

# Features of Behavior and Usage of a Total Electron Content in the Indian Region

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*Abstract- A total electron content TEC is the most important parameter of the ionosphere for operation of navigational and telecommunication system. There is an urgent necessity in development of the TEC model however values of TEC may differ in 1.5-2 times depending on a method of measurement and calculation, region. In the present paper regional Indian values are compared with global models most widely used. These models are global maps of TEC, the International Reference model of the ionosphere IRI and the Neustrelitz Global Model (NGM). It is shown that values of global maps in most cases are overestimated in relation to the Indian values, the IRI model also overestimates values, and the basic reason of differences is a topside part of the Nh-profile. A plasmaspheric part of the Nh-profile corresponds to an independent model RPI (radio plasma imager). The NGM model yields the better results than IRI. The innovative element consists in usage of TEC for calculation of NmF2. It is shown that usage of an observational median of an equivalent slab thickness of the ionosphere, being well proved itself in various regions of the globe, allows to obtain values of NmF2 closer to real than NmF2(IRI), and to reconstruct missing values in Indian region.*

**Index Terms**—empirical models, ionosphere, plasmasphere, total electron content

## I. INTRODUCTION

The total electron content (TEC) plays a huge role both in environment research, and in practical applications. It has defined development of variety of empirical TEC models. Knowledge of behavior of TEC in the Indian region is interesting from the several points of view. First, the region includes ionospheric and GPS stations lying on crests of equatorial anomaly and near to its top. Secondly, there is a wide experience of study and usage of TEC. Thirdly, own methods are used for obtaining values of TEC from initial data but not global maps. It is interesting to estimate how much TEC values of India correspond to global maps and modern models of TEC for possible comparison of its behavior in various regions. The innovative element consists in usage of TEC for calculation of maximum concentration NmF2 of the ionosphere (or its critical frequency foF2).

## II. EXPERIMENTAL DATA AND MODELS USED

There are some groups of methods to obtain TEC: (1) measurements, (2) integration of theoretical or empirical N(h) - profiles, (3) empirical models. Comparison of the Indian values is fulfilled with results of the most widespread methods of each group. Global maps of TEC

are selected from the first group. The second group is presented by the International Reference model of the ionosphere IRI [1]-[2]. The Neustrelitz Global Model (NGM) is the new unique empirical model entering into the third group [3]. TEC of global maps are calculated from IONEX files (<ftp://cddis.gsfc.nasa.gov/pub/gps/products/ionex/>). TEC of the Indian region were taken from the paper [4] for 3 stations: Trivandrum (8.47°N, 76.91°E), Waltair (17.7°N, 83.3°E), Delhi (28.58°N, 77.21°E), and 2004. Annual mean values of TEC for 2005 for stations Ahmedabad (23°N, 72.6°E) and Trivandrum were taken from the paper [5]. The paper [3] presents TEC of the Dibrugarh station (27.5°N, 94.9°E) for 2009-2012. The paper [7] gives the data for May 2007. The IRI model is used along with all its versions IRI2001, IRI2007, IRI-Plas [1]-[2], [8]. The TEC(NGM) model is presented in the paper [3]. The IRI model is most widely used, but essential difference between model and observational values of TEC was detected in a lot of papers. Many efforts were expended to improve definition of TEC. They are known as modifications of this model [2], [8]. In NGM, the special attention is given to equatorial area. That is why it provides the better correspondence with observational data than the IRI model [9]. Observational values of plasma frequencies fne(sat), measured on the satellites flying at various heights, are used for validating the topside parts of Nh-profiles. The model RPI (radio plasma imager) is used to validate the plasmaspheric parts of Nh-profiles. The RPI model was constructed according to data of satellites IMAGE [10]. Values of fne(sat) of the DMSP satellite were taken on a site [http://cindispace.utdallas.edu/DMSP/dmsp\\_data\\_at\\_utdallas.html](http://cindispace.utdallas.edu/DMSP/dmsp_data_at_utdallas.html). Values of fne(sat) of the CHAMP satellites were calculated according to data, that were kindly provided us by Dr Karpachev A.T. (IZMIRAN, Russia). Values of foF2 were taken from SPIDR database (<http://spidr.ngdc.noaa.gov/spidr/index.jsp>), but, unfortunately, they are very limited. The RPI model is taken from paper [10] and represents distribution of density Neq along magnetic force lines in a range of L-covers from 2 to 4.

## II. COMPARISON OF TEC OF INDIA RECEIVERS AND GLOBAL MAPS

Global maps JPL, CODE, UPC, ESA, which are provided by the various organizations and methods, are most widely used. The average value of four these global maps was accepted by the International GPS community as a standard IGS map [11]. As it is known, values of

these maps in a specific point may differ in 1.5-2 times. The example from the paper [12] is typical. It compares daily dependences of TEC for various maps JPL, CODE, UPC, ESA and other methods of TEC calculation, and also for the IRI model. These results concerned to April, 25th and 28th of 2001 and the Kiruna station. Similar results for the Ahmedabad station are shown in Figure 1.

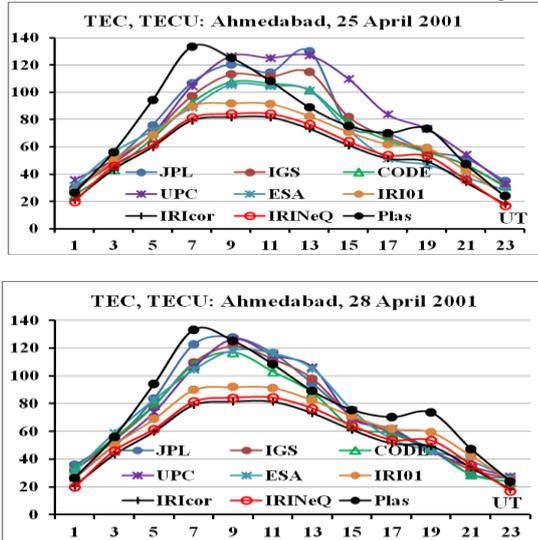


Fig. 1 Values of TEC defined by various methods (JPL, CODE, UPC, ESA, IGS) and empirical models (IRI2001, IRIcorr, IRIneQ, IRI-Plas)

The big differences both between observational, and between model values are visible. One of the purposes of the given paper is the estimation of differences between these values and TEC of the Indian region. For comparison, data of the paper [4] are used for 3 stations Trivandrum, Waltair, Delhi and 3 months 2004 (December, September, May). Results depend on a season. In December, values are very close to values of the ESA map which practically always provides the least values in comparison with other maps. In September, own observational (Indian) values of TEC lie below values of maps. In May, they are lower much more. It is illustrated by Figure 2. Values from [4] are shown by circles.

In the paper [5] own average annual observational values of TEC and models IRIcorr and NeQuick [2] were compared for Ahmedabad and Trivandrum for 2005. In Figure 3, results of comparison with global maps and the NGM model [3] are presented.

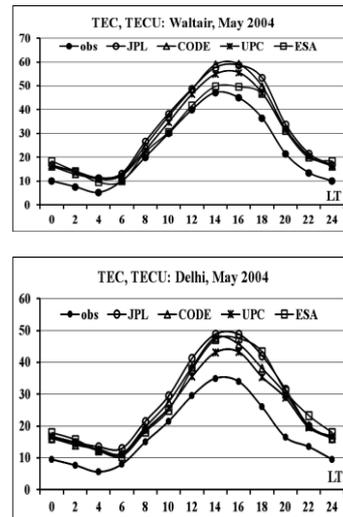
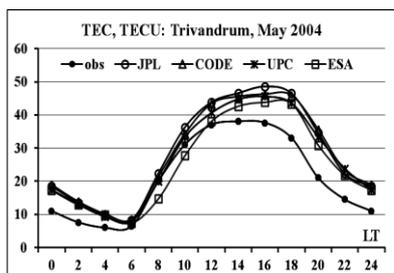


Fig. 2 Comparison of own observational values of TEC and global maps for the Indian region

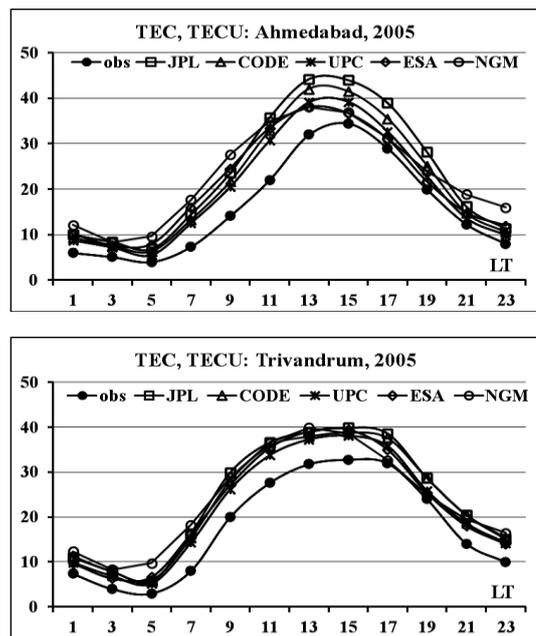


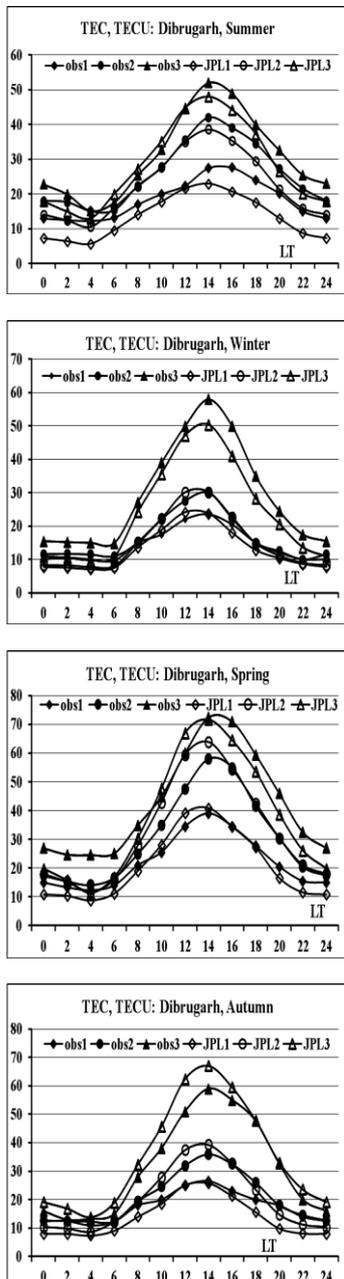
Fig. 3 Comparison of own observational values of TEC of the Indian region, global maps and the NGM model, averaged for 2005

It is accurately visible that the observational values lie below values of global maps and, accordingly, below values of the NGM model. It is important to note that the NGM model was constructed according to the CODE map. In the paper [6] behavior of TEC of the Dibrugarh station was investigated for 2009-2012. In Figure 4 comparison of Indian values of TEC with global map JPL for 4 seasons is given. We averaged values for the next months: summer (6-8), winter (12-2), a spring equinox (3-4), an autumn equinox (9-10). Full marks show the experimental values for 2009-10 (marks obs1), 2010-11 (marks obs2), 2011-2012 (marks obs3). Also plots have been constructed (not shown) for the UPC map which

gave quite good correspondence in the previous cases. Values for the JPL map are shown by hollow marks.

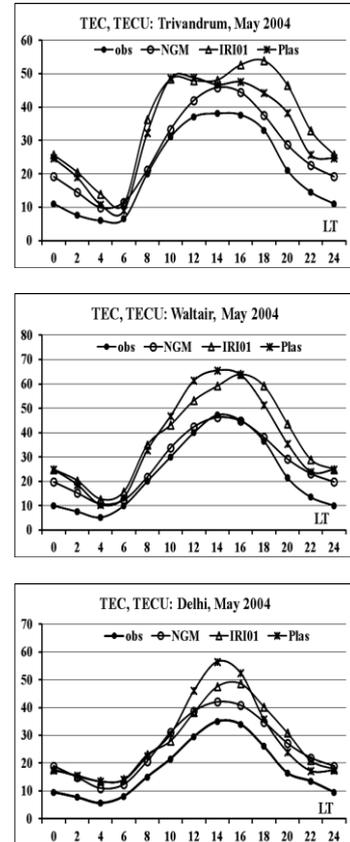
### III. COMPARISON OF TEC OF INDIA RECEIVERS AND MODELS

Figure 5 displays plots for May 2004 and stations, as Figure 2, but for comparison with models IRI [2] and NGM [3].



**Fig. 4 Comparison of Indian values of TEC with the global map JPL providing the closest results**

In summer, values of the JPL map are below observational ones for moderate solar activity in the second half of day and all the day long at low solar activity. Values of the UPC map are lower much more everywhere. During winter time values of the JPL map are below observational ones for moderate solar activity and they coincide with experiment at low solar activity. Values of the UPC map are lower much more everywhere. In an equinox, results of two methods are rather close.



**Fig. 5 Comparison of own observational values of TEC of the Indian region with models NGM and IRI**

It is seen that in most cases values of the NGM model are closer to observational ones than values of the IRI model. The best coincidence exists near to crest of equatorial anomaly. The worst coincidence was obtained on the northern wall. The IRI-Plas model [8] improved determination of TEC in comparison with the IRI2001 [1] model however it gives the overestimated values which correspond to the JPL map. Some of the selected results concerning TEC of 2010-2012 from the paper [6] are shown in Figure 6. They contain plots for which in [6] both axes of coordinates were presented. Results of calculations for the CODE map are presented which in this case gave values, the closest to the observational ones.

Values of the NGM model are closer to observational ones than values of the IRI-Plas model, and overestimation increases strongly with increasing solar activity. The previous results concerned behavior of monthly averaging values of TEC or medians however the greatest role is played by values during the specific day. In the paper [7] the approach for regional modeling

of TEC in real time is presented. Comparison of results of this approach with data of global maps is made in Figure 7 for the Bangalore station and on May, 15th 2007 (the upper panel) and on May, 28th 2007 (the lower panel). The last case includes averaging of values in some range of latitudes and longitudes. On the upper plot time axis is IST, on the lower plot it is represented by local time LT according to the paper [7].

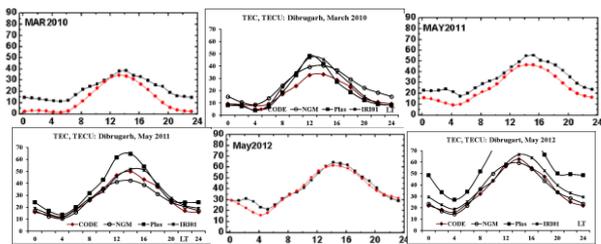


Fig. 6 Daily variations of monthly averaging values of TEC from the paper [6] and calculations

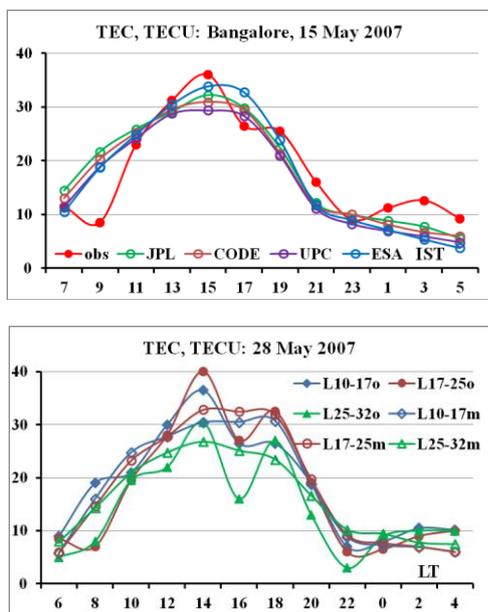


Fig. 7 Comparison of TEC, obtained by various methods, for specific days

It is visible that values of TEC during some moments are close, but as a whole maps do not reflect features of behavior in specific days.

#### IV. CORRESPONDENCE BETWEEN TEC AND NH-PROFILES

In connection with appearance of such models, as GAIM, e.g. [13], IRI-Plas [8] and others, TEC plays an important innovative role as an assimilative parameter because values of TEC are defined by the Nh-profile. Some set of TEC leads to corresponding set of Nh-profiles. The Figure 8 presents an example of such set for April, 28th 2001, the Ahmedabad station and various hours UT=1, 3, 13. In all cases the following profiles are

shown: (1) for the initial IRI model (without adaptation) and 6 profiles for the model adapted for the observational values of various parameters. These are: (2) only foF2(obs), (3) only TEC(obs), (4-7) foF2(obs) and value of TEC of an appropriate map (JPL, CODE, UPC, ESA). Option 1 is used when there is no current ionospheric information. Option 2 uses the current value of foF2. Option 3 is widely used in connection with the TEC measurements. Options 4-7 allow to determine the Ne(h)-profile up to heights of navigation satellites ~20000 km.

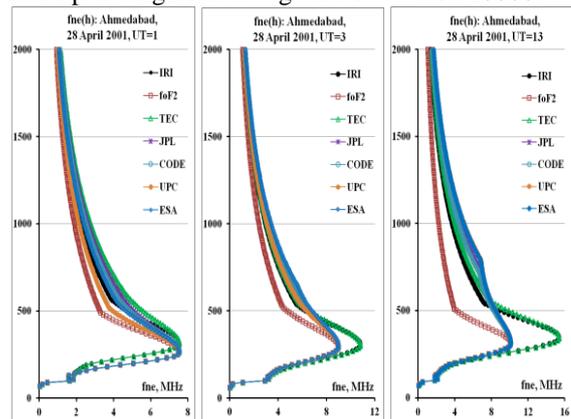
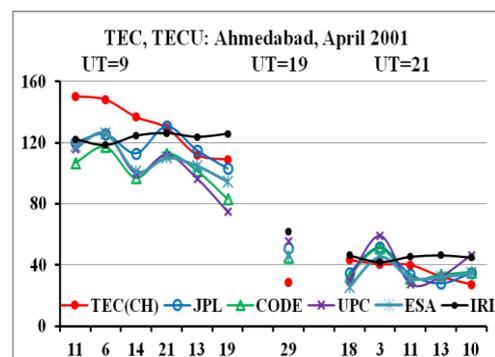
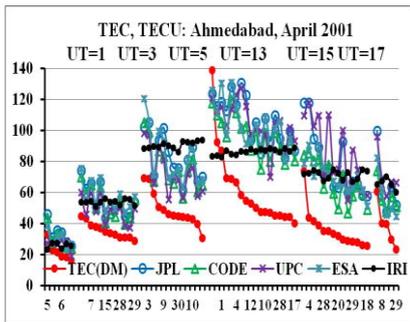


Fig. 8 Sets of the fne(h) - profiles corresponding to set of TEC values

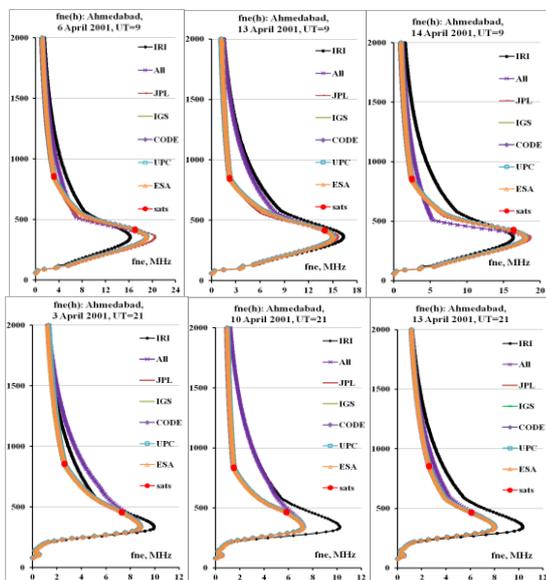
In the first case (UT=1) values of foF2(IRI) and foF2(obs) coincide and the main differences lie in topside parts. In the second case (UT=3) there is a weak negative disturbance. The third case (UT=13) shows example of ingestion of overestimated values of TEC(ESA) in the model. The Nh-profile can be criterion for determination of "reality" of TEC. The third example is a case of the big negative disturbance. For the clearing up, what Nh-profile is closer to real, plasma frequencies of satellites at various heights are used. For each satellite (CHAMP or DMSP), profiles for the model adapted for plasma frequencies are obtained, and values of TEC(fne) are calculated for them. In Figure 9, results for the Ahmedabad station and April 2001 are shown. Values of UT are postponed in the upper part of pictures. On an axis x days are postponed, in which satellites flew by over station.





**Fig. 9** Values of TEC of various global maps and TEC for the profiles transiting through plasma frequencies of one of satellites (CHAMP for the upper part and DMSP for lower one)

The Nh-profiles, transiting through values of  $f_{ne}$ (CHAMP) at heights close to  $h_mF_2$ , provide TEC( $f_{ne}$ ) close to experimental or above. The Nh-profiles, transiting through values of  $f_{ne}$ (DMSP) at heights near to 840 km, provide underestimated TEC values. Most likely, it will coincide with results of Figure 3 which testify that values of global maps for the Indian region are overestimated. Besides, there are cases of simultaneous flights of two satellites. For these cases examples of Nh-profiles are given in Figure 10.

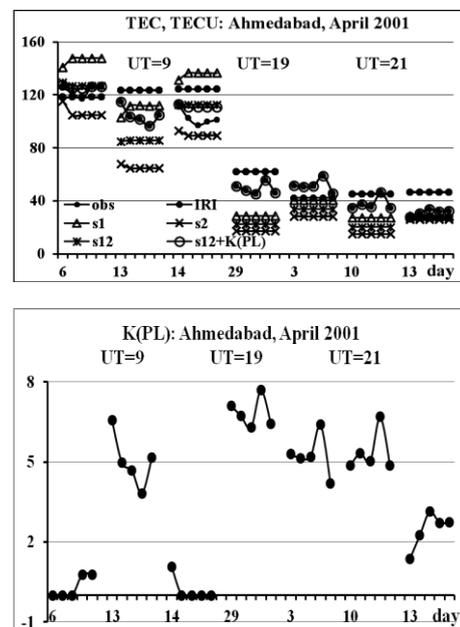


**Fig. 10** Behavior of Nh-profiles for the model adapted for plasma frequencies of two satellites, in comparison with profiles of the IRI model (black circles) and the model adapted only to  $f_oF_2$ (obs) and TEC(obs) (violet asterisks)

It is seen that the profiles transiting through two frequencies  $f_{ne}$ (sat) provide smaller Ne, hence, decreased TEC. For the conformity of the obtained profiles to the observational value of TEC, coefficient K(PL) modifying a plasmaspheric part of a profile was introduced. Calculated TEC are shown in Figure 11. The icon “obs” corresponds to the observational value of TEC(obs). The

icon “IRI” shows TEC for Nh-profiles of the IRI model. Icons “s1” and “s2” show TEC for the profiles adapted for one of plasma frequencies, “s12” - for two frequencies. It is seen that these TEC do not coincide with TEC(obs). The icon “s12+K(PL)” concerns the modified profiles. Their TEC, shown by beige hollow marks, coincide with the observational values. Examples of plasmaspheric parts of profiles are shown in Figure 12.

Figure 12 shows that in most cases modified profiles have a nonphysical view that is the result of overestimated values of TEC of global maps. Additional confirmation is provided by values of the plasmaspheric model constructed according to satellites IMAGE [10], shown by black rhombs. Similar results are obtained and for three stations from the paper [4] for 2004-2005. Examples of profiles are given in Figure 13. Figure 13 shows that the main distinctions concern the topside part of a profile. If to attribute a deviation of the calculated profile in plasmaspheric parts to difference of density distribution in equatorial anomaly  $Neq$  from the model then it is possible to use coefficients of the RPI model for specification of  $Neq$  using TEC(obs). For the Ahmedabad station and the April 2001, three stations and April 2004, results are given in Figure 14. Values of the RPI model are shown by black marks. Remaining marks designate time UT in the upper panel. On the second panel, time UT is located near to the reduced title of station.



**Fig. 11** Comparison of TEC, calculated for various Nh-profiles (the left panel), and adjusting factor K(PL) (the right panel)

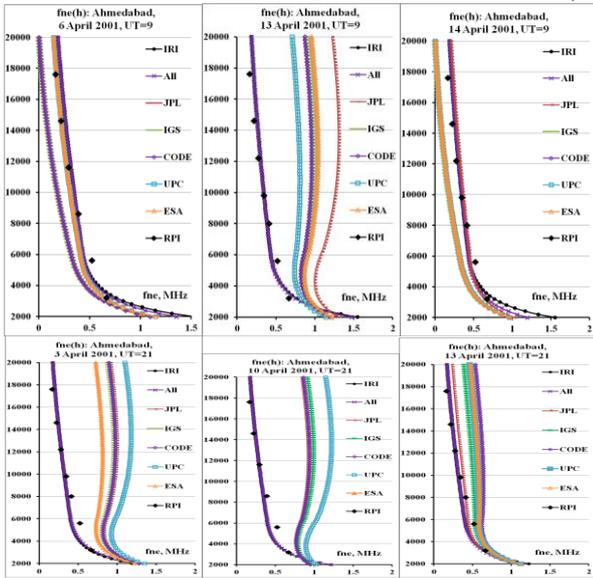


Fig. 12 Comparison of plasmaspheric parts of the profiles modified by the factor K(PL) for coincidence with TEC(obs). In addition, values of the RPI model [10] are presented

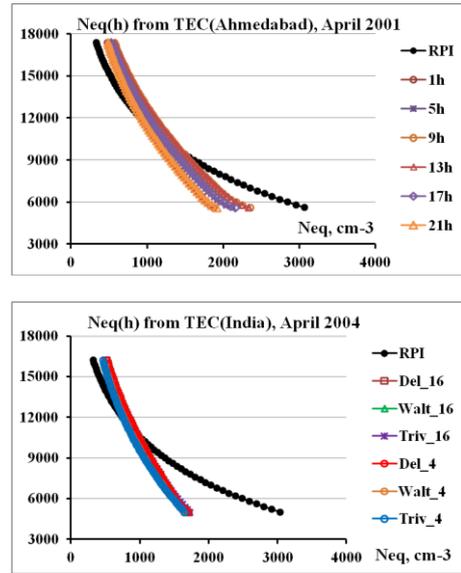


Fig. 14 Comparison of the equatorial anomaly distribution of Neq obtained by the RPI model and with usage of the experimental values TEC (obs)

It is visible that the greatest differences concern area of lower heights. In other global regions there may be a similar pattern. However there are cases of opposite behavior when values of Neq calculated from TEC(obs) at low heights exceed model values.

### V. USAGE OF THE EQUIVALENT SLAB THICKNESS OF THE IONOSPHERE FOR CALCULATION OF PARAMETER NMF2 (OR FOF2)

The simple ratio for  $\tau = \text{TEC}/\text{NmF2}$  shows that  $\tau$  is width of a layer in the form of a rectangle with constant concentration NmF2. If to have model  $\tau$  then it is possible to define values of NmF2 from the observational values of TEC, and, hence,  $\text{foF2}^2 (\text{MHz}^2) = 80.6 \text{ NmF2} (\text{cm}^{-3})$ . Traditionally a thickness  $\tau(\text{IRI})$  of the IRI model is used to calculate NmF2 from TEC(obs) [8, 14]. But  $\tau(\text{IRI})$  is not empirical model of  $\tau$  because it is calculated from the TEC(IRI) model which is calculated with usage of a model Nh-profile. Authors of [15] offered to use the experimental median  $\tau(\text{obs})$  and it was shown that  $\tau(\text{obs})$ : (1) provides the better correspondence of the calculated (reconstructed) values of foF2(rec) with experimental foF2(obs) than  $\tau(\text{IRI})$ , especially in disturbed conditions, (2) allows to fill gaps of experimental foF2. The purpose of this section is to compare  $\tau(\text{IRI})$  and  $\tau(\text{obs})$  in the Indian region and to obtain the quantitative estimation of usage  $\tau(\text{obs})$  in comparison with  $\tau(\text{IRI})$ . For calculation of  $\tau(\text{obs})$  the observational values of foF2(obs) and TEC(obs) are used. Because foF2 data in the Internet are very limited, the case of 4 serial months was found (March - June 1999). Values of global maps JPL, CODE, UPC, ESA were used as TEC(obs). Results are presented in Figure 15 for three months to underline certain

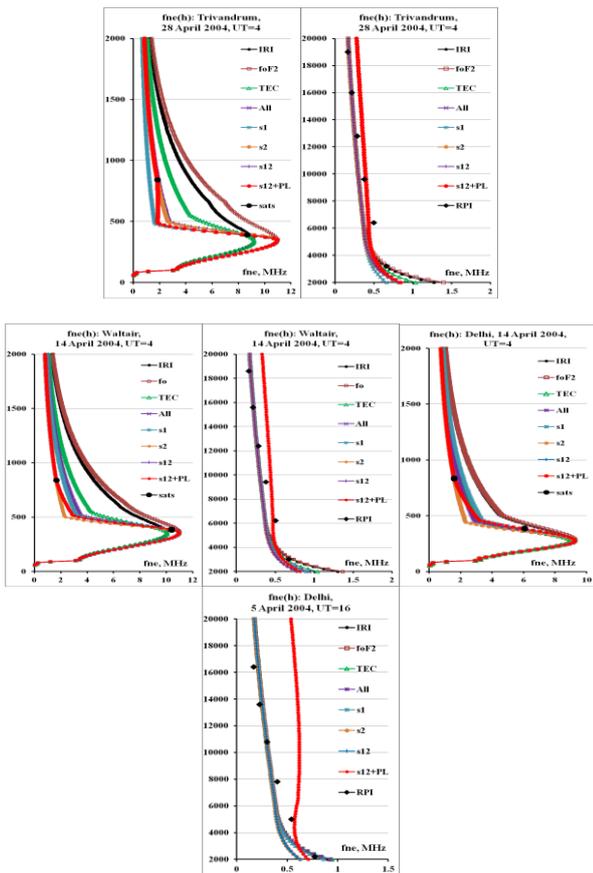
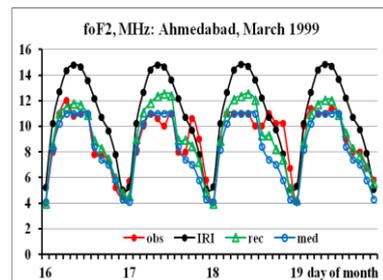
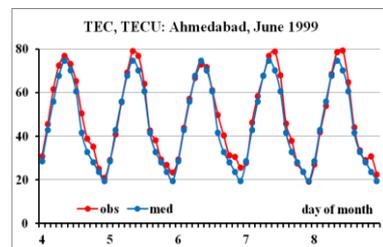
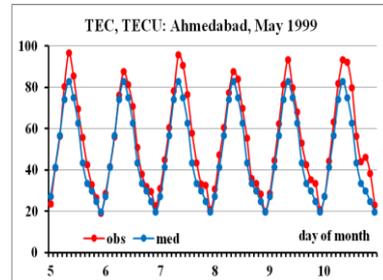
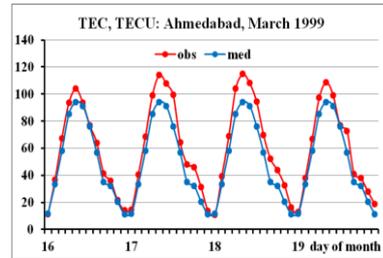
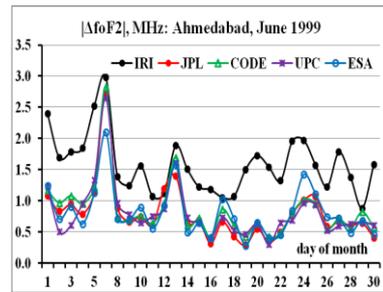
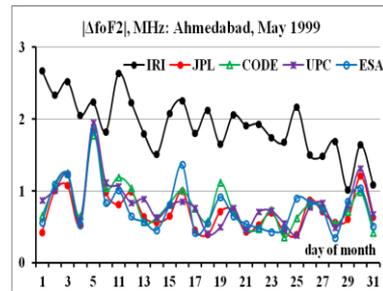
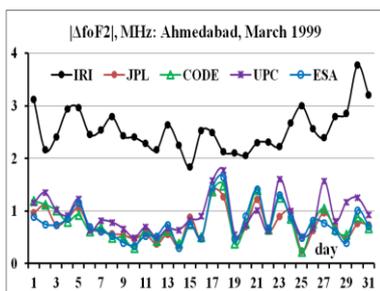
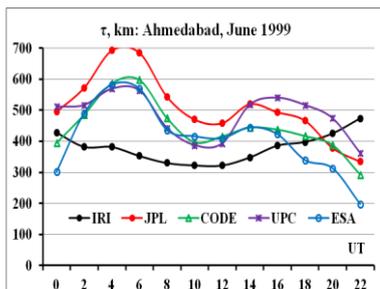
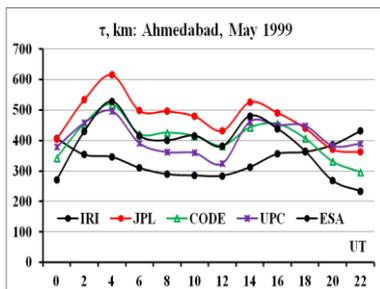
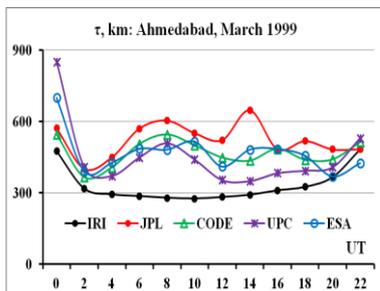
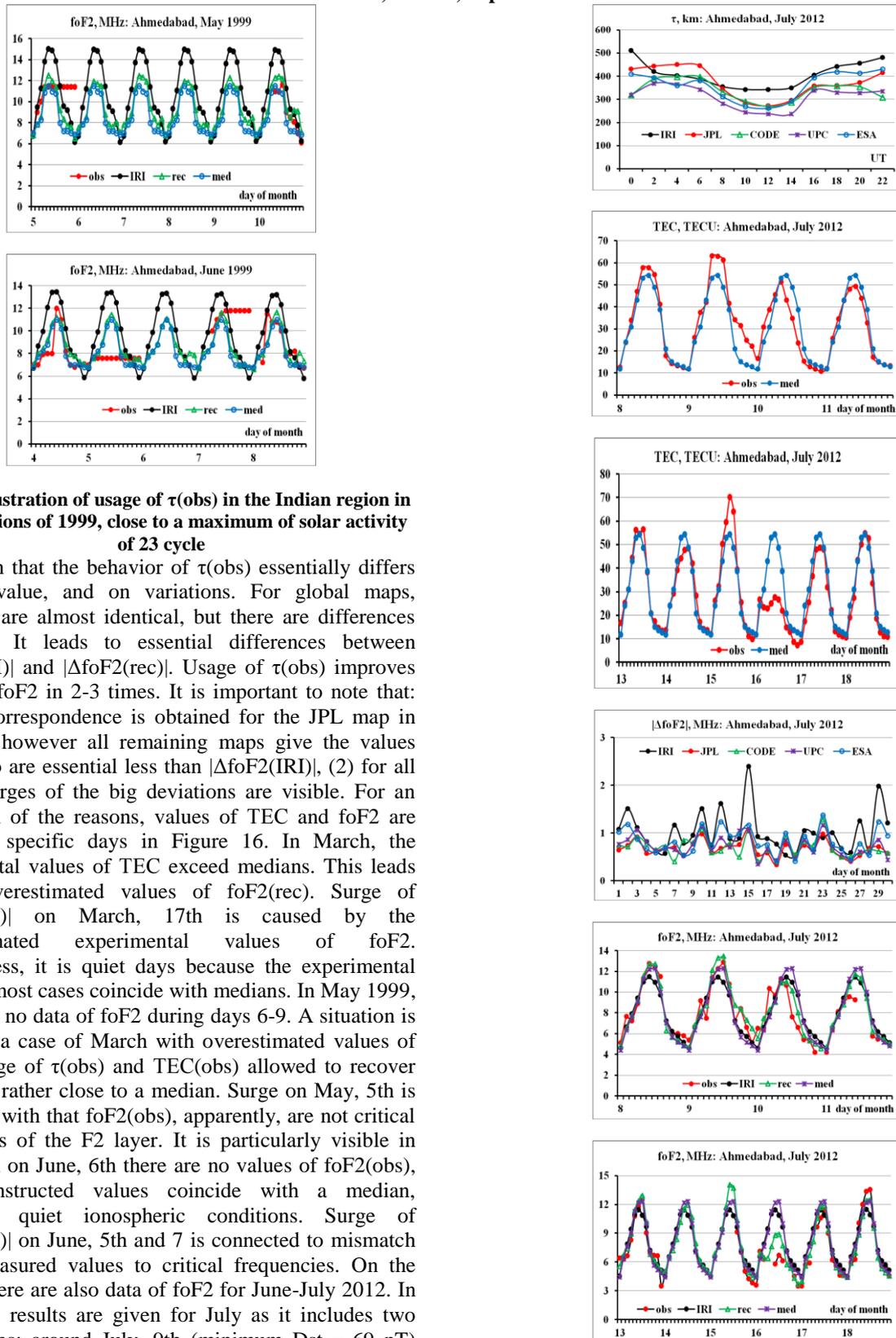


Fig. 13 Comparison of Nh-profiles for the model adapted for plasma frequencies of two satellites with the RPI model [10]

features. For each month the daily runs of  $\tau$  for the IRI model and global maps JPL, CODE, UPC, ESA are shown. The second group of plots shows absolute values of deviations  $|\Delta foF2|$  of the calculated values of foF2 from observational foF2(obs). TEC(IRI) and  $\tau$ (IRI) were used to calculate foF2(IRI). Reconstructed foF2(rec), i.e. (foF2(JPL), foF2(CODE), foF2(UPC), foF2(ESA)), were calculated with using  $\tau$ (JPL),  $\tau$ (CODE),  $\tau$ (UPC),  $\tau$ (ESA) and values TEC(JPL), TEC(CODE), TEC(UPC), TEC(ESA). The third group contains the observational values of TEC for the selected days and median TEC. The fourth group contains observational (obs), model (IRI), reconstructed (rec) (for the JPL map) and median (med) values of foF2.





**Fig. 15 Illustration of usage of  $\tau(\text{obs})$  in the Indian region in the conditions of 1999, close to a maximum of solar activity of 23 cycle**

It is seen that the behavior of  $\tau(\text{obs})$  essentially differs both on value, and on variations. For global maps, variations are almost identical, but there are differences on value. It leads to essential differences between  $|\Delta\text{foF2}(\text{IRI})|$  and  $|\Delta\text{foF2}(\text{rec})|$ . Usage of  $\tau(\text{obs})$  improves values of foF2 in 2-3 times. It is important to note that: (1) best correspondence is obtained for the JPL map in this case, however all remaining maps give the values which also are essential less than  $|\Delta\text{foF2}(\text{IRI})|$ , (2) for all months surges of the big deviations are visible. For an illustration of the reasons, values of TEC and foF2 are given for specific days in Figure 16. In March, the experimental values of TEC exceed medians. This leads to the overestimated values of foF2(rec). Surge of  $|\Delta\text{foF2}(\text{rec})|$  on March, 17th is caused by the underestimated experimental values of foF2. Nevertheless, it is quiet days because the experimental values in most cases coincide with medians. In May 1999, there were no data of foF2 during days 6-9. A situation is similar to a case of March with overestimated values of TEC. Usage of  $\tau(\text{obs})$  and TEC(obs) allowed to recover foF2(rec), rather close to a median. Surge on May, 5th is connected with that foF2(obs), apparently, are not critical frequencies of the F2 layer. It is particularly visible in June when on June, 6th there are no values of foF2(obs), and reconstructed values coincide with a median, specifying quiet ionospheric conditions. Surge of  $|\Delta\text{foF2}(\text{rec})|$  on June, 5th and 7 is connected to mismatch of the measured values to critical frequencies. On the Internet there are also data of foF2 for June-July 2012. In Figure 16, results are given for July as it includes two disturbances: around July, 9th (minimum Dst = -69 nT) and around July, 15th (minimum Dst = -133 nT). This period is interesting because it is also close to a maximum of solar activity, as 1999, but absolute level of this activity is lower more.

**Fig. 16 Illustration of usage of  $\tau(\text{obs})$  in the Indian region in the conditions of 2012, close to a maximum of solar activity of 24 cycle**

Differences between  $\tau(\text{IRI})$  and  $\tau(\text{obs})$  and between results for  $\tau(\text{IRI})$  and  $\tau(\text{obs})$  are essential less in 2012 than in 1999. It is defined, apparently, by level of solar activity. In the right plots, examples of behavior of TEC and foF2 are given. Actually, in both cases we see variations close to the classical form of a storm development: the positive phase is followed by the negative one. This is especially clearly seen in case of the second disturbance. For 14 and half on July, 15-16<sup>th</sup>, there are reconstructed values which reflect a real pattern more precisely.

## VI. CONCLUSION

Comparison of the total electron content of the ionosphere of the Indian region with most widely used methods show that Indian values fall out global maps. This testifies to necessity of regional models. Usage of experimental median of the equivalent slab thickness  $\tau(\text{obs})$  and TEC(obs) to obtain NmF2 provide results similar results of other areas because  $\tau(\text{obs})$  turned out to be the good calibration coefficient leveling distinctions of TEC for various methods of determination of TEC.

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