır. Güneş etkinliği seviyeleri arasındaki büyük farka rağmen, hem 2009 hem de 2014 için kestirilen düzlemsel modelin gerçek GIM-TEC değerlerinden sapma oranı genellikle %0.1'in altında kalmış, sapma oranı şiddetli jeomanyetik fırtınaların kaydedildiği günlerde dahi %0.9'un üzerine çıkmamıştır. Güneş etkinliğinin yüksek olduğu dönemlerde kestirilen model katsayılarının daha büyük değerler aldığı gözlenmiştir.

***Anahtar Kelimeler**: düzlemsel yönseme modeli, orta enlem iyonküresi, katsayı kestirimi.*

1. INTRODUCTION

The midlatitude ionosphere is constantly under the influence of polar and equatorial regions and is the subject of many works aiming to present its structure and determine a model. Most of these studies focus on indicators such as maximum ionization height (h_mF_2), the critical frequency of the F_2 layer (f_oF_2) and the Total Electron Content (TEC).

The complex nature of ionospheric variability and the dependency of the f_oF_2 trends on the geomagnetic latitude is extensively explained in Mikhailov and Marin (2001) and Rishbeth and Mendillo (2001). Variations of ionospheric parameters are observed in the diurnal and seasonal periods. It is also reported that a semiannual pattern is observed with peaks at equinoxes. Danilov (2015) demonstrated the dependence of f_oF_2 trends on local time and season and the dependence of f_oF_2 variability on latitude is shown by Fotiadis and Kouris (2006). Geomagnetic activity is claimed to be the major cause of this variability and the impact of space weather and geomagnetic disturbances on the F_2 layer directly affect the characteristics of TEC (Mikhailov and Marin, 2001, Laštovička, 2005). To take into account regional differences, it is proposed to examine the data on a more local basis, for example with respect to latitude. A review of the coupling between the lower and upper atmosphere for long temporal trends is presented in Laštovička (2017). The regional dependency of these long term trends is reported to be highly complex. The long term temporal trends of f_oF_2 and h_mF_2 are found to be linear in Cnossen and Franzke (2014). It is apparent that, monitoring the ionosphere to better understand the nature of this variability is an important subject and an ongoing effort.

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An effective way of observing the general trend behavior of ionospheric parameters is using TEC maps over a desired region. These TEC maps, called Global Ionospheric Maps (GIM), are provided by International Global Navigation Satellite Systems (GNSS) Service (IGS) analysis centers. GIM-TEC has a spatial resolution of 2.5° by 5° in latitude and longitude, respectively. The temporal resolution varies from a few minutes to several hours depending on the analysis center providing the data.

In Toker, Gokdag, Arikan and Arikan (2012) and Toker, Arikan and Arikan (2014), it is observed that several midlatitude ionospheric parameters generally follow a local planar trend which can be represented by a linear dependency on latitude and longitude. According to Turel and Arikan (2010), the probability density functions of TEC can be optimally categorized when regions of 10° in latitude are taken into consideration. Additionally, a region of size 10° by 20° in latitude and longitude, respectively, is found suitable to be represented by such a planar trend model in Deviren, Arikan and Arikan (2013).

Lean, Emmert, Picone and Meier (2011) focus on extracting a global and regional TEC trend structure by a regression model. The model parameters, which are obtained using daily mean GIM-TEC, strongly depend on the level of solar and geomagnetic activities and long term trends, thus pointing at a complex ionospheric trend structure. Laštovička, Urbar and Kozubek (2017) uses GIM-TEC from Jet Propulsion Laboratory (JPL) in the investigation of long term trends of TEC.

This study focusses on a locally planar TEC trend model representing the ionospheric structure of a northern hemisphere midlatitude region of dimensions 10° in latitude and 20° in longitude. The coefficients for the planar trend model are estimated in the least square (LS) sense using GIM-TEC for 2009 and 2014, the solar minimum and maximum years of the 24^{th} solar cycle. The estimated coefficients for 2009 and 2014 and their 7-day and 27-day medians are analyzed in a comparative fashion. The performance of the planar trend model is examined by means of a performance measure.

The paper is organized as follows: Section 2 covers the midlatitude region, the data for the years 2009 and 2014, the model and the estimation algorithm for its coefficients. The results are provided in Section 3 and Section 4 contains the concluding remarks.

2. DATA AND METHODOLOGY

Detailed information regarding the data and methodology used for the analyses in this study are provided in this section.

a. The Region

In this study, a region of dimensions 10° x 20° in latitude and longitude, respectively, is taken into consideration to test a locally planar trend structure of the ionosphere. This midlatitude region encompasses most of Turkey and some Balkan countries as shown in Figure 1a, where dotted and dashed lines indicate geographic and geomagnetic coordinates, respectively and the transparent blue shape marks the region of interest. This region is represented by a rectangle in Figure 1b and the geographic center and corner coordinates of the region of interest are also indicated. In order to remove the dependency of the trend model coefficients to the numeric values of the geographic coordinates, the region is assumed to have a normalized coordinate frame as shown in Figure 1c. The center coordinates are taken as (0,0) and the corner coordinates are shifted accordingly.

b. The Data

Toward calculating the linear trend coefficients, GIM-TEC from JPL are utilized. The data files are in IONEX format and are obtained from the IGS Ionosphere Working Group Analysis Center of JPL, NASA (CDDIS, n.d.). The spatial resolution of GIM-TEC is 2.5° x 5° in latitude and longitude, respectively. The temporal resolution is 2 hours. The center coordinates of the region shown in Figure 1 are chosen such that they coincide with a grid point in GIM-TEC. All grid points where GIM-TEC are specified in the selected region are also shown in Figure 1c.

The GIM-TEC for 2009 and 2014 are used to calculate the trend model coefficients for the selected midlatitude region. 2009 marks the solar minimum of the 24^{th} solar cycle which reached its maximum in 2014. The difference in the level of solar activities and TEC values between 2009 and 2014 can be observed through GIM-TEC data as shown in Figure 2 where GIM on four different days are plotted at 00:00, 06:00, 12:00 and 18:00 local time (LT) over the midlatitude region chosen for this study. Figures 2a-2d correspond to a geomagnetically quiet day of 2009 whereas Figures 2e-2h show TEC data on a day with a geomagnetic disturbance (IZMIRAN, n.d.) in the same year with recorded TEC values ranging

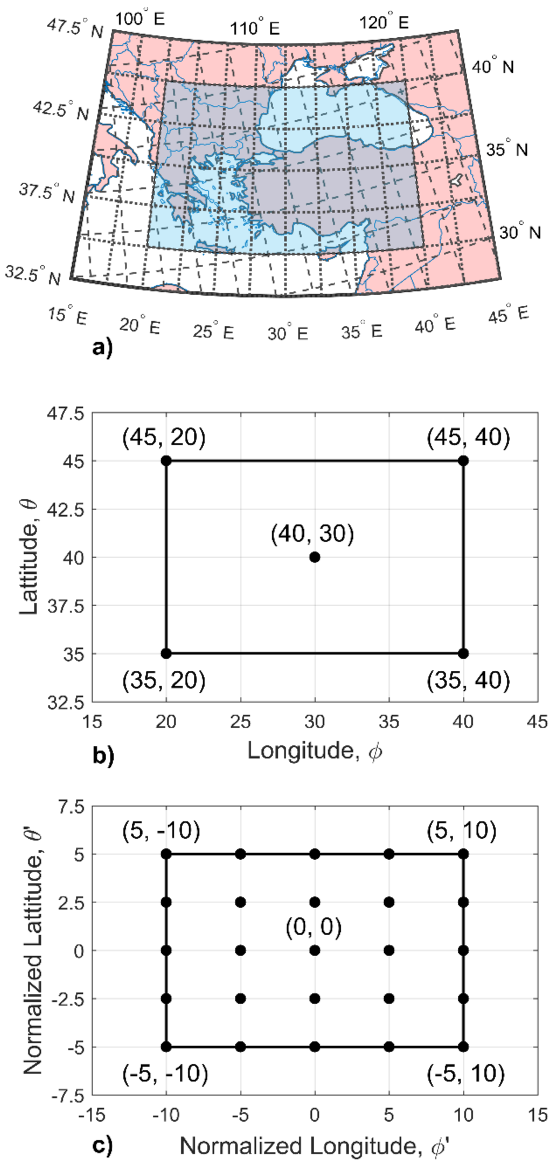

Figure 1. The midlatitude region and its geographic structure: a) Map of the region, b) Center and corner coordinates, c) Normalized coordinates and data points on the GIM grid.

between 7 and 18 TECU. Similarly, Figures 2i-2l and 2m-2p provide GIM for a quiet and a disturbed day of 2014 with maximum and minimum TEC values of 11.5 TECU and 75.10 TECU, respectively. The highest TEC value recorded on the day of 2009 with the geomagnetic disturbance is lower than the lowest TEC value obtained for the quiet day of 2014. The TEC values for the disturbed day, especially at noon where the effect of the Sun is at maximum, are significantly higher than the values corresponding to the remaining days and hours shown in Figure 2, indicating the difference in the behavior of the ionosphere on a period with high solar activity.

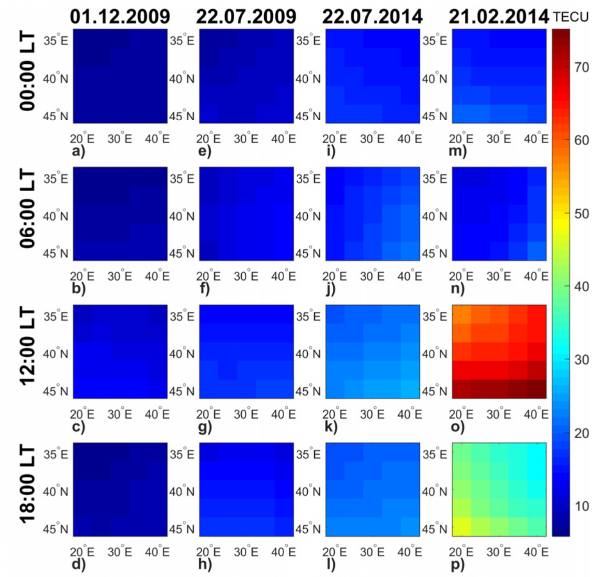

Figure 2. Four examples for GIM-TEC, a) to d): Quiet day, 2009; e) to h): Geomagnetic storm, 2009, i) to l): Quiet day, 2014; m) to p): Geomagnetic storm, 2014.

The daily Sunspot Numbers (SSN), Disturbance storm time index (Dst), planetary K-index (K_p) and Solar Radio Flux (F10.7) for 2009 and 2014 are plotted in Figure 3 in order to compare these two years in terms of proxies indicating solar activity (OMNIWeb, n.d.). According to Figure 3a, 2009 began with sunspot numbers less than 10 with a slight increase to 25 in June and July, and the highest values are observed between September and December (less than 50). There are significant periods of time with no sunspot numbers in 2009. The year of 2014, on the other hand, displays SSN values above 75 on the majority of the days with peak values around and above 200. The negative peaks of Dst values seen in Figure 3b are significantly lower for 2009 than for 2014 in both number of occurrences and in amplitude. There are 6 major TEC storms recorded for 2009 with durations ranging from 20 to 53 hours. In 2014, the number of major TEC storms is 17 with durations between 26 to 80 hours (IZMIRAN, n.d.). The negative peak around -80 nT for 2009 and -120 nT for 2014 correspond to the peak days of disturbances recorded on 22 July 2009 and 21 February 2014, respectively. The GIM for these days are shown in Figure 2. It can be noted that the number of negative peaks of Dst and their values for 2009 are significantly lower than those for 2014. In contrast to 2014, K_p values for 2009 generally remain under 3 in Figure 3c. Similarly, F10.7 values for 2009 provided in Figure 3d stay around 75 sfu while a severely oscillatory behavior

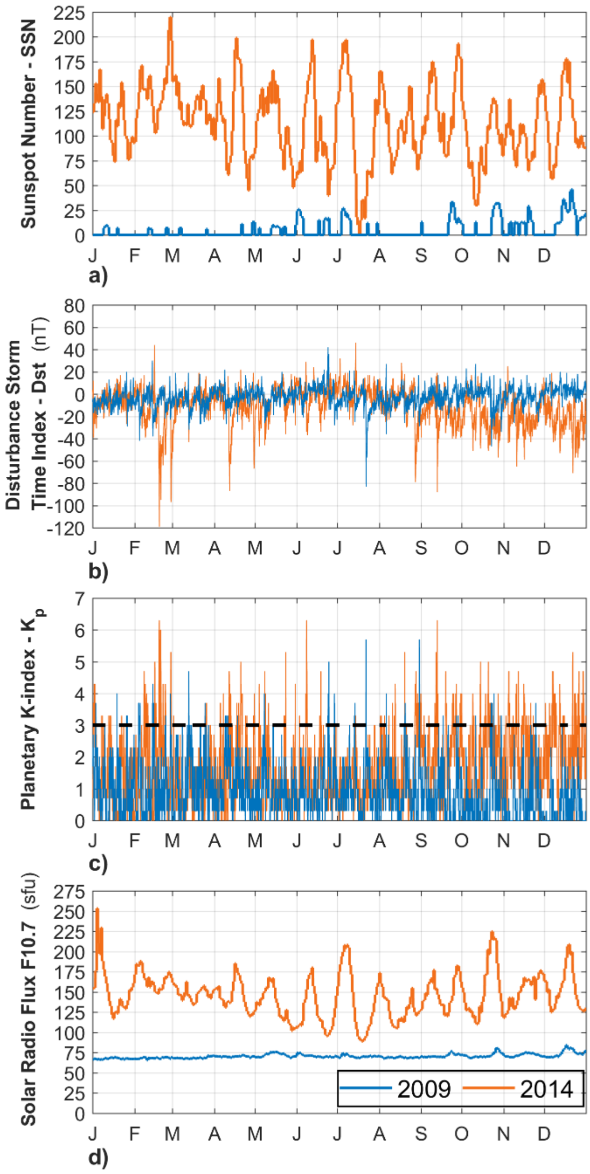

Figure 3. Solar geomagnetic indices for 2009 and 2014: a) SSN, b) Dst, c) K_p, d) F10.7.

is observed for 2014 with values generally ranging between 100 and 250 sfu.

c. The Planar Trend Model

A planar model describing the trend in TEC distribution for a midlatitude region at normalized coordinates (θ', ϕ') and time t is of the form

$$\mu\,(\theta', \phi'; t) = a_{\mu}(t) + a_{\theta}(t)\theta' + a_{\phi}(t)\phi' \qquad (1)$$

where $a_{\mu}(t)$, $a_{\theta}(t)$ and $a_{\phi}(t)$ are the model coefficients. $a_{\mu}(t)$ indicates the constant level of GIM-TEC and is in TECU. $a_{\theta}(t)$ and $a_{\phi}(t)$ are in TECU/° and represent the declination and inclination of the planar surface with respect to latitude and longitude, respectively. Defining the planar model matrix as

$$\mathbf{M} = \begin{bmatrix} 1 & \theta'_1 & \phi'_1 \\ \vdots & \vdots & \vdots \\ 1 & \theta'_{n_g} & \phi'_{n_g} \\ \vdots & \vdots & \vdots \\ 1 & \theta'_{N_g} & \phi'_{N_g} \end{bmatrix} \qquad (2)$$

with $N_g = 25$, which is the number of sample points shown in Figure 1c, the discrete planar model of the midlatitude ionosphere at time index n_t can be expressed as in Eq. (3).

$$\mathbf{M}\mathbf{a}(n_t) = \mathbf{g}(n_t) \qquad (3)$$

Here, $\mathbf{a}(n_t)$ denotes the discrete model coefficients in vector form. $\mathbf{g}(n_t)$ is the vector containing GIM-TEC values at all normalized grid coordinates (θ', ϕ') and time index n_t for the region depicted in Figure 1c.

$$\mathbf{a}(n_t) = [a_{\mu}(n_t) \quad a_{\theta}(n_t) \quad a_{\phi}(n_t)]^T \qquad (4)$$

$$\mathbf{g}(n_t) = \left[g(\theta'_1, \phi'_1; n_t) \quad \cdots \quad g(\theta'_{N_g}, \phi'_{N_g}; n_t)\right]^T \qquad (5)$$

The coefficients in Eq. 4 are estimated in the LS sense as:

$$\hat{\mathbf{a}}(n_t) = (\mathbf{M}^T\mathbf{M})^{-1}\mathbf{M}^T\mathbf{g}(n_t) \qquad (6)$$

Using the estimated coefficients, an estimate of the model provided in Eq. 1 can be calculated at normalized coordinates (θ', ϕ').

$$\hat{\mu}\,(\theta', \phi'; n_t) = \hat{a}_{\mu}(n_t) + \hat{a}_{\theta}(n_t)\theta' + \hat{a}_{\phi}(n_t)\phi' \qquad (7)$$

Considering all grid points in the region the discrete estimated map is given as follows:

$$\hat{\boldsymbol{\mu}}(n_t) = \left[\hat{\mu}(\theta'_1, \phi'_1; n_t) \quad \cdots \quad \hat{\mu}(\theta'_{N_g}, \phi'_{N_g}; n_t)\right]^T \qquad (8)$$

The measure given below is used to assess the performance of the model and represents the difference between the estimated map in Eq. 8 and GIM-TEC. $\|\cdot\|_2^2$ denotes the square of the Euclidean or L_2 norm.

$$e_{\hat{\mu}}(n_t) = \frac{\|\hat{\boldsymbol{\mu}}(n_t) - \mathbf{g}(n_t)\|_2^2}{\|\mathbf{g}(n_t)\|_2^2} \times 100 \qquad (9)$$

The results for the years 2009 and 2014 are presented in the following section.

3. RESULTS

The coefficients of the proposed planar trend model for the midlatitude region shown in Figure 1 are estimated in the LS sense using JPL GIM-TEC as described in the previous section. Since the temporal resolution of JPL-TEC is two hours, these coefficients, i.e. $\hat{a}_\mu$, $\hat{a}_\theta$ and $\hat{a}_\phi$, are obtained at every two hours on each day of the years 2009 and 2014. However, for simplicity, they are only shown at four different hours in local time (LT) with respect to the center coordinates, namely at 00:00 (midnight), 06:00 (sunrise), 12:00 (noon) and 18:00 (sunset), and are presented in Figure 4. As explained previously, $\hat{a}_\mu$ (first column) represents a constant average level. Positive and negative values of $\hat{a}_\theta$ (second column) indicate higher TEC values in the north (the plane is said to tilt toward south) and south (northern tilt) of the plane, respectively. Similarly, positive and negative values of $\hat{a}_\phi$ (third column) mean an increase in TEC toward east (western tilt) and west (eastern tilt) of the planar surface, respectively.

According to Figure 4a, the values of $\hat{a}_\mu$ are between 6 and 12 TECU for 2009. For 2014 the spread and the values are higher, between 10 and 29 TECU. The highest values are observed in May and October of 2009 and between April and August of 2014. While $\hat{a}_\theta$ values for 2009 remain mostly around zero indicating no north-south tilt of the planar surface, the estimates for 2014 indicate a significant northern tilt, except in winter months, despite the fact that the effect of the Sun is minimal at midnight. The tilt is more pronounced between March and July. No east-west tilt is observed for 2009 in Figure 4c, and the estimated planar surface for 2014 slightly tilts toward east during summer months.

There is a small increase in $\hat{a}_\mu$ values at 06:00 for both 2009 and 2014 according to Figure 4d. $\hat{a}_\theta$

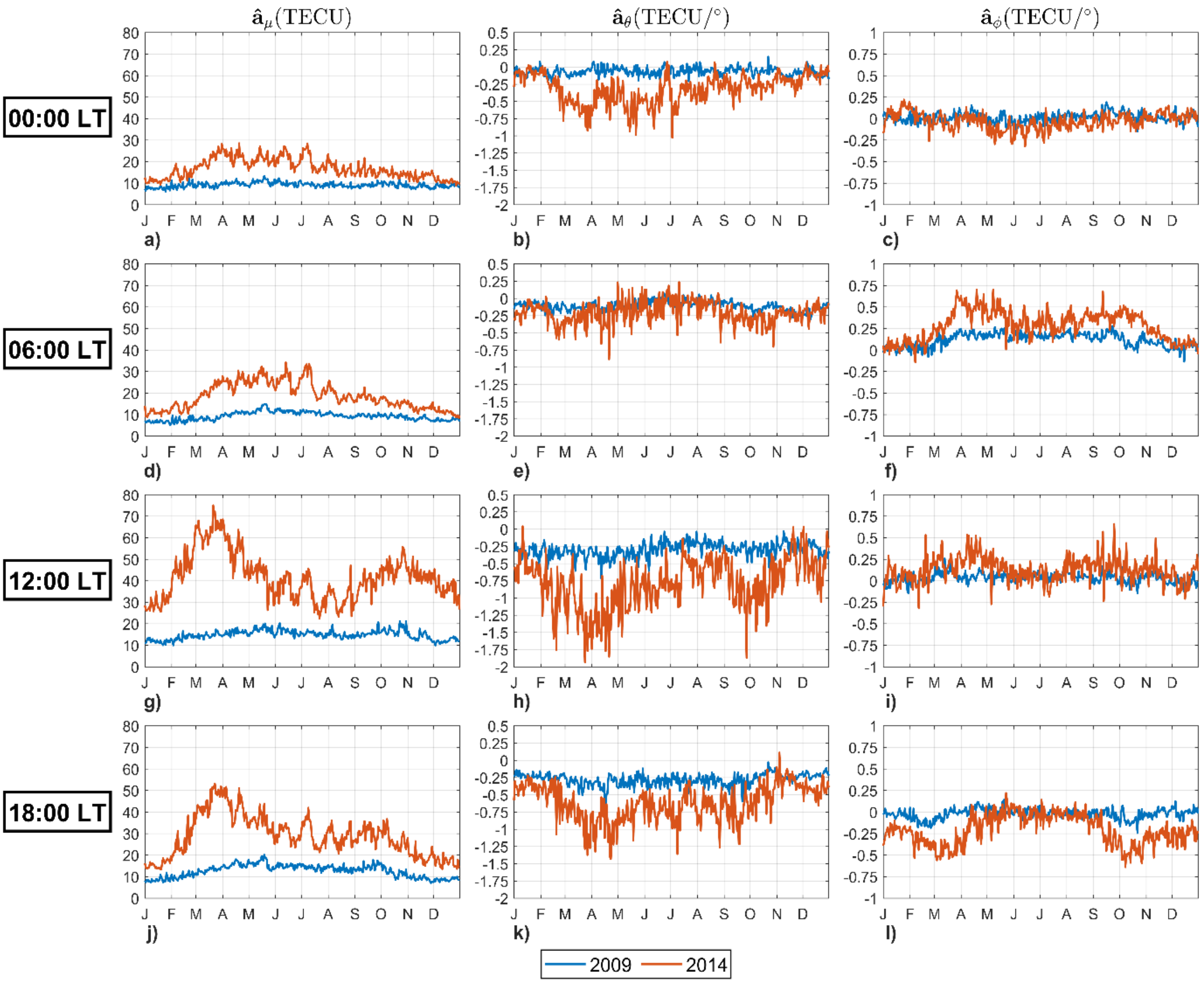

Figure 4. Estimated planar trend coefficients for the midlatitude region shown in Figure 1 using JPL GIM-TEC in 2009 and 2014.

in Figure 4e indicate that the estimated planar surfaces for both years tend to slightly tilt toward north during fall and spring equinoxes. The tilt is more apparent for 2014 and is minimum in summer months. Due to the Sun rising, positive $\hat{a}_{\phi}$ values are observed in Figure 4f for both years, as the TEC values start increasing toward east. This increase is more evident for 2014.

At noon, the effect of the Sun is at maximum, thus a significant increase in $\hat{a}_{\mu}$ can be observed in Figure 4g. While the average TEC value increases up to only 20 TECU for 2009, it peaks at 75 and 55 TECU during spring and fall equinoxes of 2014, respectively. A definite northern tilt for 2009 can be seen while the tilt for 2014 is very strong (Figure 4h). $\hat{a}_{\phi}$ values at noon indicate little to no east-west tilt for 2009 and a slight westerly tilt for 2009 in both equinoxes (Figure 4i).

For sunset hours shown in Figures 4j, 4k and 4l, the average TEC values for 2009 still remain generally between 10 and 20 TECU with peaks observed in May and September. For 2014, there is still a prominent increase in average TEC values between February and April. This level reduces slightly during the summer; another yet lower increase follows during the fall equinox. A northern tilt can be seen throughout the year for both 2009 and 2014, however the tilt is more distinctive in 2014, especially in equinoxes. The planar surface for 2009 tilts briefly toward east in February and October, and no east-west tilt is observed in the remainder of the year. In contrast, a prominent easterly tilt can be observed for 2014 even during winter months and the amount of tilt increases during both equinox periods. Similar to 2009, $\hat{a}_{\phi}$ values remain around zero during the summer.

The average TEC values ($\hat{a}_{\mu}$) tend to increase with increasing effect of the Sun. $\hat{a}_{\phi}$ for 2009 display peaked values in May and October, while for 2014 these peaks are observed in March and October. $\hat{a}_{\phi}$ values for 2014 are overall higher than those for 2009 since 2014 is a year with high solar activity, which is in agreement with the solar proxies previously shown in Figure 3. A similar result can be inferred for $\hat{a}_{\theta}$ and $\hat{a}_{\phi}$. The trends displayed in both 2009 and 2014 are similar, yet the effect of increased solar activity in 2014 manifests itself in coefficients with much larger values, thus indicating stronger north-south and east-west tilts.

A running 7-day median filter is applied to the estimated planar trend model coefficients for 2009 and 2014 and the results are shown in Figure 5. Each median is calculated over a sliding window of length 7 across neighboring elements of the coefficients estimated at midnight, sunrise, noon and sunset hours and presented in a similar fashion as in Figure 4. The 7-day median helps remove the effects of short-term deviations which are not normally a part of the trend and usually caused by magnetically disturbed conditions and allows to demonstrate the weekly dominant trend of TEC (Gulyaeva, Arikan and Stanislwska, 2014).

From Figure 5, the 27 days TEC oscillation due to solar rotation can easily be observed. This cycle of 27 days is particularly conspicuous in the $\hat{a}_{\mu}$ values for 2014, seen in the first column of Figure 5, as the amplitude and the spread of the data are higher than those for 2009. The amplitude of these oscillations appear to increase during summer months of 2014, especially in June and July. Oscillations in a comparable way stand out in the $\hat{a}_{\theta}$ and $\hat{a}_{\phi}$ values in the second and third columns of Figure 5, respectively, indicating the planar surface representing the ionosphere is tilted toward north and south, and east and west with the same periodicity throughout the year with varying degrees depending on the local time and thus the ionization due to the Sun.

Figure 6 shows the planar trend model coefficients passed through a running 27-day median filter, smoothing the effect of 27-day solar rotation (Gulyaeva, Stanislwska and Tomasik, 2008, Vita-Finzi 2009). The objective is to observe the dominant TEC trend of the midlatitude region of interest.

According to Figures 6a and 6d, when the effect of the Sun is low, that is at 00:00 and 06:00, an increase in $\hat{a}_{\mu}$ is noted between February and May. This level is kept roughly until July, at which point there is a decreasing trend of TEC during fall. At 12:00 and 18:00, on the other hand, the average TEC trend indicates two local maxima in both years. For 2009 these peak values occur in May and fall equinox, while for 2014 both peaks coincide with the spring and fall equinoxes. Figure 6b indicates that the planar surface displays a very small and almost constant level of northern tilt at midnight for 2009, yet there is a strong northern tilt in 2014 with sharply increasing values between February and March, continued until June. Starting from 06:00 until sunset (Figures 6f, 6i and 6l), the trend shows stronger northern tilts in equinoxes when compared to the remainder of the year in both years. $\hat{a}_{\phi}$ levels for 2009 at midnight (Figure 6c) remain almost constant around zero, whereas the planar surface representing the data

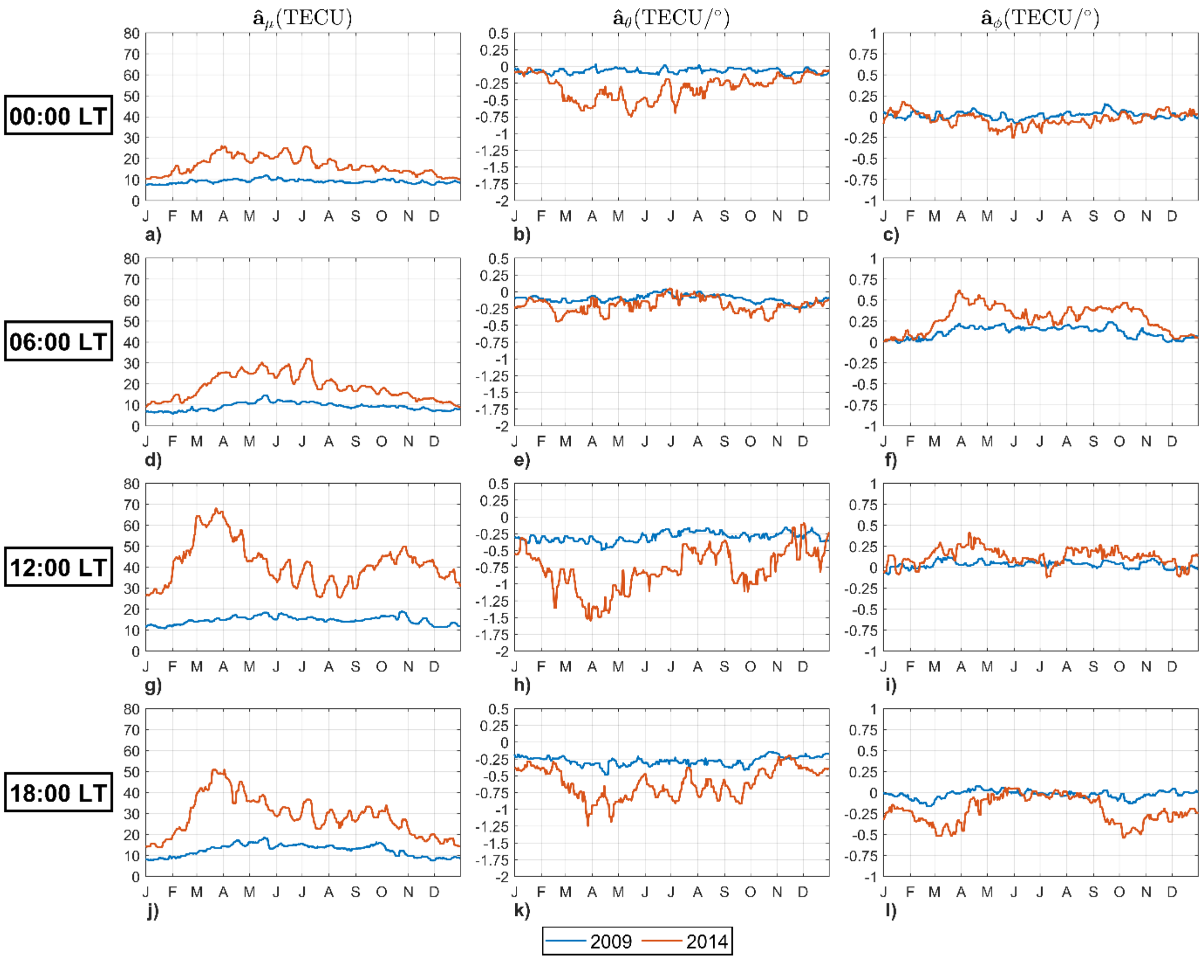

Figure 5. 7-day median values of the estimated planar trend coefficients shown in Figure 4.

for 2014 displays a slight eastern tilt between March and October, a weak western tilt in January and November and almost no tilt in December. At 06:00 (Figure 6f), the TEC values in both years are higher towards east, however, the plane for 2009 is tilted at a constant rate between April and September, but for 2014 this inclination towards west peaks during equinoxes. There is little to no east-west inclination in January and December in both years. At noon (Figure 6i), the $\hat{a}_\phi$ values for 2009 are around zero, meaning similar TEC values in the east-west direction. In 2014, on the other hand, a certain amount of westerly slant can be spotted in equinox seasons. As expected, the planar model indicates elevated TEC values towards west for both years at 18:00 in equinoxes, with larger coefficients in 2014. In summer months, the plane shows no east-west inclination as the effect of the Sun is still stronger in comparison.

Figure 7 provides the estimated planar trend model coefficients for the midlatitude region over Turkey and the Balkans, calculated at every two hours of every day of the years 2009 and 2014 using JPL GIM-TEC. The values obtained by applying a 7-day (solid black line) and 27-day (solid red for 2009 and solid blue for 2014) running median filter are also indicated on the same axes for each model coefficient. Upon comparing the $\hat{a}_\mu$ values for 2009 and 2014 given in Figures 7a and 7d, it is evident that, although the average TEC values are much higher in the solar maximum year of 2014 than in 2009, a semiannual trend is exhibited that manifests itself in two peak values in both years. The difference in the trends is that the maximum average TEC values in 2014 coincide with the spring equinox while it is recorded later in May for 2009. The second peak for both years has a lower value and they are both observed in the fall equinox. The 27-day oscillation of TEC can be noted in both years by examining the 7-day median values of the coefficients. The amplitude of oscillation is more prominent in May for 2009 and in summer months for 2014. The general trend of $\hat{a}_\theta$ values shown in Figures 7b and 7e indicate that these values for both years remain mostly negative, i.e. the TEC

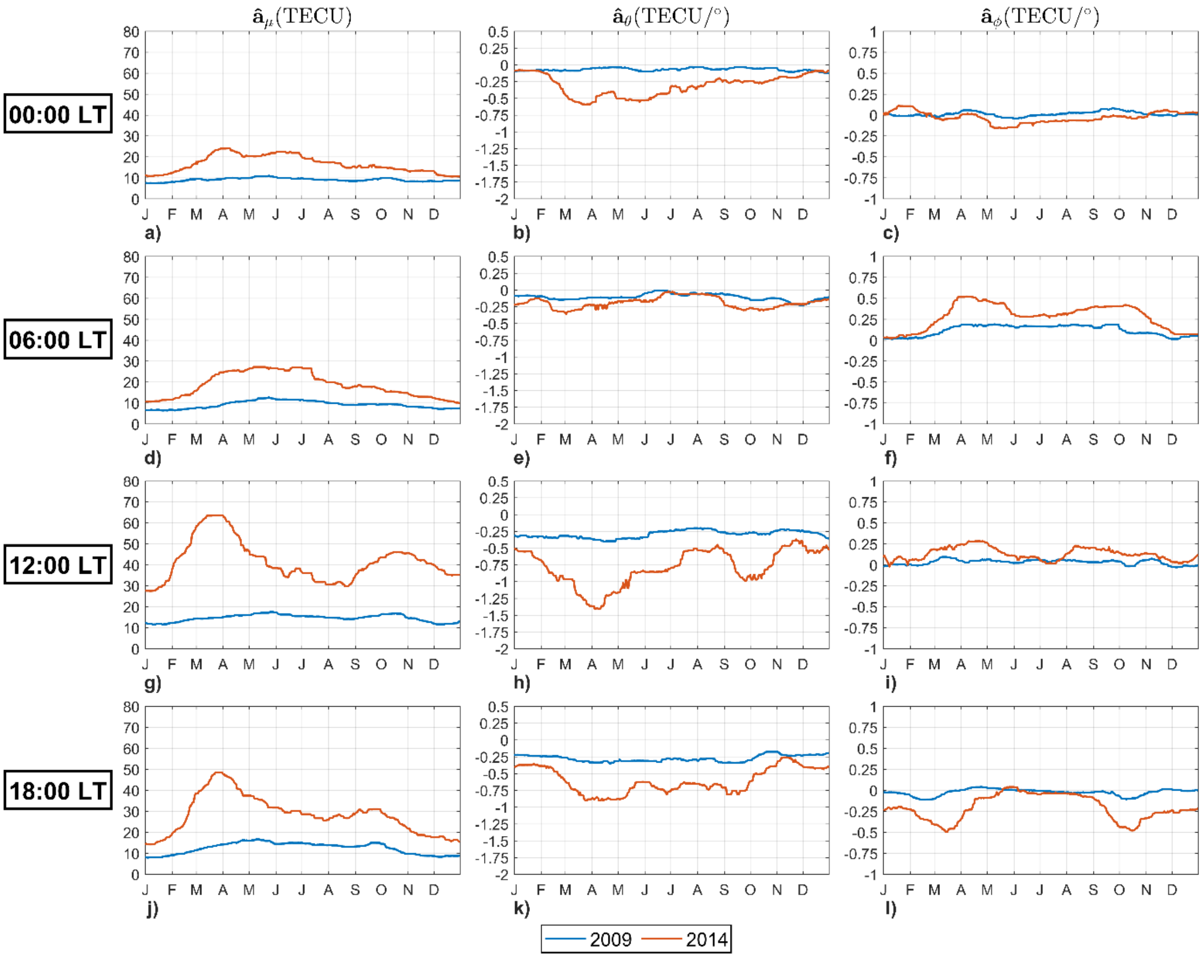

Figure 6. 27-day median values of the estimated planar trend coefficients shown in Figure 4.

values towards the south of the planar surface are higher than those towards north. This is an expected result for a midlatitude region in the northern hemisphere. The difference in the level of solar activity between both years causes generally a stronger inclination toward north in 2014. This inclination is particularly prominent in the spring equinox as seen in Figure 7e. $\hat{a}_\phi$ values estimated for 2009 and given in Figure 7c oscillate around zero with an amplitude of roughly 0.15 TECU/°. The weekly and monthly trends indicate the planar surface shows no east-west slant on the average during winter months and a slight inclination toward west between May and September. Similarly, the $\hat{a}_\phi$ values for 2014 (Figure 7f) also oscillate around zero due to the diurnal trend, yet the amplitude of oscillation becomes higher in equinox months indicating stronger east-west tilts at sunrise and sunset. Unlike in 2009, there is no significant inclination between May and September, however slight tilts towards west and towards east are noted in January and February, respectively.

In order to assess the performance of the planar trend model in representing the TEC in the midlatitude region chosen for this study, the performance measure given in Eq. 9 is calculated for 2009 and 2014 and presented in Figures 8a and 8b, respectively. For both years, the overall difference between the actual GIM-TEC values and those calculated using the estimated trend model coefficients remains below 0.1%, indicating a very good fit for the planar trend model in this region. The planar model represents the GIM-TEC data even better during summer months in both years with overall lower $e_{\hat{\mu}}$ levels. Several of the spikes in $e_{\hat{\mu}}$ values coincide with recorded geomagnetic storms listed in (IZMIRAN, n.d.). For instance, the spike close to 0.7% in February 2009 and the one close to 0.9% in October 2014 are both listed as strong geomagnetic storms. The deviation of the planar model from the actual GIM-TEC is slightly higher in equinox months resulting in several spikes in the $e_{\hat{\mu}}$ values, yet they rarely exceed 0.3%, overall indicating a very successful representation of the GIM-TEC data in both years.

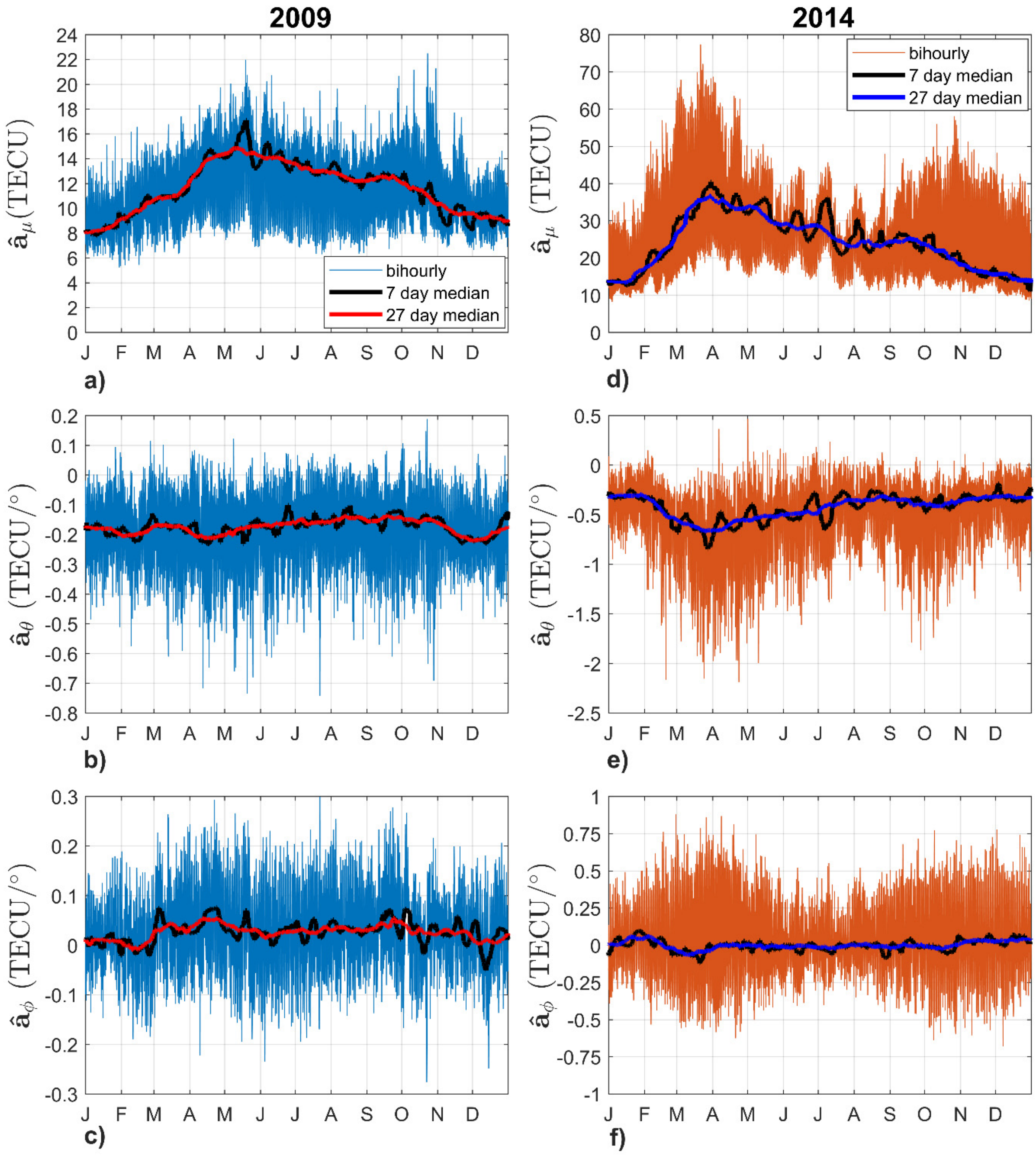

Figure 7. Planar trend model coefficients for the midlatitude region shown in Figure 1 estimated bihourly for one year: a) – c) Coefficients for 2009, d) – f) Coefficients for 2014.

4. CONCLUSIONS

In this study, the coefficients of a planar TEC trend model are estimated using JPL GIM-TEC The chosen area for this study is a 10° x 20° northern midlatitude region situated over Turkey and part of the Balkan countries. The estimation of the model coefficients is carried out in the LS sense. For the calculation of the model coefficients, the GIM-TEC data for the solar minimum and maximum years of the 24th solar cycle, namely 2009 and 2014, are considered. To better present the underlying trends, the weekly and monthly medians of the estimated coefficients are also analyzed. How well the planar model represents the TEC trend in the chosen region is assessed using a performance measure, in which the difference between the actual GIM-TEC values and those obtained using the estimated

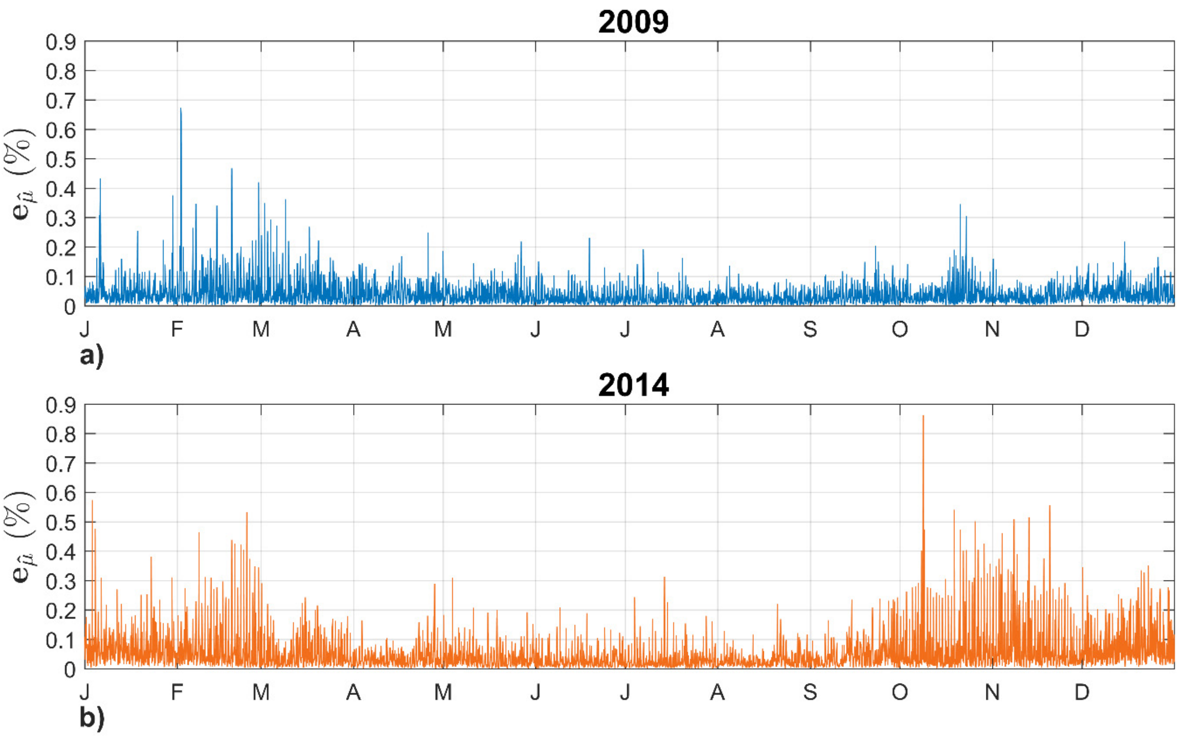

Figure 8. Percentage difference between GIM-TEC and estimated planar model: a) 2009, b) 2014.

model is calculated and presented in percentage for both years.

The planar trend model represents the chosen midlatitude region quite well in both 2009 and 2014. Although the levels of solar activity are very distinct between these two years, as apparent from the provided solar proxies, the differences between the TEC values calculated with the model and the actual GIM-TEC are substantially low, indicating a successful fit to the data for both years. In other words, the performance of the locally planar trend model for the midlatitude region does not depend on the level of solar activity; it provides a good estimation for the TEC trend under significantly different ionospheric conditions. The different TEC characteristics between 2009 and 2014 merely affect the numerical values and the spread of the estimated model coefficients. Both the average TEC values and coefficients representing the inclination in the north-south and east-west are in general higher for 2014 than those estimated for 2009. Yet in both extreme cases, the percentage difference between actual and estimated TEC mostly remains below 0.1% for both years, except during equinoxes and magnetically disturbed days. The performance measure for the planar trend model will be tested for different midlatitude regions and with different choices of region dimensions, and the results with be reported in future works.

The 7-day median eliminates the effects of the diurnal cycle and sudden deviations from the trends which are mostly caused by geomagnetic storms and reveal the 27-day oscillation in the TEC trend. This trend is especially visible in the coefficients for 2014 as their spread and values are higher when compared to 2009. The 27-day median, on the other hand, suppresses this oscillation and represents the dominant trend within the months of the years. Both in 2009 and 2014, seasonal and semiannual patterns are observed.

For 2009, the estimated average value of the trend model peaks around May and fall equinox, whereas both peaks in 2014 occur in the spring and fall equinoxes. Negative north-south inclination coefficients ($\hat{a}_\theta$) are estimated for both years as expected, since the chosen northern hemisphere region traces the maximum solar radiation along the equator. The highest tilts and spread occur at noon hours. Following the sunrise and sunset, the east-west tilt coefficient $\hat{a}_\phi$ oscillates around zero. For 2014, the values exceed ± 0.5 TECU/° during equinoxes and are lower during summer months. For 2009, the levels stay around ± 0.15 TECU/° throughout the year.

The temporal and spatial variability of the ionosphere is known to have significant effects on GNSS positioning. A more comprehensive and elaborate TEC trend model will result in a better understanding of the ionosphere and thus help provide desired ionospheric corrections for applications such as precise point positioning (PPP), real-time kinematic (RTK) and network RTK. To that end, coefficients for a variety of midlatitude regions over a series of years will be estimated in future studies. The validity of the locally planar trend model will be evaluated for a full solar cycle and with different median filter windows, providing further insight on the temporal trend of the ionosphere. The results will then be used in building and improving statistical models toward prediction of TEC.

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