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Variability of the behavior of the bottomside (B0, B1) parameters obtained from the ground-based ionograms at China's low latitude station

M.-L. Zhang [a,*], W. Wan [a], L. Liu [a], J.K. Shi [b]

[a] Institute of Geology and Geophysics, Chinese Academy of Sciences, P.O. Box 9825, 100029 Beijing, PR China

[b] Key Laboratory for Space Weather, Center for Space Science and Applied Research, Chinese Academy of Sciences, P.O. Box 8701, 100080 Beijing, PR China

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Abstract

In this paper, data of (B0, B1) parameters deduced from the electron density profiles that are inverted from the ionograms recorded at Hainan (19.4°N, 109.0°E), China during a three year period from March 2002 to February 2005 are used to study the diurnal and seasonal variation of (B0, B1) parameters at low latitude. The observational results are compared with the IRI2001 model predictions. Variability study of (B0, B1) in terms of percentage ratio of the inter-quartiles to the median values and correlative analysis between (B0, B1) parameters and other ionospheric characteristics such as *hm*F2 and M(3000)F2 are also made. Our present study showed that: (1) for daytime hours, the IRI2001 model results with new table option (B0_Tab) is in a better agreement with the observational results (B0_Obs) than the IRI2001 model results with Gulyaeva option (B0_Gul) for summer season, whereas B0_Gul is in a better agreement with B0_Obs than B0_Tab for winter season. For nighttime, in general, B0_Gul is in a better agreement with B0_Obs than B0_Tab. For other occasions, both B0_Tab and B0_Gul showed some systematic deviations from the observational ones. Moreover, the deviations of B0_Tab and B0_Gul from B0_Obs showed opposite trends; (2) the monthly upper (lower) quartiles of (B0, B1) parameter showed a good linear relationship with the monthly median values, this makes it possible to do the regression analysis between the monthly upper (lower) quartiles and the monthly median values, which can give a measure of the variability of these parameters. In terms of the percentage ratio of the inter-quartiles to the median values, the variability of B0 showed a diurnal variation ranging between 22% and 36% with maximum value occurring at pre-sunrise hours, whereas the variability of B1 showed a diurnal variation ranging between 15% and 30% with higher value by daytime than at night; (3) B0 shows high linear correlative relationships with *hm*F2 and M(3000)F2 for most of the local time period of a day except for a few hours around midnight, whereas B1 showed high linear correlations with B0, *hm*F2 for daytime hours, but not for nighttime hours. This suggests that it maybe is possible to obtain the synthetic database of (B0, B1) parameter or to construct the model of (B0, B1) using database of *hm*F2 or M(3000)F2 which is much easier to obtain from experimental measurements.

Keywords: Low latitude ionosphere; Ionospheric variability; IRI model; Ionospheric modeling

1. Introduction

The International Reference Ionosphere (IRI), which was developed by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI), is a widely used global empirical model of the ionosphere. It specifies monthly averages of the ionospheric plasma parameters for given location, time and date (Bilitza, 1990, 2001). IRI was developed, and is updated periodically, by a joint working group of COSPAR and URSI. Since its first release in 1978, many improvements

* Corresponding author. Fax: +86 10 62010846.
E-mail address: zhangml@mail.iggcas.ac.cn (M.-L. Zhang).

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had been made to this model (Rawer et al., 1978; Bilitza, 1990, 1997, 2001, 2003; Bilitza et al., 2000). In the current version, IRI2001, many new changes have been made to this model (Bilitza, 2001, 2003). One of the most important changes made is the inclusion of a new table of (B0, B1) values that is an achievement after various attempts made through a series of IRI Task Force Activities (Radicella et al., 1998; Bilitza et al., 2000).

In IRI, the electron density $N(h)$ profile for the bottomside F2 layer is described by the following analytic function in terms of the F2 peak density NmF2, the F2 peak height hmF2, the bottomside thickness parameter B0 and the shape parameter B1 (Bilitza, 1990):

$$N(h) = Nm\mathrm{F2} \cdot \frac{\exp(-x^{\mathrm{B1}})}{\cosh(x)}, \quad x = \frac{hm\mathrm{F2} - h}{\mathrm{B0}} \tag{1}$$

Therefore, B0 and B1 are two key parameters to specify the entire profile. IRI offers two options for B0 parameter; standard table and Gulyaeva's option. The Gulyaeva's option is based on the model for half density height $h0.5$ (Gulyaeva, 1987), which is defined as the height where the bottomside electron density drops to half of the F2 peak density: $N(h0.5) = 0.5Nm\mathrm{F2}$. In the earlier versions of IRI, the standard table of B0 values was deduced from ionograms recorded at three middle latitude stations (Mexico City, Huancayo, Lindau), and the B0 value for magnetic equatorial latitudes is based on extrapolation. Testing and validation studies by many people using different datasets showed shortcomings of both options, in particular for the low and equatorial latitudes (Mahajan et al., 1995; Pandey and Sethi, 1996; De Gonzalez, 1996; Aggarwal et al., 1996; Adeniyi, 1997; Zhang and Huang, 1998; Adeniyi and Radicella, 1998; and others). In view of this, in 1995, the IRI taskforce group decided to establish a new table of B0 values directly from the measured bottomside profiles. Based on the analysis of a large volume of ionosonde data in the framework of the ICTP Task Force Activities (Bilitza et al., 2000), a new table of B0 values was assembled for different latitudes, times of day, levels of solar activity, and seasons and this new table of B0 values are included into the most updated version of IRI model (IRI2001). This new table of B0 values is a great improvement over the previous table of B0 values, in particular near the magnetic equator, where the previous IRI B0 model was based on extrapolations rather than experimental data. However, recent studies using different datasets showed that large discrepancies still exist between the (B0, B1) values calculated using the new table of (B0, B1) values and the experimental ones even after the improvement mentioned above (Sethi and Mahajan, 2002; Lei et al., 2004; Zhang et al., 2004a; Chen et al., 2006; Sethi et al., 2007). In the present study, we will use the experimental data from China's low latitude station, Hainan (geographical coordinates: 19.4°N, 109.0°E; geomagnetic coordinates: 8.0°N, 178.9°E, DIP 22.8°), which is not used when establishing the new table of (B0, B1) values, to study in detail the variation of (B0, B1) parameters and compare them with the IRI2001 results.

2. Data used and methodology

The bottomside electron density profiles, inverted from the ionograms recorded at Hainan, China are used to deduce the (B0, B1) parameters through best-fitting approaches. Since IRI model represents an average ionosphere, we use the monthly median data for the present study. Time resolution of the data for the diurnal variation is one hour. Time coverage of the data is for a 3-year period from March 2002 to February 2005.

The (B0, B1) values used for present study are obtained this way: the recorded ionograms, after manually editing with SAO-explorer software for quality control, are converted to the true height electron density profiles by the NHPC program (Huang and Reinisch, 1996) which is embodied in the SAO-explorer software developed by University of Lowell Massachusetts, Center for Atmospheric Research (Sao Explorer, Interactive Ionogram Scaling Technologies, http://ulcar.uml.edu/SAO-X/SAO-X.html; Reinisch et al., 2004).

Then the obtained true height electron density profiles are fitted, in a least-square-fitting approach and using the observational NmF2 and hmF2 value as anchor point, with Eq. (1) using a FORTRAN subroutine provided by J.E. Titheridge (1995, personal communication). The profile fitting is made from hmF2 to $h0.24$ (the altitude where the electron density equals to $0.24Nm\mathrm{F2}$) if no F1-layer exists or to the F1 peak if an F1-layer occurs. The monthly median values and quartiles of (B0, B1) parameters are then calculated from the individually best-fitted (B0, B1) values. Hereafter the observational B0 and B1 are referred to as B0_Obs and B1_Obs.

3. Results

3.1. Diurnal and seasonal variation of (B0, B1)

Figs. 1(a) and (b) show, respectively, the contour plots of the monthly median values of B0_Obs and B1_Obs versus local time and month during March 2002 to February 2005. It can be seen that both B0_Obs and B1_Obs showed very well defined seasonal and diurnal variation patterns. B0_Obs has highest peak values at hours around local noontime in summer and has lowest values at hours around midnight at equinoctial months. A special feature worthy of noting is the collapse of B0 values around sunrise hours for equinoctial and winter seasons and this collapse effect is stronger in winter than in equinox. This sunrise collapse feature for equinoctial-winter seasons has also been observed in Wuhan station (Chen et al., 2006) with ground-based ionogram data and in Millstone Hill (Lei et al., 2004) with incoherent scatter radar measurements. Results predicted by IRI2001 model (Figs. 1(c)–(e)) showed that this feature is more or less reflected in the Gulyaeva B0

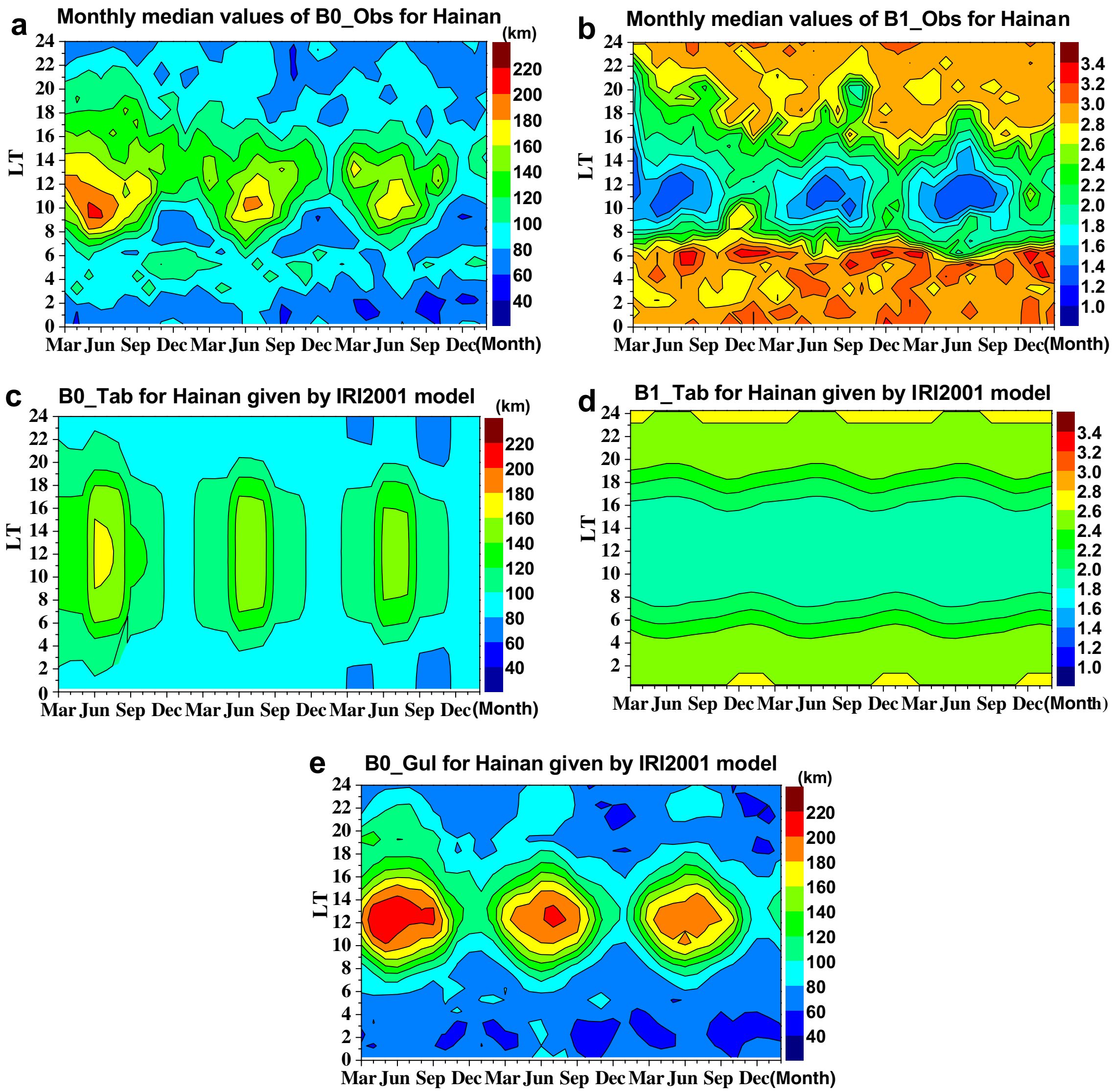

Fig. 1. Diurnal and seasonal variation of (a) B0_Obs, (b) B1_Obs, (c) B0_Tab, (d) B1_Tab and (e) B0_Gul for Hainan during March 2002 to February 2005.

option results but not in the new B0-Table option results. For B1 parameter, the observational B1_Obs showed strong diurnal and seasonal dependences. B1_Obs has the lowest value of about 1.2 occurring at hours around local noon time in summer season and it has higher values during nighttime hours than during daytime hours for all seasons. The highest value of B1_Obs is about 3.4 which occurred near sunset hours

3.2. Comparison with IRI model results

IRI model offers two options for B0 and B1 parameters. One is based on the newly updated table of (B0, B1) values (referred to as B0_Tab, B1_Tab hereafter), and the other is the B0 value based on Gulyaeva-*h*0.5 (Gulyaeva, 1987; Bilitza, 1990) with B1 = 3 (referred to as B0_Gul, B1_Gul hereafter). Figs. 1(c)–(e) show the contour plots of B0_Tab, B1_Tab and B0_Gul, respectively. Comparing Figs. 1(c) and (e) with Fig. 1(a), it is evidently shown that there are some systematic discrepancies between observational B0 and those predicted by IRI2001 model. Line plots showing the variations of the observed and IRI2001 model predicted B0 parameter at fixed local time for 00LT, 06LT, 12LT and 18LT are shown in Figs. 2(a)–(d), respectively. The difference between the IRI model results with both options and the observational ones for B0 and B1 parameters are calculated and shown in Figs. 3(a)–(c).

Fig. 3(a) shows the contour plots of the diurnal and seasonal variation of the difference between the results predicted by IRI2001 with B0_Tab option and those obtained with the experimental data ($\Delta B0 = B0\_Tab - B0\_Obs$). It can be seen that around local noontime hours B0_Tab in general underestimates the B0_Obs values, especially for the spring season of the year 2002 which probably is due to its being higher solar activity period. However, there is exception for the summer season in which

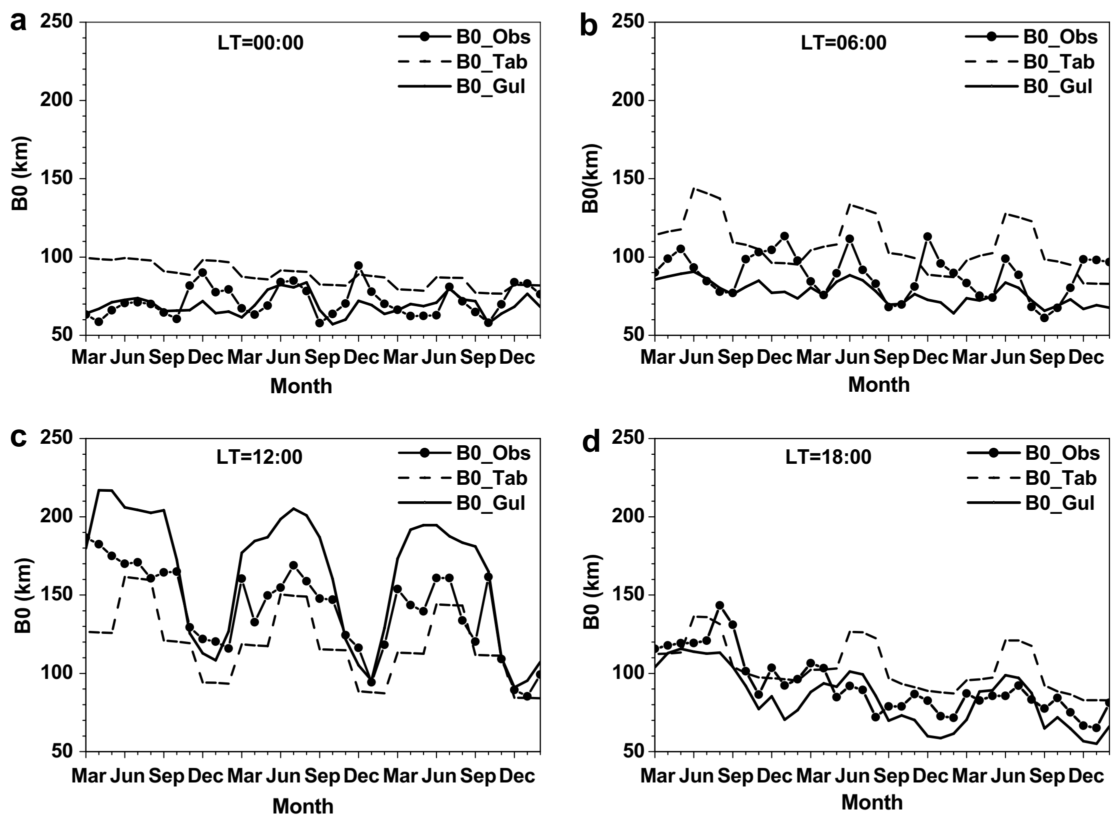

Fig. 2. Variations of B0_Obs, B0_Tab and B0_Gul at fixed local time during March 2002 to February 2005 for Hainan, China.

B0_Tab is reasonably in good agreement with B0_Obs. For the time around sunrise hours, B0_Tab overestimates B0_Obs, in particular for the autumn season. For the time around sunset hours in summer season, B0_Tab overestimates B0_Obs, whereas for the winter season B0_Tab is in reasonable good agreement with B0_Obs.

Fig. 3(b) is similar to Fig. 3(a) but for the results with Gulyaeva-B0 option (ΔB0 = B0_Gul − B0_Obs). As can be seen in Fig. 3(b), the difference between B0_Gul and B0_Obs has a strong diurnal and seasonal dependence, i.e., B0_Gul showed a systematic deviations from B0_Obs. It largely overestimated B0_Obs during daytime post-noon hours in summer but agreed reasonably well with B0_Obs in winter; and for the pre-sunrise hours, B0_Gul slightly underestimates B0_Obs except for the equinoctial seasons where B0_Gul showed reasonably good agreement with B0_Obs; whereas for other time periods, results given by B0_Gul option agreed reasonably well with B0_Obs.

The results showed above indicate that the deviations of the IRI2001 model results from the observational ones showed opposite trends for two options. That is, when B0_Tab tends to overestimate the B0_Obs, B0_Gul tends to underestimate B0_Obs, and vice versa. These opposite trends can be seen clearly in Fig. 2.

For the B1 parameter, it was found that B1_Obs deduced from the experimental data has larger diurnal and seasonal amplitude of changes than the results given by IRI2001 model. For the years studied here, the monthly median values of B1_Obs changed between 1.2 (daytime in summer season) and 3.4 (nighttime in winter season), whereas B1 values given by IRI2001 model with (B0, B1)_Tab option changes between 1.9 for daytime and 2.6 for nighttime and with only a small seasonal changes. The result for the difference between the B1_Tab and B1_Obs is shown in Fig. 3(c). It is observed that B1_Tab overestimates B1_Obs at the hours around local noontime, whereas for the hours around sunrise, B1_Tab underestimates B1_Obs for all seasons. For the hours around sunset, B1_Tab underestimates B1_Obs, in particular for the winter season.

These results indicate that the deviations of B0_Tab and B1_Tab from the B0_Obs and B1_Obs values showed opposite trends. That is, when B0_Tab deviated negatively from B0_Obs, B1_Tab deviated positively from B1_Obs and vice versa.

3.3. Variability of (B0, B1)

We have also studied the relationship of the monthly upper and lower quartiles with the monthly medians for B0 and B1 parameters. Fig. 4 shows the scatter plots of the monthly upper and lower quartiles versus monthly median values of the best fitted B0 and B1 parameters for all data used in the present study. It is observed that both the monthly upper and lower quartiles showed a very

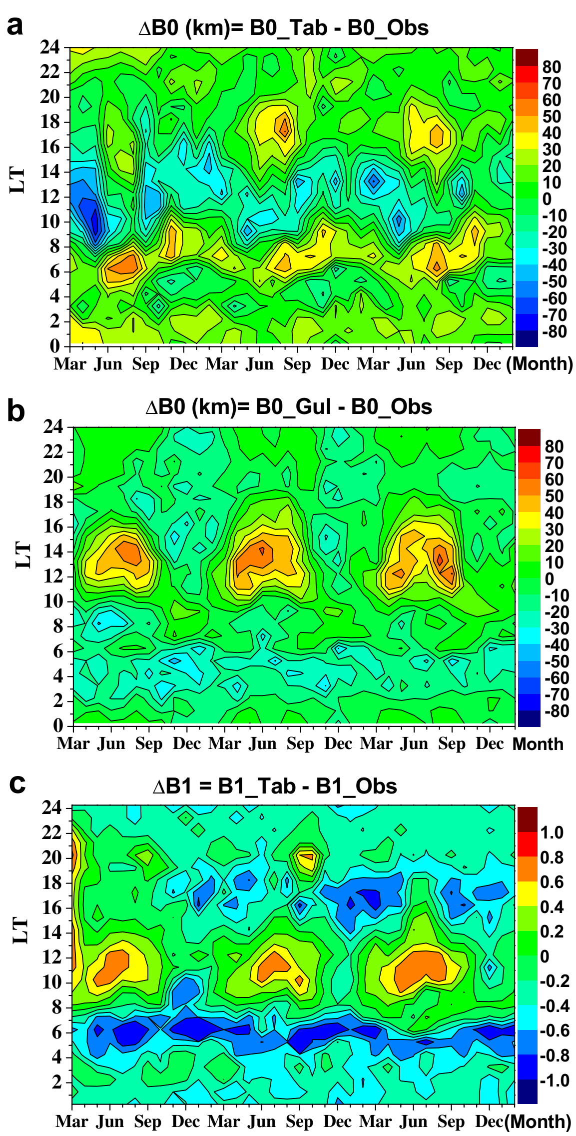

Fig. 3. Diurnal and seasonal variation of (a) B0_Tab – B0_Obs, (b) B0_Gul – B0_Obs and (c) B1_Tab – B1_Obs for Hainan during March 2002 to February 2005.

good linear relationship with the monthly median values. This suggests that it is reasonable to do regression analysis between the monthly upper (lower) quartiles and the monthly median values. The regression analysis results are shown in Fig. 5 that plots the diurnal variations of the regression coefficient CU and CL of Uqt = CU ∗ Med and Lqt = CL ∗ Med obtained for B0 and B1 parameters, respectively. In Fig. 5, the thin curves are the results obtained when the data are divided into 12-month year groups (March 2002–February 2003, March 2003–February 2004 and March 2004–February 2005). It can be seen that CU and CL of (B0, B1) showed a well defined diurnal variation pattern. The thick curves are the results obtained when all the 3-year data are used together. It is observed that CU and CL for (B0, B1) are more or less symmetric to each other against the value of 1.

The percentage ratio of the inter-quartiles to the median value defined as InterQuartiles/Median ∗ 100(%) can be used as a measure of the variability of a parameter (Zhang et al., 2004b). It is easy to prove that InterQuartiles/Median ∗ 100% = (CU − CL) ∗ 100%. Fig. 6 shows the diurnal variation of InterQuartiles/Median ∗ 100(%) for B0 and B1 parameters. It can be seen that in terms of the percentage ratio of the inter-quartiles to the median value, B0 has the largest variability around pre-sunrise hours, but has the smallest variability around post-sunrise and post-sunset hours, whereas the variability of B1 has larger values by daytime than at night. Moreover, the magnitude of the variability of B0 is larger than that of B1, in particular for nighttime hours. The variability of the B0 changed between 22% and 36% with maximum value occurring at pre-sunrise hours, whereas the variability of the B1 changed between 15% and 30%.

3.4. Correlation analysis of (B0, B1) with hmF2, M(3000)F2

We have also studied the correlative relationships of (B0, B1) with the F2 peak height *hm*F2 and the transmit factor M(3000)F2 parameters. Fig. 7(a) plots the local time variation of the correlation coefficients *R* obtained by correlation analysis between the observed B0 and *hm*F2 (B0–*hm*F2) and between B0 and M(3000)F2 (B0–M(3000)F2)

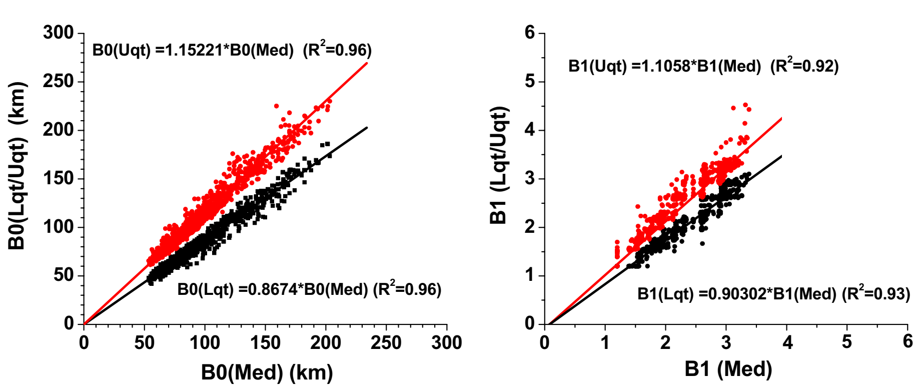

Fig. 4. Scatter plots of the monthly lower and upper quartiles of the observational B0 (left panel) and B1(right panel) parameters versus their monthly median values for Hainan, China.

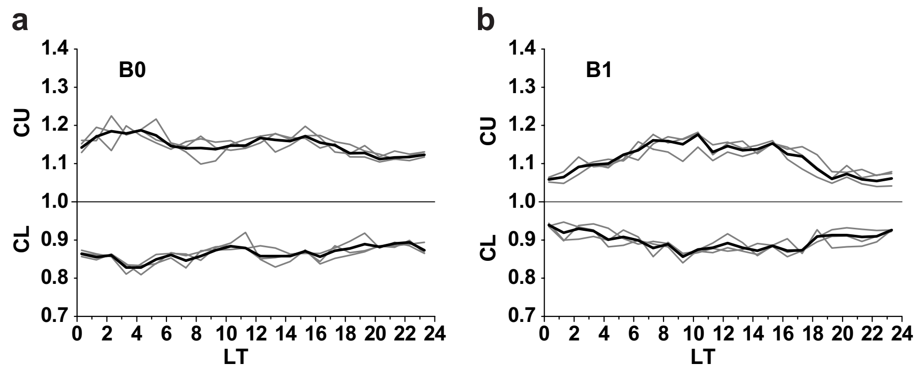

Fig. 5. Diurnal variations of the regression coefficients CU and CL for (a) B0 and (b) B1.

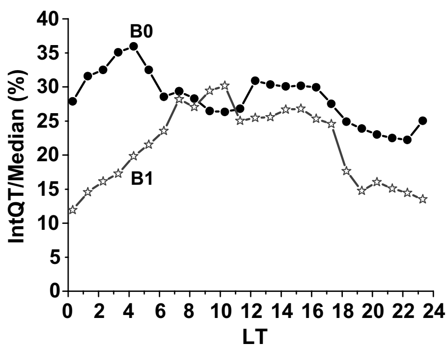

Fig. 6. Diurnal variations of the percentage ratios of inter-quartiles to monthly median value for B0 and B1.

for each hour's data. The correlation coefficient R can be regarded as an indicator of the 'goodness of fit' when a scatter linear fitting is made between two parameters. It can be seen in Fig. 7(a) that B0 has a good linear relationship with *hm*F2 and M(3000)F2 during most local time period of a day except for a few hours around local midnight. Moreover, B0 is highly positively correlated with *hm*F2, and highly negatively correlated with M(3000)F2 (or highly positively correlated with 1/M(3000)F2). Similar correlation analysis results for B1 with *hm*F2, M(3000)F2 as well as B0 are shown in Fig. 7(b). It can be seen that B1 showed high negative linear correlations with B0 and *hm*F2 for daytime hours, but not for nighttime hours.

These correlation analysis results imply that it maybe is possible to obtain the synthetic database of (B0, B1) parameter or to construct the model of (B0, B1) using the *hm*F2 or M(3000)F2 which is easier to obtain from experimental measurements.

4. Summary and discussion

In the present study, we have used experimental data obtained at Hainan (19.4°N, 109.0°E), China for a period of three years to study the diurnal and seasonal variation of (B0, B1) parameters and their comparison with IRI2001 model results are also made. We also studied the variability of (B0, B1) in terms of the percentage ratio of the inter-quartiles to the median values. Correlation analysis between the (B0, B1) parameters and the ionospheric characteristics *hm*F2 and M(3000)F2 are also made. From the present study, the following remarks can be made:

(1) For daytime hours, B0_Tab is in a better agreement with B0_Obs than B0_Gul for summer season, whereas B0_Gul is in a better agreement with B0_Obs than B0_Tab for winter season. For the nighttime, in general, B0_Gul is in a better agreement with B0_Obs than B0_Tab. For other occasions, both B0_Tab and B0_Gul showed some systematic deviations from the observational B0_Obs. Moreover, the deviations of B0_Tab and B0_Gul from B0_Obs

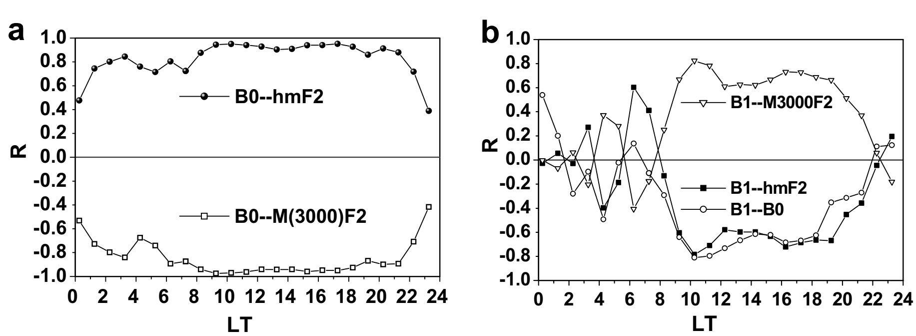

Fig. 7. Diurnal variations of the correlation coefficient R for (a) B0–*hm*F2 and B0–M(3000)F2 and (b) B1–*hm*F2, B1–M(3000)F2 and B1–B0.

showed opposite trends: B0_Tab underestimated the B0_Obs values around noon-time hours (equinox and winter) but overestimated the B0_Obs values at pre-sunrise hours (in equinox and summer), whereas B0_Gul largely overestimated the B0_Obs values around noon-time hours, in particular for summer season, but slightly underestimates the B0_Obs value at pre-sunrise hours.

(2) The deviations of the B0_Tab and B1_Tab results from their observational values showed opposite trends, in particular for the hours around local noon-time. This must stem from the high negative correlative relationship found between the B0 and B1 parameter, as shown in Fig. 7(b).

(3) The high linear correlative relationships found between the monthly upper (lower) quartiles of (B0, B1) with their monthly median values makes it possible to do the regression analysis between the monthly upper (lower) quartiles and the monthly median values, which gives a measure of the variability of the parameters.

(4) In terms of the percentage ratio of the inter-quartiles to the median value, the variability of the B0 showed a diurnal variation ranging between 22% and 36% with maximum value occurring at pre-sunrise hours, whereas the variability of the B1 showed a diurnal variation ranging between 15% and 30% with higher value by daytime than at night.

(5) B0 shows high linear correlations with *hm*F2 and M(3000)F2 for most of the local time period of a day except for a few hours around midnight, whereas B1 showed high linear correlations with B0, *hm*F2 for daytime hours, but not for nighttime hours.

The results obtained in the present study indicate that database or model of (B0, B1) used in the current IRI version need to be updated for the low latitude regions for further improvement to be made. Developing local models using database from individual single stations, like the work down by Blanch et al. (2007) for the mid-latitude, maybe is a good start in this direction. The problem is that at present, for low latitude regions, there seems no available database of (B0, B1) with enough length of time accumulation for this kind of modeling study.

The results obtained in this paper showed that (B0, B1) is highly linearly correlated with *hm*F2 and M(3000)F2 during daytime hours. Although the results obtained in this paper are for the particular station of Hainan, it is worth mentioning that a recent study made by Sethi et al. (2007) using data of high solar activity year (2001–2002) from Indian's low latitude station New Delhi (28.61N, 77.21E, dip 42.41N) also showed good linear correlation between B0 and *hm*F2 for daytime hours. Similar investigation for other low latitude stations would be useful. The high correlation found between (B0, B1) and *hm*F2, M(3000)F2 during daytime hours in the present study and that by Sethi et al. (2007) maybe has a significant implication that it is possible to obtain the synthetic database of (B0, B1) parameter or to construct the model of (B0, B1) using database of *hm*F2 or M(3000)F2 which is easier to obtain from experimental data.

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