Thailand low and equatorial F_2-layer peak electron density and comparison with IRI-2007 model

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Ionosonde measurements obtained at two Thailand ionospheric stations, namely Chumphon (10.72°N, 99.37°E, dip 3.0°N) and Chiang Mai (18.76°N, 98.93°E, dip 12.7°N) are used to examine the variation of the F_2-layer peak electron density (N_mF_2) which is derived from the F_2-layer critical frequency, f_oF_2. Measured data from September 2004 to August 2005 (a period of low solar activity) are analyzed based on the diurnal and seasonal variation and then compared with IRI-2007 model predictions. Our results show that, in general, the diurnal and seasonal variations of the N_mF_2 predicted by the IRI (URSI and CCIR options) model show a feature generally similar to the observed N_mF_2. Underestimation mostly occurs in all seasons except during the September equinox and the December solstice at Chumphon, and the September equinox and the March equinox at Chiang Mai, when they overestimate those measured. The best agreement between observation and prediction occurs during the pre-sunrise to post-sunrise hours. The best agreement of the %PD values of both the options occurs during the March equinox, while the agreement is the worst during the September equinox. The N_mF_2 values predicted by the CCIR option show a smaller range of deviation than the N_mF_2 values predicted by the URSI option. During post-sunset to morning hours (around 21:00–09:00 LT), the observed N_mF_2 at both stations are almost identical for the periods of low solar activity. However, during daytime, the observed N_mF_2 at Chumphon is lower than that at Chiang Mai. The difference between these two stations can be explained by the equatorial ionospheric anomaly (EIA). These results are important for future improvements of the IRI model for N_mF_2 over Southeast Asia, especially for the areas covered by Chumphon and Chiang Mai stations.
Key words: Equatorial latitude, ionosonde, ionogram, IRI model, N_mF_2, solar activity.

1. Introduction

The ionosonde is one of the most widely-used instruments for studying ionospheric variability, which is important for a better understanding of the ionosphere and the design of HF, VHF and UHF communication systems. The F_2-layer peak electron density (N_mF_2) is an important parameter which is derived from the F_2-layer critical frequency (f_oF_2) measured by ionosondes. This parameter is used for the development and improvement of ionospheric models, such as the International Reference Ionosphere (IRI) (Bilitza, 2001). The IRI is a widely-used global empirical ionospheric model, which describes the electron density, electron temperature, ion temperature and ion composition in the altitude range of approximately 50 to 1,500 kilometers, for a given location, time and sunspot number. Many improvements have been made to this model (IRI-80, IRI-90, IRI-95, IRI-2000 and IRI-2001). The most recent update was released in 2007, known as IRI-2007 (Bilitza and Reinisch, 2008). The most important changes in IRI-2007 are: (1) two new options for the topside electron density, (2) a new model for the topside ion composition, (3) the first-time inclusions of a model for the spread F occurrence probability, (4) a Neural Net model for the auroral D-region electron densities, (5) a model for the plasmasphere electron temperature and (6) the latest International Geomagnetic Reference Field (IGRF) model for the computation of magnetic coordinates, including their changes due to the secular variation of the magnetic field. The IRI model has two options for the prediction of the N_mF_2: one is the model developed by the International Radio Consultative Committee, namely CCIR (CCIR, 1966) and the other is the model developed by the International Union of Radio Science, namely URSI (Rush *et al.*, 1989). The CCIR options are based on monthly median values obtained by a worldwide network of ionosondes (about 150 stations). The URSI options are based on both ionosonde data (about 180 stations) and the values obtained by aeronomic theory for filling the data gaps above the oceans and in the southern hemisphere.

The observed ionospheric data in many parts of the world have been analyzed by investigating the diurnal and seasonal variations, and then compared with the IRI model. In Africa, the variations of the F_2 peak parameters obtained by the ionosonde at Ouagadougou (12.4°N, 1.5°W, dip 5.9°N), Burkina Faso and Korhogo (9.3°N, 5.4°W, dip 0.67°S), Cote-d'Ivoire, were compared with IRI model predictions (Adeniyi *et al.*, 2003; Obrou *et al.*, 2003; Bilitza *et*

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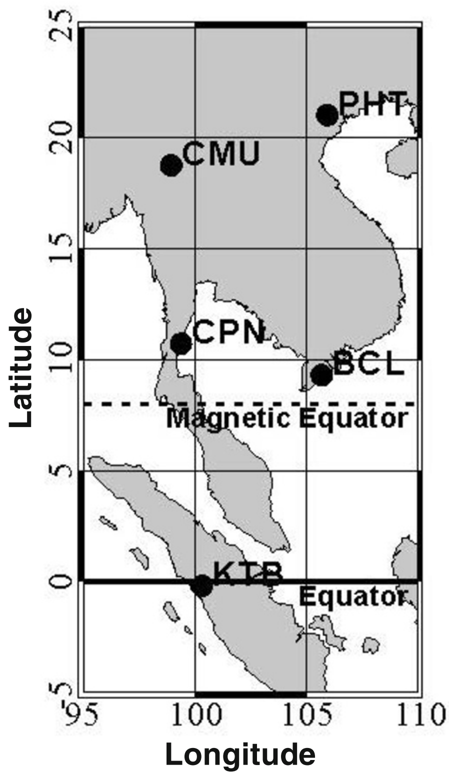

Fig. 1. Locations of the five ionosonde stations in the SEALION project-project {Phu Thuy (PHT), Chiang Mai (CMU), Chumphon (CPN), Bac Lieu (BCL), Koto Tabang (KTB)}.

al., 2004). In South America, a comparison was made between the results from the IRI model and the ionospheric data collected by digisondes located at Sao Luis (2.6°S, 44.2°W, dip 0.5°S), Cachoeira Paulista (22.5°S, 45°W, dip 28°S), Palmas (10.7°S, 45.20°W, dip 10.8°S), Sao Jose dos Campos (23.20°S, 45.86°W, dip 38.41°S), Brazil, and Jicamarca (12.0°S, 76.9°W, dip 1.0°N), Peru, and the data measured by the ionosonde at Tucuman (26.9°S, 294.6°E), Argentina (Batista and Abdu, 2004; Bertoni *et al.*, 2006; Lee and Reinisch, 2006; Lee *et al.*, 2008; Ezquer *et al.*, 2008). In Europe, Ratovsky *et al.* (2009) compared the observed ionospheric data with the IRI model at Irkutsk (52.3°N, 104.3°E), Russia. In Asia, Zhang *et al.* (2007), Sethi *et al.* (2007), Chuo and Lee (2008), Ayub *et al.* (2009), Wichaipanich *et al.* (2010) compared the IRI model results with experimental data at Hainan (19.4°N, 109.0°E, dip 22.8°N), China, New Delhi (28.6°N, 77.2°E, dip 42.4°N), India, Chung-Li (24.9°N, 121.1°E, dip 35°N), Taiwan, Karachi (24.95°N, 67.14°E), Islamabad (33.75°N, 72.87°E), Pakistan, and Chumphon (10.72°N, 99.37°E, dip 3.0°N), Thailand, respectively. Although studies of the observed ionospheric data are common in many parts of the world, only a few studies of ionospheric conditions have been carried out for the region over Southeast Asia.

Since 2003, two frequency modulate-continuous waves (FM/CW) ionosondes have been installed at two stations in Thailand, one is close to the magnetic equator, namely Chumphon (CPN) and the other is close to the northern crest of the Equatorial Ionization Anomaly (EIA), namely Chiang Mai (CMU). Both stations are two of the 5 SEALION (South East Asia Low-latitude Ionospheric Network) ionosondes supported by the National Institute of Information and Communications Technology (NICT), Japan. The other SEALION ionosondes consist of one station in Indonesia, namely Koto Tabang (KTB), and two stations in Viet Nam, namely Bac Lieu (BCL) and Phu Thuy (PHT). All of the SEALION ionosonde stations are shown in Fig. 1. SEALION is an ionospheric observation network for studying the equatorial ionosphere at a magnetic conjugate point and is named the Conjugate Point Equatorial Experiment (COPEX) in South East Asia. The COPEX includes the northern and southern hemispheres and around the magnetic equator. In this paper, we take F_2-layer peak electron density ($N_\mathrm{m}F_2$) data derived from the F_2-layer critical frequency ($f_\mathrm{o}F_2$), which is manually scaled from bottomside ionograms recorded by the FM/CW ionosonde at Chumphon and Chiang Mai, and compare these data with the IRI-2007 model. This is a continuation of a previous study (Wichaipanich *et al.*, 2010) on F_2-layer peak parameters measured by a FM/CW ionosonde at Chumphon province, Thailand, and a comparison with the IRI-2001 model.

2. Data and Methodology

The data used in this study are collected by two FM/CW ionosonde (Maruyama *et al.*, 2007) stations at Chumphon campus of King Mongkut's Institute of Technology Ladkrabang, Chumphon province (10.72°N, 99.37°E, dip angle: 3.0°N), denoted by CPN, and Chiang Mai University, Chiang Mai province (18.76°N, 98.93°E, dip angle: 12.7°N), denoted by CMU, Thailand. The CPN station is near the magnetic equator while the CMU station is near the northern crest of the Equatorial Anomaly. The FM/CW ionosonde is a type of transceiver that continuously transmits a radio frequency signal in the range of 2–30 MHz into the ionosphere and receives an echo. The echo returns to the receiver and is collected as a photographic display, called an ionogram. The ionogram is used to infer the structure of the E and F-layers which illustrate virtual height (h') versus frequency (f). In this work, the ionograms are every 15 minutes and manually scaled. The obtained F_2-layer critical frequency ($f_\mathrm{o}F_2$) values are converted into $N_\mathrm{m}F_2$ according to (Davies, 1990), i.e.,

$$N_\mathrm{m}F_2 = 1.24\,(f_\mathrm{o}F_2)^{\,2} \times 10^{10}, \tag{1}$$

where $N_\mathrm{m}F_2$ is in electron/m^3 and $f_\mathrm{o}F_2$ is the F_2-layer critical frequency in MHz.

The monthly hourly medians and the seasonally hourly medians of $N_\mathrm{m}F_2$ at Chumphon and Chiang Mai for four seasons, including the September equinox (September and October in 2004), the December solstice (November, December in 2004 and January and February in 2005), the March equinox (March and April in 2005), and the June solstice (May, June, July and August in 2005), have been plotted and compared with the IRI model predictions.

For the comparison between observation and the model, both the URSI and CCIR options of the IRI-2007 model are used to predict the $N_\mathrm{m}F_2$ values, which can be downloaded from the site: http://ccmc.gsfc.nasa.gov/modelweb/models/iri_vitmo.php.

Fig. 2. The observed $N_{\rm m}F_2$ and IRI-2007 model predictions (left panels) and the percentage deviation between data and model (right panels) at Chumphon station for different seasons from September 2004 to August 2005.

In addition, the $N_{\rm m}F_2$ percentage deviation (PD) is computed from

$$\%\text{PD} = \frac{(N_{\rm m}F_{2\rm IRI} - N_{\rm m}F_{2\rm obs})}{N_{\rm m}F_{2\rm obs}} \times 100\%, \qquad (2)$$

where $N_{\rm m}F_{2\rm IRI} = N_{\rm m}F_{2\rm URSI}$ for the URSI option and $N_{\rm m}F_{2\rm IRI} = N_{\rm m}F_{2\rm CCIR}$ for the CCIR option. The parameter $N_{\rm m}F_{2\rm obs}$ is derived from the $f_{\rm o}F_2$ observations obtained from the ionosondes at Chumphon and Chiang Mai stations.

3. Results and Discussions

3.1 Chumphon station

Figure 2 shows the diurnal variations in the $N_{\rm m}F_2$ parameter versus local time (LT) at Chumphon station. The left panels are the observed $N_{\rm m}F_2$ labeled as $N_{\rm m}F_{2\rm obs}$ compared with the predicted $N_{\rm m}F_2$ values from the URSI and CCIR options of the IRI-2007 model, labeled as $N_{\rm m}F_{2\rm URSI}$ and $N_{\rm m}F_{2\rm CCIR}$, respectively, and the right panels show the $N_{\rm m}F_2$ percentage deviation (%PD) of both options in each of the four seasons from September 2004 to August

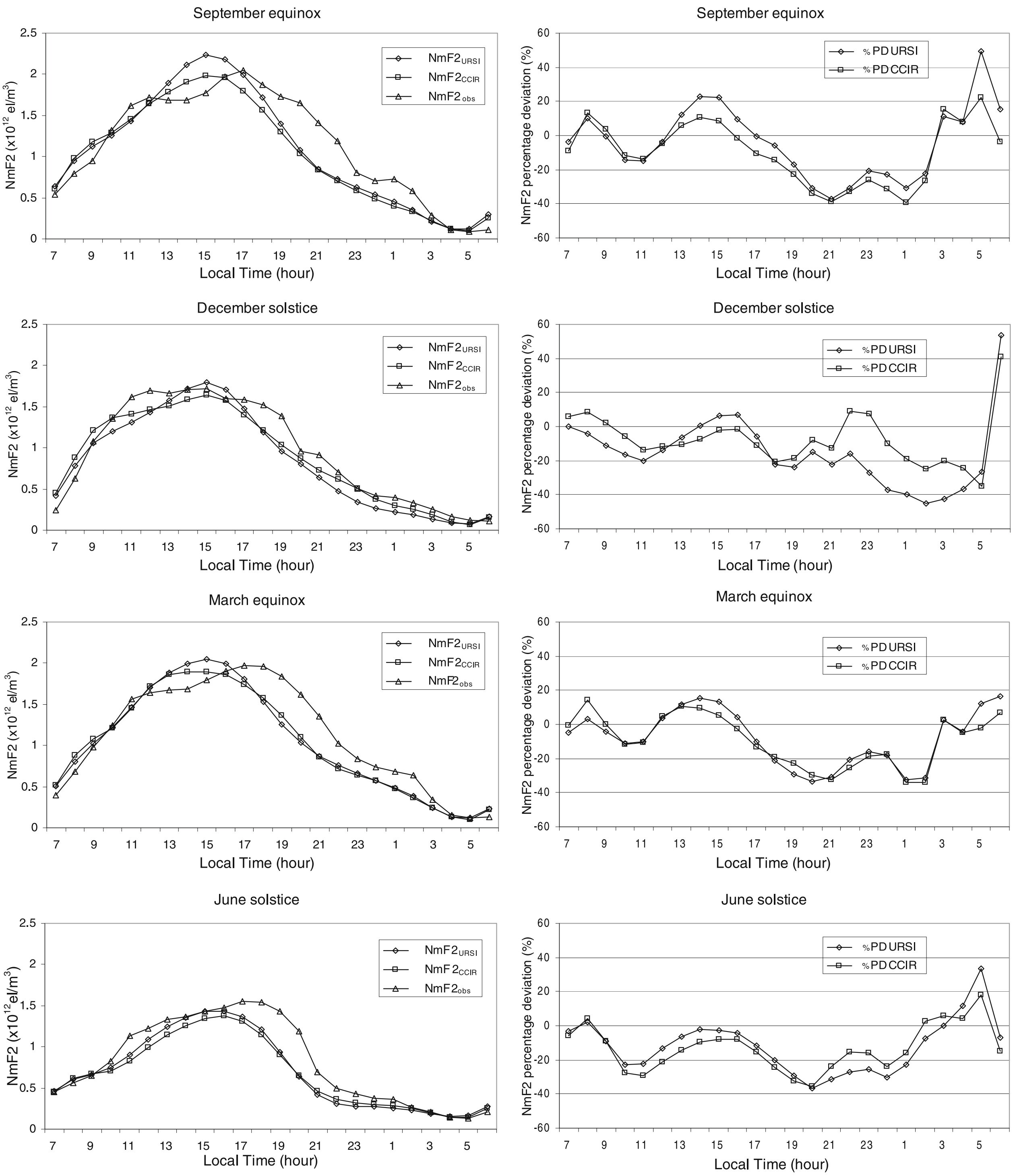

Fig. 3. The observed N_mF_2 and IRI-2007 model predictions (left panels) and the percentage deviation between data and models (right panels) at Chiang Mai station for different seasons.

2005. In the left panels, most the results show similar trends in the variation of N_mF_2, increasing during sunrise hours (around 06:00 LT), reaching the highest values in the pre-sunset hours (around 17:00–19:00 LT) with a noon bite-out around 11:00–13:00 LT, and decreasing during post-sunset hours, until the lowest levels occur during pre-sunrise hours (around 05:00 LT). For the September equinox, both $N_mF_{2\mathrm{URSI}}$ and $N_mF_{2\mathrm{CCIR}}$ overestimate $N_mF_{2\mathrm{obs}}$ during the daytime hours except during the morning hours (around 06:00–09:00 LT), when $N_mF_{2\mathrm{URSI}}$ underestimates, but $N_mF_{2\mathrm{CCIR}}$ overestimates, $N_mF_{2\mathrm{obs}}$. During the post-sunset hours (around 19:00–21:00 LT), both $N_mF_{2\mathrm{URSI}}$ and $N_mF_{2\mathrm{CCIR}}$ underestimate $N_mF_{2\mathrm{obs}}$. For the night-time, $N_mF_{2\mathrm{URSI}}$ predicts values close to $N_mF_{2\mathrm{obs}}$, but $N_mF_{2\mathrm{CCIR}}$ underestimates $N_mF_{2\mathrm{obs}}$. For the December solstice season, both $N_mF_{2\mathrm{URSI}}$ and $N_mF_{2\mathrm{CCIR}}$ underestimate $N_mF_{2\mathrm{obs}}$ during the daytime hours except during post-noontime to sunset hours, when they overestimate those observed. During the night-time, $N_mF_{2\mathrm{URSI}}$ is close to $N_mF_{2\mathrm{obs}}$, but $N_mF_{2\mathrm{CCIR}}$ underestimates the measured

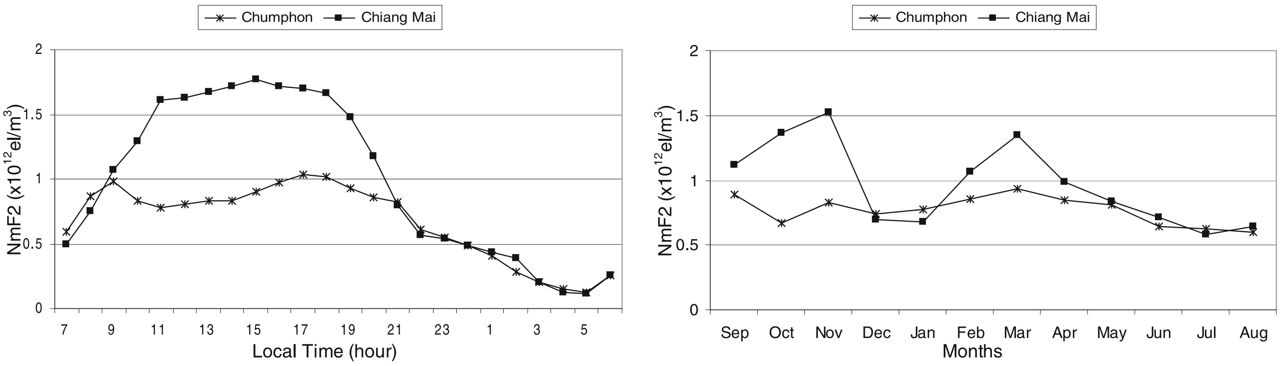

Fig. 4. Diurnal variation of hourly medians of N_mF_2 over all months (left panel) and the annual variation of the monthly N_mF_2 median values (right panel) at Chumphon and Chiang Mai stations.

results during 20:00–01:00 LT. For the March equinox, $N_mF_{2\mathrm{obs}}$ is higher than $N_mF_{2\mathrm{URSI}}$ during daytime, but is lower than $N_mF_{2\mathrm{CCIR}}$. For night-time, both $N_mF_{2\mathrm{URSI}}$ and $N_mF_{2\mathrm{CCIR}}$ underestimate $N_mF_{2\mathrm{obs}}$, especially during 21:00–00:00 LT, but are close to $N_mF_{2\mathrm{obs}}$ during the pre-sunrise hours. The results for the June solstice show that the $N_mF_{2\mathrm{CCIR}}$ model is close to $N_mF_{2\mathrm{obs}}$, but $N_mF_{2\mathrm{URSI}}$ underestimates $N_mF_{2\mathrm{obs}}$ during the daytime, except during 14:00–17:00 LT when both $N_mF_{2\mathrm{URSI}}$ and $N_mF_{2\mathrm{CCIR}}$ overestimate $N_mF_{2\mathrm{obs}}$. In the right panels, the results of the N_mF_2 percentage deviation (%PD) of the CCIR options for the four seasons show a similar feature: the %PD values vary between around ±27% during daytime to pre-midnight hours, the lowest levels occur around 18:00 LT (±5%), fluctuations during post-midnight to pre-sunrise hours (±45%) except during the September equinox, when it reaches 80%. The results of the %PD of the CCIR option show a good agreement during daytime for all seasons when compared with the %PD of the URSI option, especially during the March equinox (±20%). The agreement between prediction and observation is the worst during night-time, especially for the %PD of the CCIR option during the September equinox.

3.2 Chiang Mai station

Similarly, we compared the observed N_mF_2 and the IRI model, and the N_mF_2 percentage deviations (%PD) at Chiang Mai station, which are shown in Fig. 3. In the left panel of Fig. 3, the N_mF_2 values for the September equinox show that both $N_mF_{2\mathrm{URSI}}$ and $N_mF_{2\mathrm{CCIR}}$ predict N_mF_2 values close to $N_mF_{2\mathrm{obs}}$ during pre-sunrise to the morning hours (around 03:00–09:00 LT), but they underestimate $N_mF_{2\mathrm{obs}}$ during 10:00–02:00 LT, except during the hours 13:00–15:00 LT when they overestimate $N_mF_{2\mathrm{obs}}$. For the December solstice season, both $N_mF_{2\mathrm{URSI}}$ and $N_mF_{2\mathrm{CCIR}}$ underestimate $N_mF_{2\mathrm{obs}}$ between the hours of 10:00–13:00 LT and 17:00–21:00 LT. In addition, $N_mF_{2\mathrm{URSI}}$ underestimates the observed data except during 15:00–16:00 LT, when it overestimates $N_mF_{2\mathrm{obs}}$. In the March equinox season, good predictions are provided by the URSI and CCIR options for the hours of 03:00–09:00 LT. However, both $N_mF_{2\mathrm{URSI}}$ and $N_mF_{2\mathrm{CCIR}}$ underestimate the observed data during the hours of 10:00–11:00 LT and 17:00–02:00 LT, and they overestimate during the hours of 13:00–15:00 LT. During the June solstice season, most of the results show that both $N_mF_{2\mathrm{URSI}}$ and $N_mF_{2\mathrm{CCIR}}$ underestimate $N_mF_{2\mathrm{obs}}$, except during 02:00–08:00 LT, when they are close to $N_mF_{2\mathrm{obs}}$. In the right panels, the %PD values vary between −25 and 22% during the daytime for both the URSI and CCIR options. For night-time, the results of both the options show the %PD values vary between −40 and −20% during post-sunset to post-midnight hours except during the December solstice, when the %PD values for the CCIR option vary between −20 and +10%. During pre-sunrise hours, the %PD values increase and reach the highest level of 50% especially during the December solstice, when the %PD for the URSI option reaches 50%. For all the seasons, in general, the %PD values for the CCIR option are better than the %PD values for the URSI option. The best agreement of the %PD values for both the URSI and CCIR options occurs during the March equinox.

3.3 Comparing N_mF_2 at Chumphon and Chiang Mai

The comparison between the observed N_mF_2 at the Chumphon and Chiang Mai stations are shown in Fig. 4. The left panel shows the hourly medians of all the months of N_mF_2 values and the right panel shows the monthly hourly medians of N_mF_2 values for both stations. The left panel shows that the observed N_mF_2 at both stations are almost identical during post-sunset to morning hours (around 21:00–09:00 LT), but during the daytime, the observed N_mF_2 at Chiang Mai appear much higher than that at Chumphon. The right panel shows that the observed N_mF_2 values at Chiang Mai station are higher than those at Chumphon station during the equinox seasons, while a similarity is seen during the solstice seasons except during November and February. The maximum N_mF_2 values for each season at both stations are tabulated in Table 1 and this shows that the difference in N_mF_2 values between the stations is highest during the September equinox and lowest during the June solstice. In other words, the maximum monthly N_mF_2 values during the equinox seasons are higher than that for other seasons, but they are at lower levels during the solstice seasons.

The observed N_mF_2 at Chiang Mai are higher than that at Chumphon during the daytime which can be explained by the Equatorial Anomaly (Anderson, 1973). The equatorial and low-latitude regions show some unique behavior when compared with middle and high latitudes. The vertical electromagnetic drift is enhanced and the Equatorial Ionization

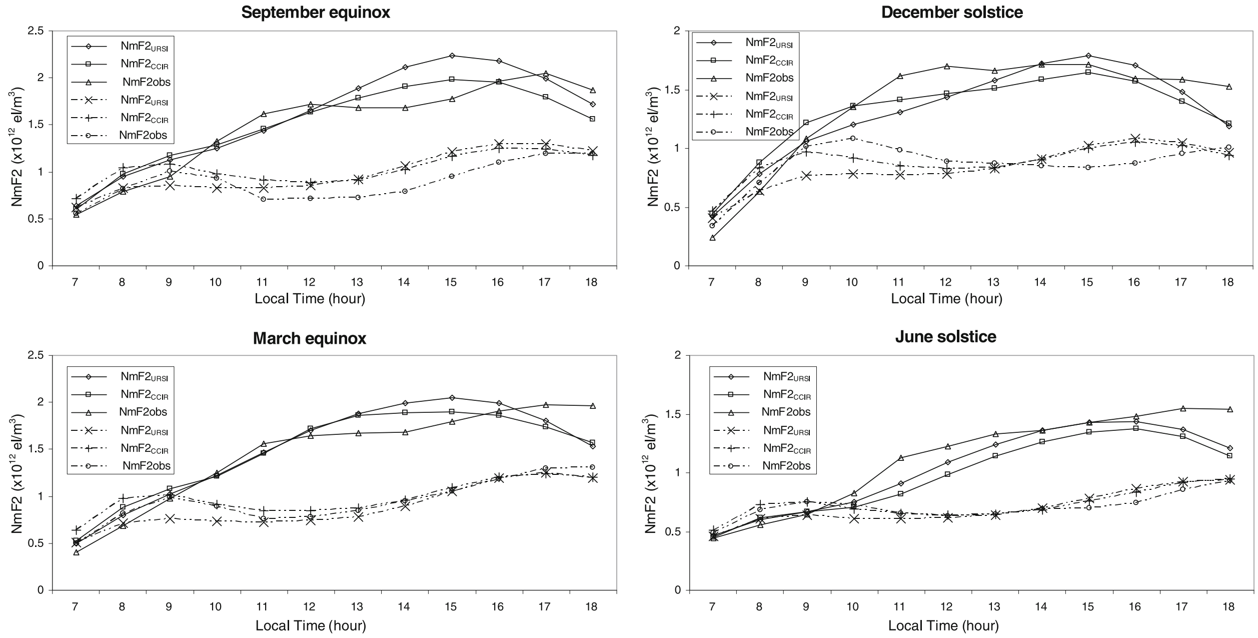

Fig. 5. The observed N_mF_2 and IRI-2007 model predictions during the daytime hours at Chumphon and Chiang Mai stations for different seasons.

Table 1. Maximum seasonal hourly medians of N_mF_2 ($\times 10^{12}$ electron/m^3).

Seasons	Chumphon	Chiang Mai	Difference in N_mF_2 between stations
September equinox	1.19	2.00	0.81
December solstice	1.07	1.71	0.64
March equinox	1.32	2.01	0.69
June solstice	0.94	1.55	0.61

Anomaly (EIA) is intensified resulting in variations in the F-layer at equatorial and low-latitudes as follows: the F-layer is lifted up at the magnetic equator but the peak density decreases, however, the F-layer peak density increases at the crest of the anomaly (located at approximately 15° north and south of the magnetic latitude, moderated by the meridional wind from the magnetic equator to the crests of the anomaly). While Chumphon is close to the magnetic equator (Geomagnetic dip latitude +3.0°N), Chiang Mai is located at the northern anomaly crest (Geomagnetic dip latitude +12.7°N), causing higher N_mF_2 median values at Chiang Mai. The location of both stations in relation to the Equatorial Anomaly explains the differences in electron density between the two stations.

Figure 5 is the same as Fig. 2, but for Chumphon (dashed lines) and Chiang Mai (solid lines) stations during the daytime hours. Generally, $N_mF_{2\mathrm{obs}}$, $N_mF_{2\mathrm{URSI}}$ and $N_mF_{2\mathrm{CCIR}}$ at Chumphon station are lower than those at Chiang Mai station in all seasons.

When compared with previous studies for periods with low solar activity, our results are similar to the study of Ayub *et al.* (2009) at two Pakistan low-latitude stations, namely Karachi and Islamabad, in that the IRI model predicts N_mF_2 values close to the observed N_mF_2 during presunrise to pre-noon (around 03:00–09:00 LT), but a difference occurred during daytime, when they found that the IRI/URSI model overestimates $N_mF_{2\mathrm{obs}}$, while our results show an underestimation. Furthermore, they found that the observed N_mF_2 values at Karachi are higher than that at Islamabad due to the equatorial anomaly. While Karachi is located in the EIA, Islamabad is outside the anomaly, explaining the higher N_mF_2 median values and bite-outs at Karachi. The maximum N_mF_2 values reach a peak during the equinox seasons and a minimum level during the solstice seasons. In addition, our results differ from the study of Ezquer *et al.* (2008) at Tucuman, Argentina, in that good predictions are provided by the URSI option for night-time and the agreement between prediction and measurement is worst during the June solstice in that the %PD varies between −50 and 80% during the prenoontime hours (10:00–11:00 LT), while our results show good predictions from the CCIR option, with a disagreement between prediction and measurement occurring during the September equinox where the %PD varies between −70 and +80% during night-time at Chumphon station and between −40 and +50% during night-time at Chiang Mai station. Furthermore, our results differ from the studies of Lee and Reinisch (2006) and Lee *et al.* (2008) at the equatorial latitude station in Peru, namely Jicamarca, in that both the URSI and CCIR options of the IRI-2007 model are generally close to the observed values, but our results show that both models underestimate observed values during the midnight and pre-sunrise hours, especially in 2005. This underestimation is consistent with the results of Wichaipanich *et al.* (2010) although, in that work, f_oF_2 is studied from 2004–2006.

4. Conclusions

This paper presents the monthly hourly median values of the F_2-layer peak electron density (N_mF_2) during September 2004 to August 2005, a period of low solar activity, as compared with the IRI-2007 model. A summary of all the results from Chumphon and Chiang Mai stations are as follows.

1. The diurnal and seasonal variations of N_mF_2 predicted by the IRI (URSI and CCIR options) model generally show the same features as the observed N_mF_2.
2. In most cases both the URSI and CCIR options underestimate the observed N_mF_2 except during the September equinox and the December solstice at Chumphon, and the September equinox and the March equinox at Chiang Mai, when they overestimate $N_mF_{2\text{obs}}$.
3. The best agreement between observation and prediction occurs during pre-sunrise to post-sunrise hours (around 03:00–09:00 LT).
4. The best percentage agreement occurs during the March equinox for Chumphon and Chiang Mai stations.
5. The worst %PD values are found during night-time during the September equinox for both stations with the highest value observed at Chumphon, where %PD reaches 80% for the CCIR option.
6. Although both the URSI and CCIR options of the IRI model predict N_mF_2 close to the $N_mF_{2\text{obs}}$ especially during daytime, the CCIR option produces a smaller range of deviation than the URSI option.
7. During post-sunset to morning hours (around 21:00–09:00 LT), the observed N_mF_2 at both stations are almost identical for the periods of low solar activity. However, during daytime, the observed N_mF_2 values at Chiang Mai are larger than those at Chumphon due to the higher dip angle related to the Equatorial Anomaly.
8. A bite-out phenomenon is clearly seen during noontime hours (around 11:00 LT) at Chumphon for all seasons, but it rarely occurs during the equinox seasons at Chiang Mai.

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References

Adeniyi, J. O., D. Bilitza, S. M. Radicella, and A. A. Willoughby, Equatorial F2-peak parameters in the IRI model, *Adv. Space Res.*, **31**(3), 507–512, 2003.

Anderson, D. N., A theoretical study of the ionosphere F region equatorial anomaly. II: Results in the American and Asian sectors, *Planet Space Sci.*, **21**, 421–442, 1973.

Ayub, M., S. Iqbal, M. A. Ameen, and B. W. Reinisch, Study of maximum electron density NmF2 at Karachi and Islamabad during solar minimum (1996) and solar maximum (2000) and its comparison with IRI, *Adv. Space Res.*, **43**, 1821–1824, 2009.

Batista, I. S. and M. A. Abdu, Ionospheric variability at Brazilian low and equatorial latitude: Comparison between observations and IRI model, *Adv. Space Res.*, **34**, 1894–1900, 2004.

Bertoni, F., Y. Sahai, P. R. Fagundes, V. G. Pillat, F. B. Guedes, and J. R. Abalde, IRI-2001 model predictions compared with ionospheric data observed at Brazilian low latitude stations, *Ann. Geophys.*, **24**, 2191–2200, 2006.

Bilitza, D., International Reference Ionosphere 2000, *Radio Sci.*, **36**(2), 261–275, 2001.

Bilitza, D. and B. W. Reinisch, International Reference Ionosphere 2007: Improvements and new parameters, *Adv. Space Res.*, **42**, 599–609, 2008.

Bilitza, D., O. K. Obrou, J. O. Adeniyi, and O. Oladipo, Variability of foF2 in the equatorial ionosphere, *Adv. Space Res.*, **34**, 1901–1906, 2004.

CCIR: Comite Consultatif International des Radio communications, Reports, 340-1 and 340-6, *International Telecommunication Union*, Geneva, Switzerland, 1966.

Chuo, Y. J. and C. C. Lee, Ionospheric variability at Taiwan low latitude station: Comparison between observations and IRI-2001 model, *Adv. Space Res.*, **42**, 673–681, 2008.

Davies, K., in *Ionospheric Radio*, edited by Clarricoats, P. J. B., Y. Rahmat-Samii, and J. R. Wait, 580 pp., Peter Peregrinus Ltd., London, United Kingdom, 1990.

Ezquer, R. G., M. Mosert, L. Scida, and J. Lopez, Peak characteristics of F2 region over Tucuman: Predictions and measurements, *Atmos. Terr. Phys.*, **70**, 1525–1532, 2008.

Lee, C. C. and B. W. Reinisch, Quiet-condition hmF2, NmF2, andB0 variations at Jicamarca and comparison with IRI-2001 during solar maximum, *Atmos. Terr. Phys.*, **68**, 2138–2146, 2006.

Lee, C. C., B. W. Reinisch, S. Y. Su, and W. S. Chen, Quiet-time variations of F2-layer parameters at Jicamarca and comparison with IRI-2001 during solar minimum, *Atmos. Terr. Phys.*, **70**, 184–192, 2008.

Maruyama, T., M. Kawamura, S. Saito, K. Nozaki, H. Kato, N. Hemmakorn, T. Boonchuk, T. Komolmis, and C. Ha Duyen, Low latitude ionosphere-thermosphere dynamics studies with ionosonde chain in Southeast Asia, *Ann. Geophys.*, **25**, 1569–1577, 2007.

Obrou, O. K., D. Bilitza, J. O. Adeniyi, and S. M. Radicella, Equatorial F2-layer peak height and correlation with vertical ion drift and M(3000)F2, *Adv. Space Res.*, **31**(3), 513–520, 2003.

Ratovsky, K. G., A. V. Oinats, and A. V. Medvedev, Diurnal and seasonal variations of F2 layer characteristics over Irkutsk during the decrease in solar activity in 2003–2006: Observations and IRI-2001 model predictions, *Adv. Space Res.*, **43**, 1806–1811, 2009.

Rush, C., M. Fox, D. Bilitza, K. Davies, L. Mcnamara, F. Stewart, and M. Pokempner, Ionospheric mapping—an update of foF2 coefficients, *Telecomm. J.*, **56**, 179–182, 1989.

Sethi, N. K., R. S. Dabas, and Y. Ninawe, foF2 variability over New Delhi during different solar cycle conditions and comparison with IRI-2001 model, *Adv. Space Res.*, **40**, 855–860, 2007.

Wichaipanich, N., P. Supnithi, M. Ishii, and T. Maruyama, Ionospheric variations at Thailand equatorial latitude station: Comparison between observations and IRI-2001 model predictions, *Adv. Space Res.*, **45**, 284–293, 2010.

Zhang, M. L., J. K. Shi, X. Wang, S. P. Shang, and S. Z. Wu, Ionospheric behavior of the F2 peak parameters foF2 and hmF2 at Hainan and comparisons with IRI model predictions, *Adv. Space Res.*, **39**, 661–667, 2007.

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