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Comparison of NeQuick, PIM, and TSM model results for the topside ionospheric plasma scale and transition heights

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Abstract

The topside ionospheric scale height (T_s) and the O^+–H^+ transition height (T_h) are key ionospheric characteristics that are of special interest when studying and modelling the plasma composition and dynamics. Recently, a new Topside Sounder Model (TSM) has been developed which provides the T_s and T_h quantities together with the ratio between them, T_s/T_h. The database for this model has been built upon thousands of T_s and T_h values deduced from electron density profiles retrieved from topside sounding measurements. For validation purposes, it would be interesting to compare calculations of the ionospheric scale/transition heights from TSM with corresponding calculations from two other well-known models – the NeQuick Model (NeQ) and the Parameterized Ionospheric Model (PIM). For the purpose, electron density profiles have been computed with both the NeQuick and PIM models over suitable grids of input parameters such as month, local time, geomagnetic latitude, solar activity, and in the altitude range between 200 and 2000 km. The topside ionospheric scale height and the O^+–H^+ transition height values have been extracted from each profile in the same manner as previously done for the TSM development database. Finally, the T_s and T_h values deduced from the NeQuick and PIM profiles have been compared with the respective values provided by the TSM. Results of this comparison are analysed and suggestions are put forward for further improving the models in question. TSM applications are discussed as well.

Keywords: Ionospheric plasma scale height; Ion transition height

1. Introduction

The topside ionosphere and the plasmasphere are still difficult and/or expensive to observe regularly and reliably with the traditional methods available today. Therefore, the development and use of empirical models of the main ionospheric characteristics is well substantiated. The O^+–H^+ ion transition height (T_h) and the topside ionospheric scale height (T_s) are key ionospheric parameters (Fig. 1) that are of particular interest when studying and modelling the topside plasma composition and dynamics. The O^+–H^+ ion transition height is defined as the altitude were the O^+ and H^+ ion densities become equal. The topside ionospheric plasma scale height is the height interval over which the plasma density decreases by a factor of e (the Euler's number, $e \approx 2.71828$).

Recently, new empirical models of T_h (Marinov et al., 2004) and T_s (Kutiev et al., 2006) have been developed using topside ionospheric sounding measurements from the Alouette-1a, -1b, -1c, -2 and ISIS-1, -2 satellite missions. In both models, the T_h and T_s quantities have been deduced from electron density profiles. Practically, if assuming an exponential distribution of the O^+ density, the transition height is determined as the height where the upward extrapolated O^+ density equals half of the value of the electron density (Ne). Concerning the T_s deduction, it is assumed that the lowest gradient on the topside Ne profile represents the gradient of the O^+ density

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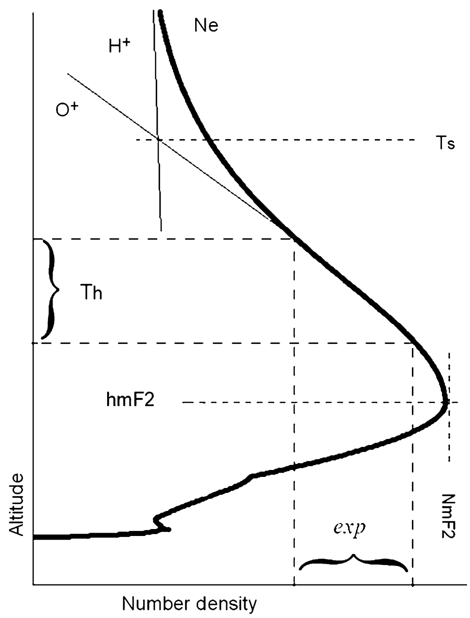

Fig. 1. Idealized scheme of the vertical ion (O^+ and H^+) and electron (Ne) density profiles and some of their main characteristics – the F2 layer peak density (N_mF_2) and height (h_mF_2), topside ionospheric scale height (T_s) and O^+–H^+ transition height (T_h).

profile. Instead of picking the smallest gradient in the Ne profiles, the model technique takes a regression over several Ne values that have gradients within 30% from the minimum. The regression line accounts for increasing plasma temperature with height and actually represents a scale height with a plasma temperature averaged with 30% tolerance. On average, the approximated O^+ gradient is found somewhere between 380 and 545 km in altitude. In this altitudinal range the plasma temperature increases with about 30%. After that, the O^+ gradient inferred from the Ne profile is converted into scale height. Since it has been found that the plasma scale height and the transition height strongly correlate (the correlation coefficient exceeding 0.8 at middle latitudes) developed also was a T_s/T_h ratio model, called Topside Sounder Model (Kutiev and Marinov, 2007). Both the scale and transition heights are considered as functions of the following parameters: month of year, geomagnetic latitude, local time, solar flux F10.7, and geomagnetic activity index Kp.

The purpose of this publication is to present results from a comparison between the ionospheric plasma scale height and upper ion transition height calculations by the TSM model and by two other well-known models – the NeQuick model (NeQ) and the Parameterized Ionospheric Model (PIM). Since neither NeQuick nor PIM provide T_s and T_h explicitly, these quantities have been extracted from model simulations of electron density profiles.

2. The models

The NeQuick model (Hochegger et al., 2000; Radicella and Leitinger, 2001) is a user-friendly quick-run model for trans-ionospheric applications that enables the calculation of either the vertical or slant electron density profile and the total electron content (TEC) for any specified path. For bottom-side ionosphere simulations, the model uses five semi-Epstein layers with modelled thickness parameters and is based on anchor points defined by f_0E, f_0F_1, f_0F_2 and $M_{3000}F_2$ values. The topside ionosphere is modelled by a semi-Epstein layer with a height dependent thickness parameter that is empirically determined. As input, the model uses ITU-R (International Telecommunication Union – Radiocommunication) monthly median coefficients for f_0F_2 and $M_{3000}F_2$ determination. As output, the model provides the ionospheric and plasmaspheric electron density as a function of height (from 90 up to 20,000 km), latitude and longitude, solar activity, month, and local/universal time. The electron concentration can be calculated along an arbitrarily chosen ray path and the resultant profile is smooth (continuous first-order spatial derivatives) which is important for ray tracing and location finding applications.

The Parameterized Ionospheric Model (Daniell et al., 1995) is a climatological global ionospheric and plasmaspheric model based on the parameterized output of several regional theoretical ionospheric models and an empirical plasmaspheric model (Gallagher et al., 1988). The ionospheric part combines the results of the theoretical ionospheric models that, taken together, cover the ionospheric E and F layers for all latitudes, longitudes, and local times, while the plasmaspheric part is taken from the empirical model. Mathematically, the model is a semi-analytic representation of diurnally reproducible runs of the above-mentioned models for all levels of solar and geomagnetic activity, for March equinox, June and December solstice conditions. In effect, the parameterization compresses the output from the theoretical models while preserving important ionospheric characteristics such as density peaks and scale heights. Ultimately, PIM produces output that includes electron density profiles in the altitudinal range from 90 up to 25,000 km (incl. f_oF_2, h_mF_2, total electron content), and ion composition (O^+, NO^+, and $O_2{}^+$ ion densities). This output can be delivered in various user-selectable formats such as global or regional latitude–longitude grids (in either geographic or geomagnetic coordinates), a set of user-specified points (which could lie along a satellite orbital path), or an altitude-azimuth-elevation grid for a user-specified location. All these features allow PIM to be computationally fast while basically retaining the physics of the ionospheric models used.

The Topside Sounder Model (Marinov et al., 2004; Kutiev et al., 2006; Kutiev and Marinov, 2007) is a global empirical model of the topside ionospheric scale height (T_s), the ion transition height (T_h), and the ratio T_s/T_h. The database consists of more than 170,000 topside electron density (Ne) profiles accumulated from the Alouette-1a, -1b, -1c, -2 and ISIS-1, -2 satellite missions during the 1962–1979 period. The input parameters are local time, month of year, geomagnetic latitude, longitude, and solar activity. Both, the scale height and transition height values are extracted from each individual Ne profile and sorted into 6-dimensional bins corresponding to the above-mentioned input parameters. After that, the data are fitted with a multivariable polynomial, containing a set of base functions (algebraic, trigonometric, or Tchebishev). The polynomial coefficients are obtained using the least square approximation method. The seasonal (annual) variation is approximated with yearly and semi-yearly waves, diurnal (local time) variation with diurnal and semi-diurnal waves, latitudinal variation with a 6th-degree polynomial, and the variations due to solar (F10.7) and magnetic activity (Kp) with 2nd order polynomials. The wave functions are used with an average offset and pairs of *sin* and *cosine* functions in order to decouple the time argument and the phase. It is found that T_s and T_h have a dispersion of about 40% around the respective average, while the model reduces the dispersion (deviation of model from data) to 27%. The most remarkable fact is that the dispersion of Rt (T_s/T_h) is only 25% and model error is reduced to 18%. The average value of T_s is 138 km and that of T_h is 862 km.

3. Comparison – method

For comparison purposes, electron density profiles in the altitude range 200–2000 km have been obtained from NeQuick and PIM models, run over suitable grids of input parameters: month, local time, geomagnetic latitude, and solar activity (Table 1). Both the topside ionospheric scale height and the O^+–H^+ transition height values have been extracted from each of the electron profiles. The T_s and T_h value extraction procedures were the same that have already been used for building the TSM model development database. In fact, the NeQuick, PIM, and TSM model calculations have been carried out for the 15th day of each month, for every LT hour in the corresponding day/night interval, once for low solar activity (LSA), $F10.7 = 90$, and once for high solar activity (HSA), $F10.7 = 180$. Each seasonal value is the average of the monthly values in the corresponding group of months. To obtain the latitudinal variations, the models have been run for every 10 degrees, from 90°S to 90°N. The longitudinal variations have been neglected and values for the 0°E longitude have only been obtained. The T_s and T_h model results have been plotted in such a way as to emphasize the variations due to a given input parameter and to show the differences between the models. The stress is put on the latitudinal and diurnal variations of both T_s and T_h. In addition, the averaged differences between the NeQuick, PIM, and TSM model values of T_s and T_h have been calculated: $R_{PT} = T_s(\text{PIM}) - T_s(\text{TSM})$ and $R_{QT} = T_s(\text{NeQ}) - T_s(\text{TSM})$.

Table 1
Model parameters and the corresponding grid points/intervals

Parameter	Grid
Season	Summer: North (May, Jun, Jul, Aug) South (Nov, Dec, Jan, Feb) Winter: North (Nov, Dec, Jan, Feb) South (May, Jun, Jul, Aug)
Local time	Day: [1000 LT–1600LT], step 1 h Night: [2200 LT–0400LT], step 1 h
Latitude (magnetic)	High: [−90, −60) U (+60, +90], step 10° Mid: [−60, −30] U [+30, +60], step 10° Low: (−30, 0) U [0, +30), step 10°
Solar activity (F10.7)	High (HSA): F10.7 = 180 Low (LSA): F10.7 = 90
Longitude (magnetic)	[0°E–360°E), at 0°E longitude

Time resolution: model calculations have been carried out for the 15th day of each month, for every LT hour in the corresponding day/night interval, once for high and low solar activities. Spatial resolution: values obtained for every 10 degrees in latitude and for 0°E longitude.

4. Comparison – topside ionospheric scale height

Concerning the topside ionospheric scale height's latitudinal variations (Fig. 2), the TSM model values are clearly larger at high latitudes and smaller elsewhere, particularly during summer. There is also an increase over the equator which is more pronounced during winter. Although the scale height behaviour is similarly modelled by PIM and TSM, the PIM values are systematically higher than the TSM values. The difference is relatively small during night but, during summer day, it can well exceed 100% over low and middle latitudes. In contrast to both TSM and PIM, the NeQuick's night-time values for the Northern hemisphere are significantly higher during winter than the NeQuick's values during summer. In addition, it seems that NeQuick provides unrealistically large differences between summer and winter. The latter is possibly due to this model's formulation of latitudinal variations depending on month rather than season. Also, sharp discontinuities over the equator are seen in the T_s values of NeQuick at night and at low solar activity. An explanation of this observation is the fact that, during night, the NeQuick values increase steadily from South to North, irrespective of season or local time. It becomes more obvious if one compares the combinations of the North Summer with South Winter plots and the North Winter with South Summer plots.

The pattern of the scale height's diurnal variations (Fig. 3), as provided by the three models, looks more or less similar, although it varies from season to season and latitude to latitude. In general, the scale height increases with solar activity. However, at high latitudes, the TSM local time variations are negligible with values larger during summer and during HSA. At middle latitudes, there is a pronounced winter-time minimum just before noon, while in summer the minimum occurs during night. Also, there is a peak in the early morning and another in the early evening hours. At low latitudes, these two peaks are more

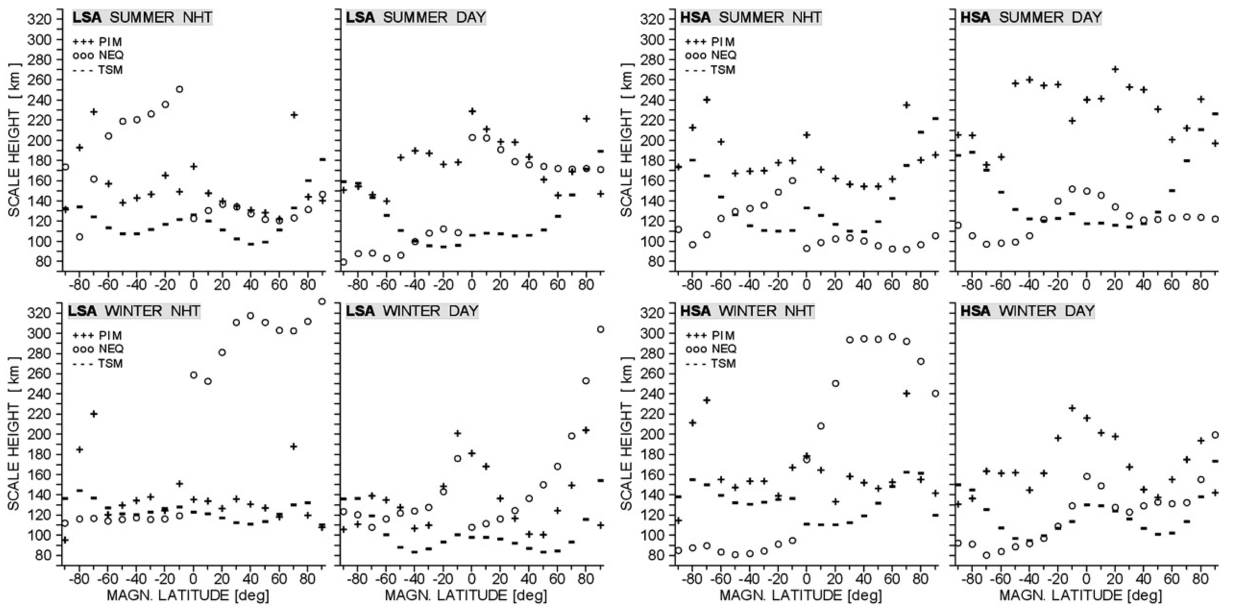

Fig. 2. Latitudinal variations of the topside ionospheric scale height (T_s) as obtained from PIM, NeQuick (NeQ), and TSM models, for low (LSA) and high (HSA) solar activity, at night (NHT) and day (DAY), during winter and summer.

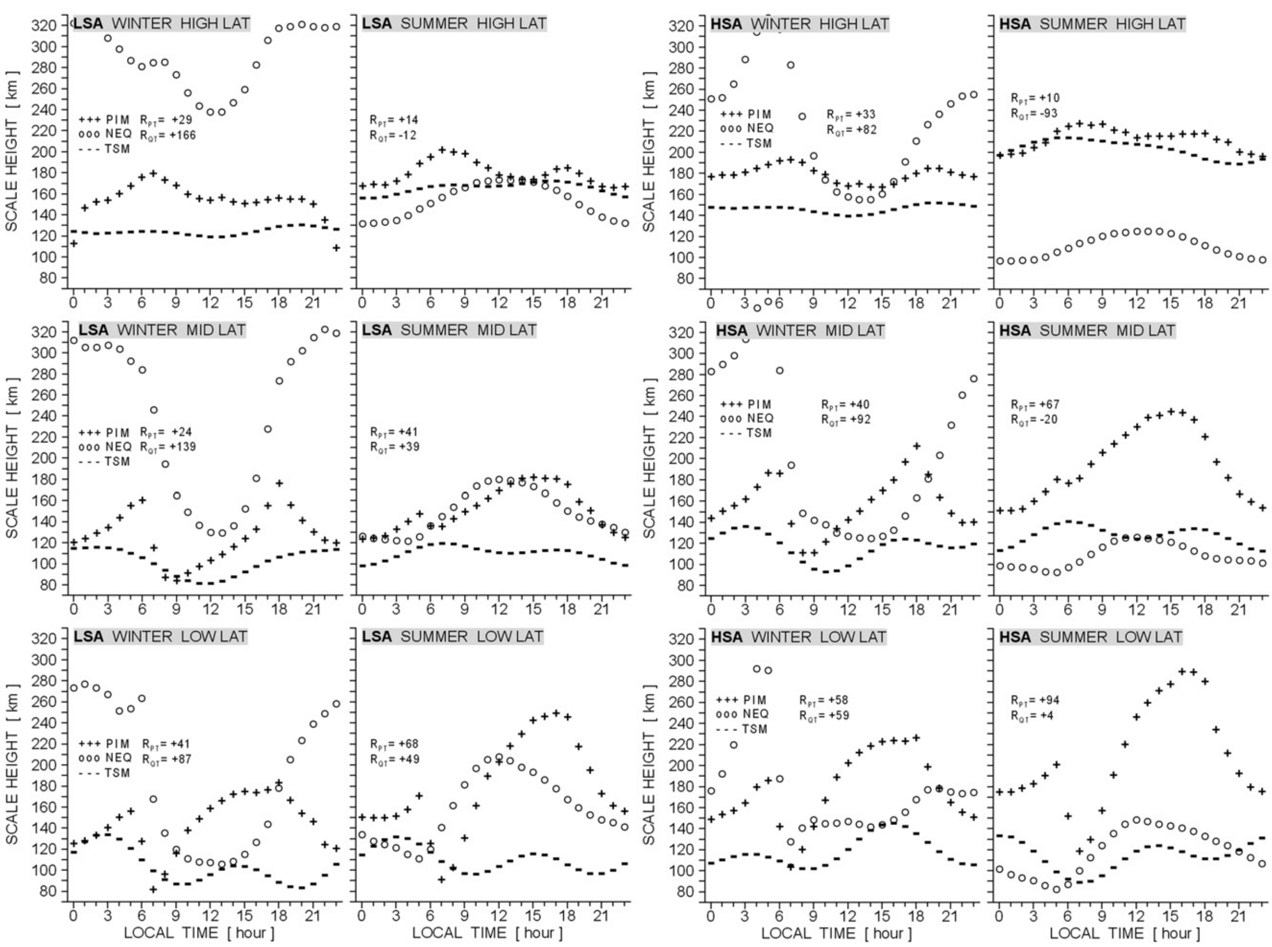

Fig. 3. Diurnal variations of the topside ionospheric scale height (T_s) for low (LSA) and high (HSA) solar activity. To highlight the model differences, the results for the Northern hemisphere only are plotted. The numbers given in each plot are the average residuals: $R_{PT} = T_s(\text{PIM}) - T_s(\text{TSM})$ and $R_{QT} = T_s(\text{NeQuick}) - T_s(\text{TSM})$.

pronounced and shifted toward earlier hours. On average, the PIM values are highest in summer, while the NeQuick values are highest in winter. At any time, the PIM values are higher than the TSM values and large differences are detected at low and middle latitudes during summer. In fact, during winter, both the PIM and NeQuick values are consistently larger than the TSM values. Again, extremely large NeQuick values are recorded during winter nights, on occasions the night-to-day ratio exceeding 2.5 at middle latitudes. The NeQuick values are smaller than PIM and TSM values at high latitudes during summer. In contrast to both PIM and TSM, the scale height values deduced from NeQuick at low solar activity are larger than the NeQuick values at high solar activity. A check of the originating electron density profiles reveals that, although the peak density is larger at HSA, the topside profile is steeper at LSA. Considering also the small/negligible differences between the density profiles in the parts that lie in the plasmaspheric region, it seems that NeQuick significantly underestimates the plasmaspheric density, particularly at high solar activity.

5. Comparison – ion transition height

The latitudinal behaviour of the ion transition height (Fig. 4), as provided by TSM, is characterised with an increase over the equator, a decrease at middle latitudes, and an increase again at high latitudes. On average, the T_h is lower during the day, however, at high solar activity, the equatorial peak is much more pronounced during day than during night. The daytime latitudinal variations are provided by PIM and TSM in a similar fashion. PIM tends to provide larger values than TSM at low and middle latitudes in summer, with differences occasionally reaching 50%. For NeQuick, the latitudinal variations of T_h, in similarity to T_s, exhibit jumps over the equator and large seasonal differences, particularly during night.

The diurnal changes in the ion transition height (Fig. 5) are modelled in a similar fashion by all models, except at high latitudes during summer. In general, the ion transition level is lower during day and higher during night. A minimum in T_h occurs between 1100LT and 1300LT at high latitudes but tends to occur earlier when moving toward lower latitudes, e.g. between 0600LT and 0700LT over the equator. Early morning and early evening maxima are clearly seen in the PIM's transition height values, the evening maxima being much more pronounced at middle and low latitudes. Thus, the average daily amplitude (max/min ratio) increases with solar activity and at lower latitudes. On average, the PIM values are highest during high solar activity and during summer at low solar activity, while the NeQuick values are highest in winter at low solar activity. Again, the NeQuick's T_h value for low solar activity is larger than for high solar activity.

6. Conclusion

A crude comparison has been made between NeQuick, PIM, and TSM model calculations of the topside ionospheric plasma scale height and the upper ion transition height. Since the PIM and NeQuick models do not directly provide the T_s and T_h quantities, the latter have been inferred from vertical electron density profiles instead.

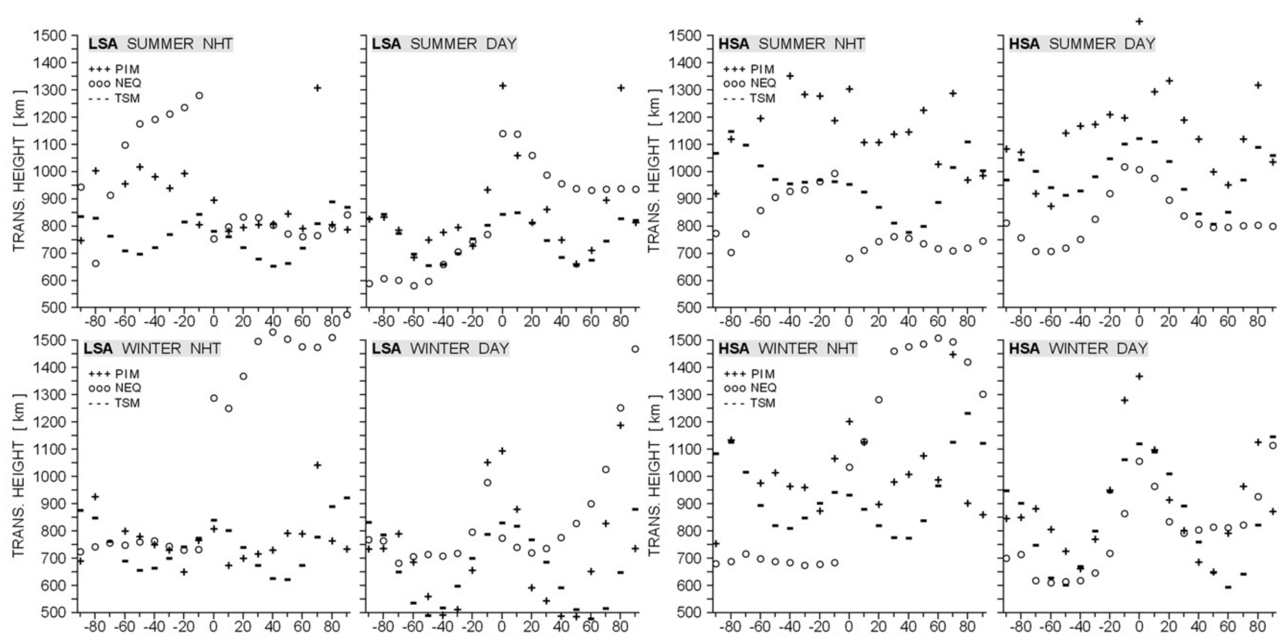

Fig. 4. Latitudinal variations of the O^+–H^+ transition height (T_h) as obtained from PIM, NeQuick (NeQ), and TSM models, for low (LSA) and high (HSA) solar activity, at night (NHT) and day (DAY), during winter and summer.

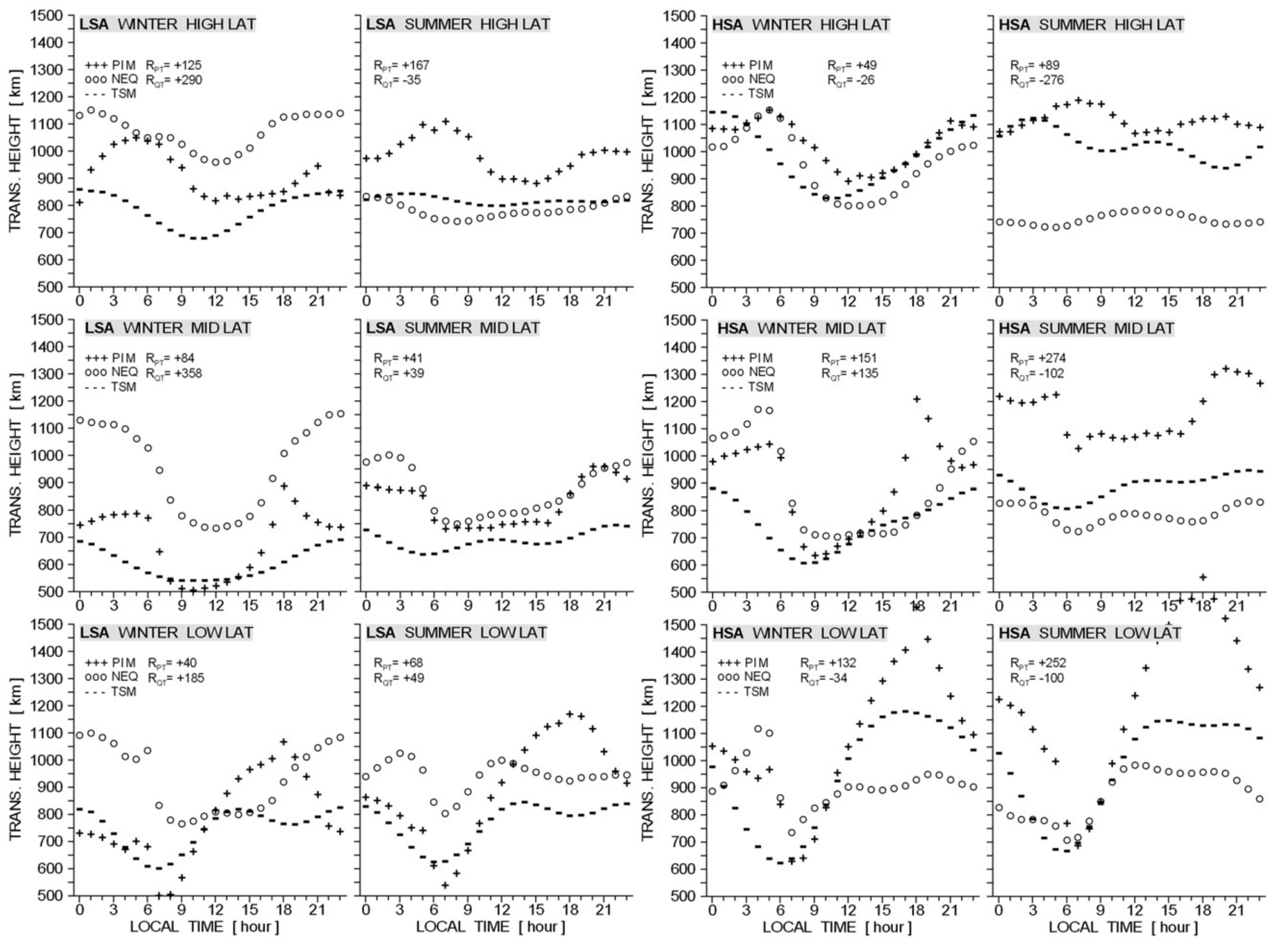

Fig. 5. Diurnal variations of the O^+–H^+ transition height (T_h) for low (LSA) and high (HSA) solar activity, and low, mid, high latitudes. To highlight the model differences, the results for the Northern hemisphere only are plotted. The numbers given in each plot are the average residuals: $R_{PT} = T_h(\mathrm{PIM}) - T_h(\mathrm{TSM})$ and $R_{QT} = T_h(\mathrm{NeQuick}) - T_h(\mathrm{TSM})$.

The three models are rarely in full agreement over the T_s and T_h values and/or pattern of variations. In many cases, the patterns of T_s and T_h variations are similar albeit the existing quantitative discrepancies. Such discrepancies between the outputs of the models are expected since the databases and the techniques utilised for development of these models are different. In other cases, model results do not match at all, neither as patterns nor as quantities, which can be explained with limited development databases. On some occasions, no clear trends were revealed in the T_s and T_h changes which caused additional difficulties in the interpretation of the results. Nevertheless, the analysis shows that there are some deficiencies in the model formulations, particularly in the cases of observed extremely large discrepancies. For example, the night-time values of T_s and T_h, deduced from NeQuick electron density profiles, are significantly higher during winter than the corresponding NeQuick values during summer. Moreover, the values at low solar activity are larger than the values at high solar activity. This is most probably due to inaccurate estimation of the plasmaspheric density/content. Sharp discontinuities over the equator are seen in the T_s and T_h values deduced from NeQuick calculations. Such discontinuities are unrealistic and it turns out that both the T_s and T_h values increase steadily in South-North direction regardless of the different seasons in the Southern and Northern hemispheres. The PIM simulation of the T_s and T_h quantities are consistently higher than the corresponding NeQuick and TSM results, particularly during high solar activity. It suggests that either PIM overestimates the topside electron concentration or both NeQuick and TSM underestimate it. In any case, it is clear that the validation should continue and new measurements should be involved. For example, a suitable database for further validation of the TSM model is available from the ionospheric radio occultation measurements onboard low-earth-orbiting satellites (Heise et al., 2002; Jakowski et al., 2002; Stankov and Jakowski, 2005).

Reliable model values of the topside ionospheric scale height, the upper ion transition height, and their ratio can be used in various applications in which the topside ionosphere and plasmasphere conditions are important. Since these three parameters over-determine the topside density profile shape, a proper combination of any two of them can complement ionospheric measurements in order to properly reconstruct the topside electron density profile. A concept for a new profiler, capable of simulating the electron profile in the topside ionosphere and plasmasphere (TIPP), has already been proposed by Kutiev and Marinov (2007). The modern digisonde software determines the neutral scale height at the ionospheric F peak height from ionograms and extrapolates the value to the topside ionosphere (Reinisch and Huang, 2001). Belehaki et al. (2006) have found that the doubled value of the digisonde-obtained scale height, which roughly represents the ionospheric plasma scale height, agrees fairly well with the T_s model values (Kutiev et al., 2004). This correlation can be utilised when constructing the entire electron profile by using a pre-defined shape for the topside part together with the topside ionospheric scale height and the T_s/T_h ratio provided by TSM.

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