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Accuracy of h_mF2 estimations, including IRI-2020 options and ionograms validated parameters, compared to ISR measurements at Millstone Hill

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Abstract

Several empirical formulations used over time to estimate the fundamental ionospheric parameter h_mF2 have been compared in this study. These are the first formulation proposed by Shimazaki (1955) (SHI-1955) as a function of the propagation parameter M(3000)F2, the more accurate BSE-1979 formula proposed by Bilitza et al. (1979) and firstly adopted by the International Reference Ionosphere (IRI) model, and the newest Altadill-Magdaleno-Torta-Blanch (AMTB-2013) (Altadill et al., 2013) and SHU-2015 (Shubin, 2015) models, obtained with a different approach with no explicit dependence on any ionospheric parameter and added as alternative options in the IRI-2016. The evaluation of the accuracy of the available formulation is performed by comparing the modeled values of h_mF2 with those simultaneously obtained with independent measurements from the Incoherent Scatter Radar (ISR) installed at the Millstone Hill ionospheric station. The database considered consists of 3626 measurements, thus allowing the evaluation of the results for different heliogeophysical conditions. SHI-1955 and BSE-1979 formulations are evaluated also using input data manually scaled from ionograms recorded at the same location, with the aim of evaluating their accuracy when updated with validated data rather than modeled ones. The SHU-2015 is confirmed the best option in any condition, while AMTB-2013 turns out to perform poorly during night, when SHI-1955 and BSE-1979 fed by validated data can be used for trend analyses due to the high correlation with ISR data. Despite this, BSE-1979 performs better with modeled parameters as input, in terms of RMSE and mean deviation from ISR data. The use of SHI-1955 with CCIR-modeled M(3000)F2 is discouraged under daytime conditions even for long trend analyses.

Keywords: h_mF2; IRI-2020; ISR; Ionosonde

1. Introduction

The altitude of maximum electron density in the ionosphere (h_mF2) has a great importance in all models that have interest for radio propagation applications. Among the models currently available, the empirical International Reference Ionosphere (IRI) model (Bilitza et al., 2022) is the most used one by the ionospheric community as a reference, providing the primary ionospheric parameters on the basis of the long data record available from ground and space observations of the ionosphere. The first estimation of h_mF2 was performed using the formulation by Shimazaki (1955) (SHI-1955), which uses the strong anti-correlation of h_mF2 with the propagation factor M(3000)F2, defined as MUF(3000)F2/f_oF2, being f_oF2 the critical frequency of the ionospheric F2 layer (i.e., the highest frequency at which the ionosphere reflects vertically), and MUF(3000)F2 the Maximum Usable

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Frequency for establishing a 3,000 km radiolink for a signal being refracted in the ionosphere. Due to its simplicity, the SHI-1955 formulation still finds application in different contexts, such as the studies on the ionospheric long-term trends (see e.g., McNamara, 2008; Elias et al., 2017; Perrone et al., 2017). However, being based on the oversimplified assumptions of an F2-layer with no underlying ionization and no magnetic field, in general it cannot be considered sufficiently accurate for modeling purposes. Hence, it was subsequently improved by more sophisticated expressions which are also based on the anti-correlation between h_mF2 and M(3000)F2, but consider the distribution of ionization below the F2 peak through the ratio f_oF2/f_oE, being f_oE the critical frequency of the E layer (see e.g., Dudeney, 1983 and references therein). Among those formulations, the one adopted and still used in the IRI model was the so-called Bilitza-Eyfrig-Sheikh (BSE-1979) (Bilitza et al., 1979), which explicitly includes an empirical dependence also on the solar activity and Earth's magnetic field through the 12-month running mean of the sunspot number (R_{12}) and the dip latitude (λ_m), respectively. All these formulations are usually fed with values of the ionospheric parameters provided by global models, although data from different sources could be easily ingested.

However, the limitations of the M(3000)F2 approach for modeling h_mF2 have been highlighted in several studies. For instance, according to Adeniyi et al. (2003), a relevant cause of limitation is due to the uncertainty introduced with the formula describing the relationship between h_mF2 and M(3000)F2, because it is only an approximation depending on several assumptions. Besides, the use of a model based on M(3000)F2 makes it very difficult to assimilate the measured values of h_mF2 into the IRI model for a real-time update. Such measurements are real-time available from modern ionosondes. Due to these limitations of the h_mF2 modeling with this approach, the IRI Panel had placed a high priority on the development of new h_mF2 models, resulting in a great effort in this direction by the entire IRI community (Bilitza et al., 2022 and references therein).

As a consequence, in IRI-2016 (Bilitza et al., 2017) two new options for the description of h_mF2 were added to the pre-existing BSE-1979. These two new formulations are the Altadill-Magdaleno-Torta-Blanch (AMTB-2013) (Altadill et al., 2013) and the SHU-2015, named after Shubin (2015), both using spherical harmonic expansions to model measured h_mF2 values, with a dependence on the solar activity embedded in the coefficients and no dependence on any ionospheric parameter. The AMTB-2013 was developed using data from 1998 and 2006 recorded by 26 digisondes (Altadill et al., 2013). The SHU-2015 was developed by Shubin et al. (2013) and subsequently extended by Shubin (2015) using data from 62 digisondes for the years 1987–2012 along with ionospheric radio occultation measurements from COSMIC (2006–2012), CHAMP (2001–2008) and GRACE (2007–2011). The two new options introduced in IRI-2016 also have the advantage of providing the user community the opportunity to assess the h_mF2 model estimates in comparison with other datasets to provide valuable feedback of uncertainty and discrepancy from the true h_mF2 value (Huang et al., 2021).

Some studies have been carried out in recent years to evaluate the performance of the different formulations of h_mF2 used in IRI, using Millstone Hill's Incoherent Scatter Radar (ISR) data for comparison: the SHU-2015 model emerged out to be the best in predicting the h_mF2 values as compared to the other two available options (Huang et al., 2021; Mengist et al., 2020). Besides, a study performed on the African sector demonstrated that the SHU-2015 model option manifests the least prediction error, best model efficiency, and correlation with the COSMIC h_mF2 values (Moses et al., 2021). For these reasons, SHU-2015 is now the recommended (and default) option in the IRI model, although BSE-1979 and AMTB-2013 are also available.

The aim of this paper is to study the performance of the different formulations available in the IRI model to estimate h_mF2, completing the analysis with the data obtained by manually scaling the ionograms recorded at Millstone Hill. The introduction of manually scaled data allows to perform a completely new comparative test including also the SHI-1955 and the BSE-1979 formulations in which the ionograms validated parameters are ingested, instead of values provided by global models.

2. Materials and methods

In this work, an initial dataset of 9058 $N_e(h)$ profiles recorded by the Incoherent Scatter Radar installed at Millstone Hill (42.6°N, 288.5°E) in the period from April 1997 to December 2017, together with ionograms recorded by the co-located Digisonde, has been considered to evaluate the performance of the different models that can be used for the estimation of h_mF2. The parameters f_oF2 and M(3000)F2 were manually scaled from such ionograms by an expert operator to include in the comparison the formulas which can be updated with measured data. For this reason we considered only those ionograms for which the critical frequency f_oF2 can be reliably scaled by the operator and it is also scaled by the ARTIST autoscaling software (Huang and Reinisch, 1996). The manual scaling was performed using the Interpre software through which M(3000)F2 is automatically calculated dividing the MUF(3000)F2 value by f_oF2, where MUF(3000)F2 is scaled from the ionograms through the transmission curve method (Pezzopane, 2004). The matching of manually scaled and ARTIST f_oF2 values with the ISR observations within 0.1 MHz, in line with International Union of Radio Science (URSI) standard (Piggot and Rawer, 1972), has been then imposed to avoid affecting the analysis with incorrect data. Besides, cases of h_mF2 values from ISR lower than 200 km were also discarded for the same reason.

In this way, it has been possible to select a validated dataset of 3626 cases actually used in the study.

For the comparison object of this study, the following models for the estimation of h_mF2 were considered:

(a) SHI-1955-UP, the formulation provided by Shimazaki (1955) upgraded with M(3000)F2 manually scaled from the ionograms;
(b) BSE-1979-UP, the formulation provided by Bilitza, Eyfrig and Sheikh (Bilitza et al., 1979) upgraded with M(3000)F2 and f_oF2 manually scaled from the ionograms;
(c) SHU-2015, the model provided by Shubin (2015);
(d) AMTB-2013, the model provided by Altadill, Magdaleno, Torta and Blanch (Altadill et al., 2013);
(e) SHI-1955-CCIR, the formulation provided by Shimazaki (1955) fed with M(3000)F2 obtained through from Consultative Committee on International Radio (CCIR) numerical maps (CCIR, 1967) based on the work of Jones and Gallet (1962, 1965) and Jones et al. (1969);
(f) BSE-1979-CCIR, the formulation provided by Bilitza, Eyfrig and Sheikh (Bilitza et al., 1979) fed with M(3000)F2 and f_oF2 from CCIR and URSI models respectively (default options in the IRI for such parameters).

Specifically, in SHI-1955 (a) and (e) and BSE-1979 (b) and (f) options, the h_mF2 values are computed through the following formulation:

$$h_mF2 = \frac{1490}{M(3000)F2 + \Delta M} - 176, \tag{1}$$

with the difference in M(3000)F2 estimation as described above and in which ΔM = 0 for SHI-1955, while for BSE-1979 it is estimated as:

$$\Delta M = \frac{\phi_1 \cdot \phi_2}{y - \phi_3} + \phi_4, \tag{2a}$$

with

$$\phi_1 = 0.00232 \cdot R_{12} + 0.222, \tag{2b}$$

$$\phi_2 = 1 - \frac{R_{12}}{150} \cdot \exp\left[-\left(\frac{\lambda_m}{40}\right)^2\right], \tag{2c}$$

$$\phi_3 = 1.2 - 0.0116 \cdot exp\left(\frac{R_{12}}{41.84}\right), \tag{2d}$$

$$\phi_4 = 0.096 \cdot \frac{R_{12} - 25}{150} \tag{2e}$$

and

$$y = \frac{f_oF2}{f_oE}, \tag{2f}$$

where a lower limit of 1.7 is set for y to avoid unrealistically low h_mF2 values which can be obtained under exceptionally low solar minimum conditions, as those occurred during the years 2008–2009.

All the options except the SHI-1955 ones (a) and (e) are computed through the IRI model computer program in which manually scaled or IRI modeled M(3000)F2 and f_oF2 values are used for the two BSE-1979 options (b) and (f), respectively, while according to their formulation SHU-2015 and AMTB-2013 options do not involve the ingestion of ionospheric parameters. Finally, f_oE in Eq. (2f) for both the BSE-1979 options is modeled by the IRI model as well (see e.g., Bilitza et al., 2022 and references therein).

The deviations $h_m\text{F2}_{[\text{mod}]} - h_m\text{F2}_{[\text{ISR}]}$ with the symbols being self-evident in meaning, were computed for the h_mF2 data across the whole dataset for each model. For each distribution of deviations, the average error Δ and the root mean square error (RMSE) were calculated as:

$$\Delta = \sum_{i=1}^{n} \frac{h_mF2_{[mod]i} - h_mF2_{[ISR]i}}{n}, \tag{3}$$

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{\left(h_mF2_{[mod]i} - h_mF2_{[ISR]i}\right)^2}{n}}, \tag{4}$$

being n the total number of data of the distribution.

The study is performed considering nocturnal (solar zenith angle $\chi > 110°$) and diurnal ($\chi < 70°$) conditions separately, under quiet and disturbed ionospheric conditions. Quiet conditions were considered when $|(f_o\text{F2}_{[\text{man}]} - f_o\text{F2}_{[\text{mod}]})/f_o\text{F2}_{[\text{mod}]}| \leq 0.2$ and disturbed conditions when $|(f_o\text{F2}_{[\text{man}]} - f_o\text{F2}_{[\text{mod}]})/f_o\text{F2}_{[\text{mod}]}| > 0.2$, being $f_o\text{F2}_{[\text{man}]}$ the f_oF2 value manually scaled from the ionogram and $f_o\text{F2}_{[\text{mod}]}$ the corresponding IRI modeled value, assumed as a reference.

3. Results and discussion

In Figs. 1(a-l)–4(a-l) the deviations $h_m\text{F2}_{[\text{mod}]} - h_m\text{F2}_{[\text{ISR}]}$ are reported in the form of histograms with the corresponding scatter plots $h_m\text{F2}_{[\text{mod}]}$ versus $h_m\text{F2}_{[\text{ISR}]}$ and their linear regressions in quiet daytime, quiet night-time, perturbed diurnal, and perturbed nocturnal conditions respectively, for the different models used. The results of the t-Student's test are also displayed in each figure.

From the results reported in the figures, some interesting features in the behavior of the models under investigation in the different conditions can be drawn.

First of all, SHU-2015 is confirmed as the most efficient formulation, with a slight tendency to overestimate ISR values under quiet conditions, and to underestimate under perturbed state. For this model, in any condition, it results $|\Delta| \leq 8.6$ km. It should be stressed that the accuracy of h_mF2 determination is around ±10 km at the Millstone Hill ISR (Ulich, 2000). Besides, Student's t-test fails in quiet conditions at night. In these conditions, in fact, there is a very small $|\Delta|$ value ($|\Delta| = 0.1$). It must be concluded that the difference between the average value of the observed data and the one obtained with the SHU-2015 is not statistically significant, confirming the good performance provided by the

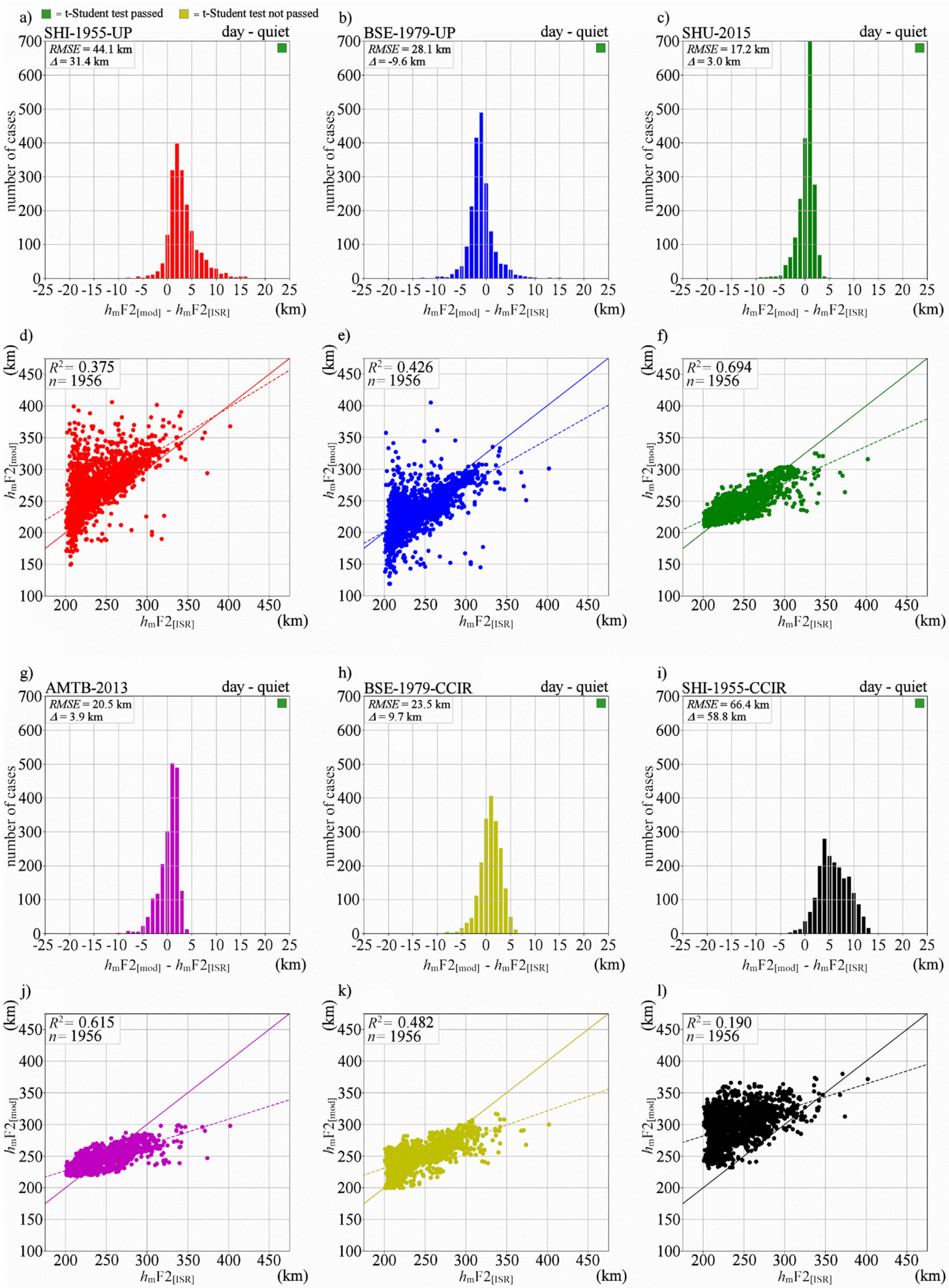

Fig. 1. Histograms of the deviations $h_mF2_{[mod]} - h_mF2_{[ISR]}$ with the corresponding statistical parameters, along with the scatter plots $h_mF2_{[mod]}$ versus $h_mF2_{[ISR]}$ and linear regressions (dotted lines) with the corresponding coefficient of determination and number of total number of paired data in quiet daytime conditions, for the different models used: SHI-1955-UP in red (a, d); BSE-1979-UP in blue (b, e); SHU-2015 in green (c, f); AMTB-2013 in purple, (g, j); BSE-1979-CCIR in yellow (h, k); SHI-1955-CCIR in black (i, e). The solid lines represent the bisectors. The results of the t-Student's test are also displayed as green squares if the test is passed and yellow squares otherwise.

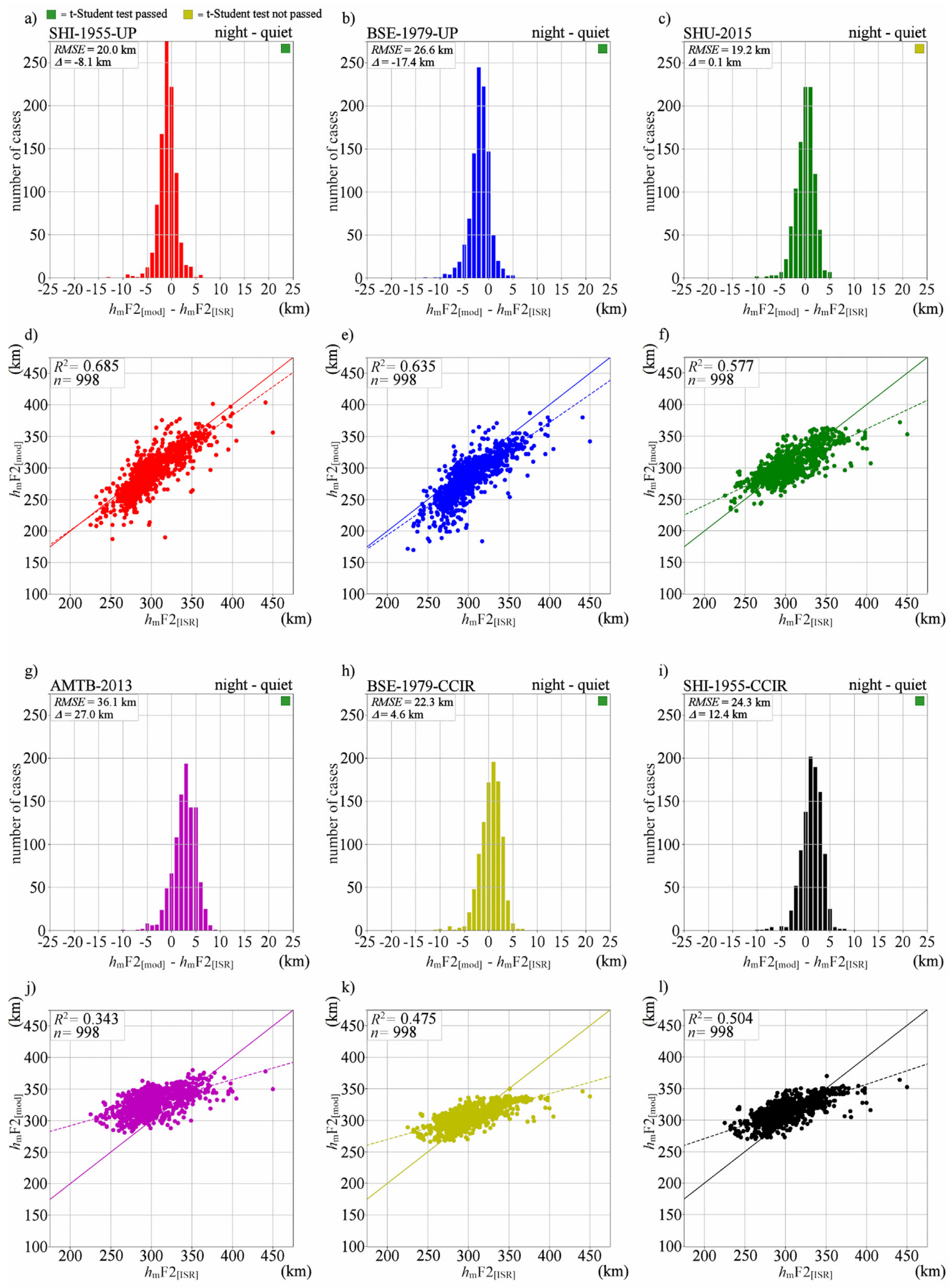

Fig. 2. Same as Fig. 1 for quiet night-time conditions.

model. The superior performance of the SHU-2015 formulation for h_mF2 in comparison with the two other options available in the IRI model was proved also by Mengist et al. (2020) using ISR data at Millstone Hill during the solar cycle 24. They generally found better agreement between ISR measurements and the models during daytime

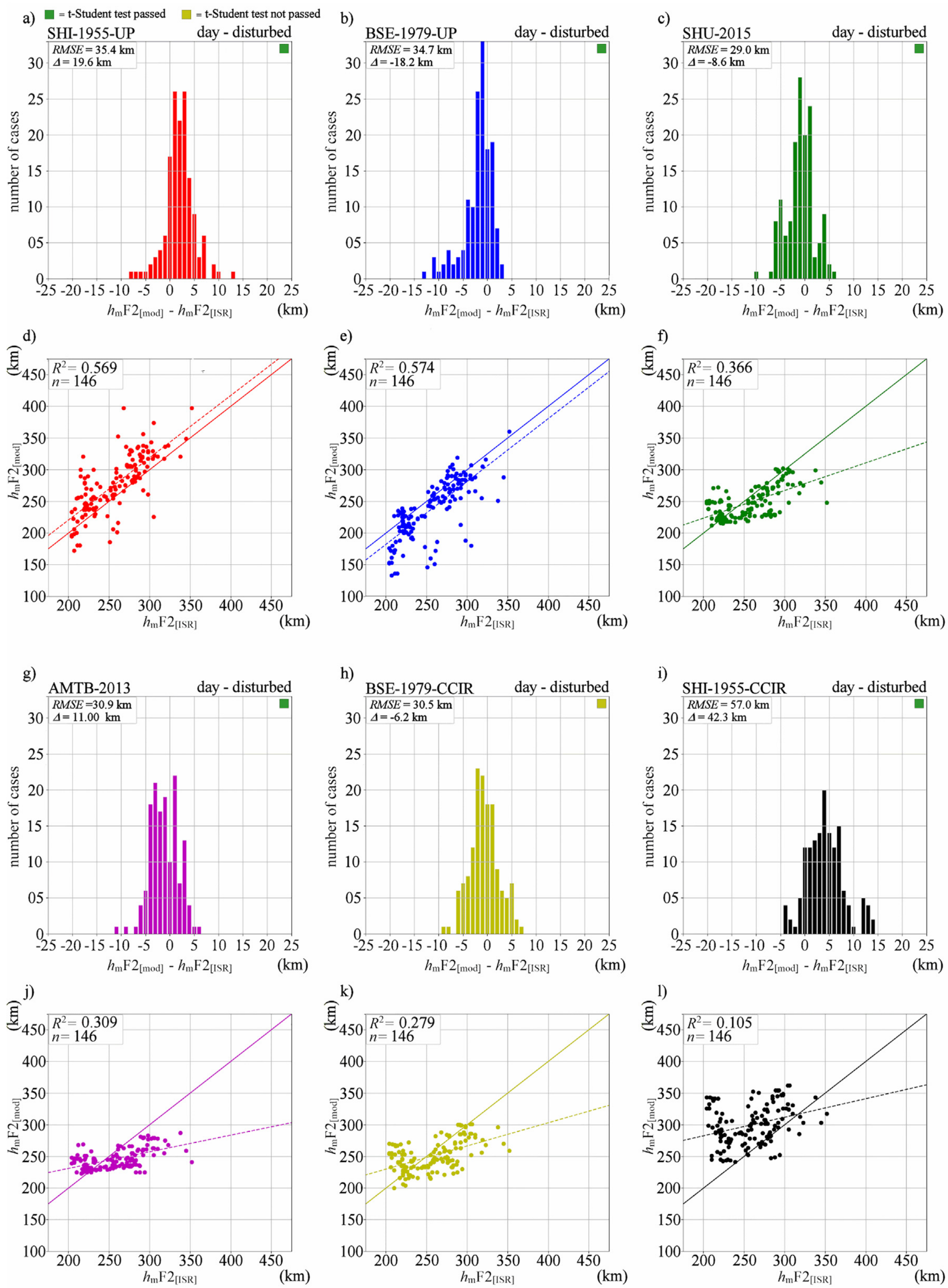

Fig. 3. Same as Fig. 1 for perturbed diurnal conditions.

and low solar activity. Huang et al. (2021) also compared all the options with digisonde, COSMIC and ISR observations and found the same result at mid-latitude both for low and high solar activity conditions. This was confirmed also by Bilitza et al. (2022) in terms of histograms of residuals and scatter plots of IRI (all three options) h_mF2 values

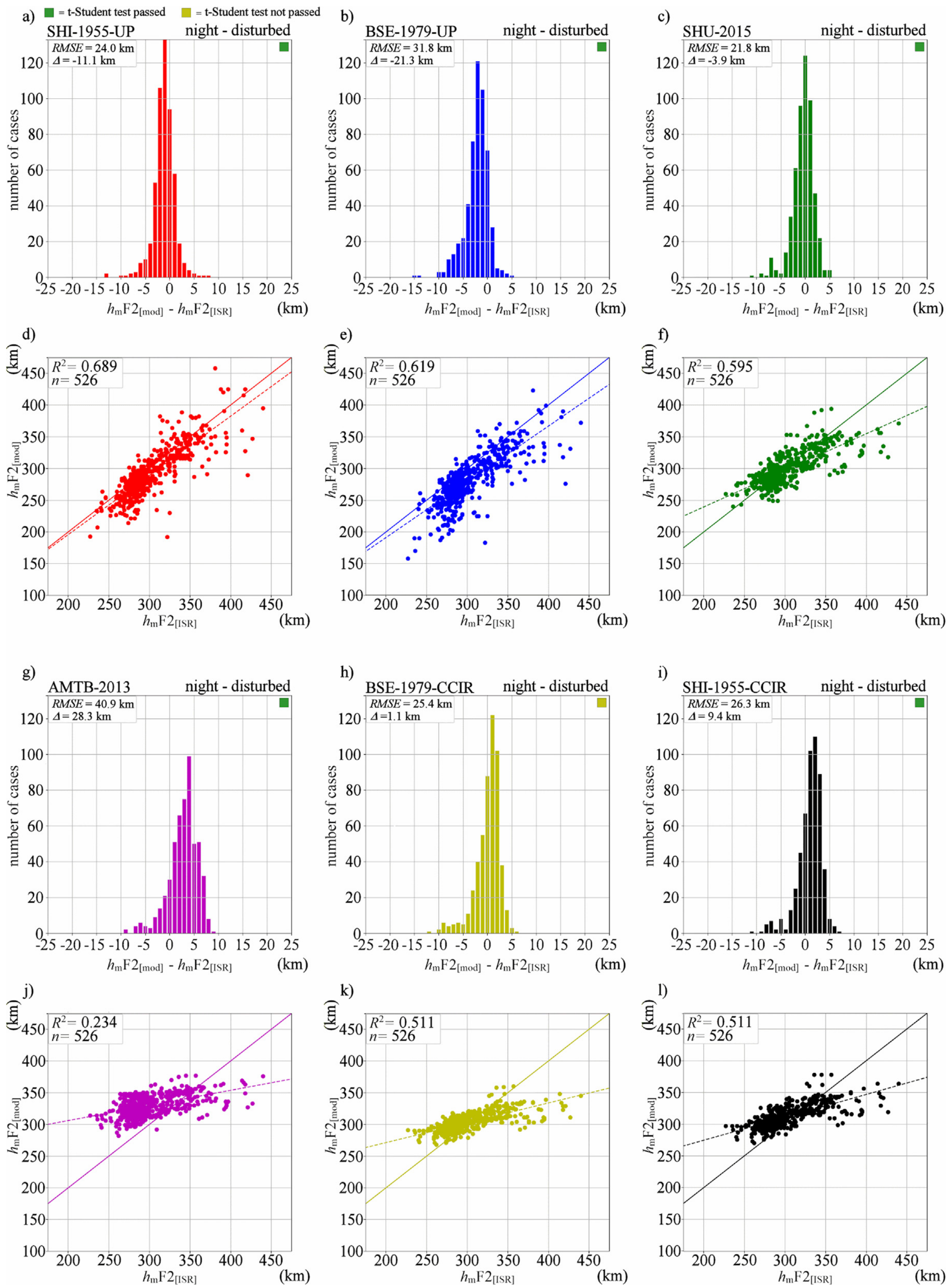

Fig. 4. Same as Fig. 1 for perturbed nocturnal conditions.

versus COSMIC measurements from a dataset selected according to Shaikh et al. (2018) and Pignalberi et al. (2020).

It is noteworthy that the SHU-2015 works better even than the formulas in which f_oF2 and M(3000)F2 values manually scaled from ionograms are ingested. In all conditions, in fact, we have lower $|\Delta|$ and RMSE for SHU-2015 than for SHI-1955-UP and BSE-1979-UP. SHI-1995 and BSE-1979 upgraded with manually scaled parameters are indeed expected to behave better than the same formulas fed by global models, with an accuracy that, to our knowledge, has never been evaluated before, nor compared with that of other formulations. This expectation is confirmed for the SHI-1955 formulation, as SHI-1955-UP clearly performs better than SHI-1955-CCIR in any condition, particularly during daytime when the general performance is lower. However, BSE-1979-UP surprisingly turns out to behave worse than BSE-1979-CCIR in terms of Δ and RMSE values, although it generally correlates better with ISR values. It should be noted that Student's *t*-test fails also for BSE-1979-CCIR under disturbed conditions, with $\Delta = 1.1$ km during night and $\Delta = -6.2$ km during daytime, although the latter case is probably affected by the poor statistics ($n = 146$).

Despite their lower performance with respect to the SHU-2015 formulation, an interesting result is that during night-time SHI-1955-UP and BSE-1979-UP show the highest correlation between modeled and measured values. In fact, we obtained R^2 values from about 0.61 to 0.69 and values of $|\Delta|$ from 8.1 km to 21.3 km, with better performance for SHI-1955-UP than BSE-1979-UP under both quiet and disturbed conditions. The high value of $|\Delta|$ shows that the SHI-1955-UP and the BSE-1979-UP are not to be preferred for the estimation of h_mF2, while the high values of R^2 suggest the presence of a constant systematic error. Therefore, the results obtained from these formulas can be used for studies on the long-term trend of night-time h_mF2.

Concerning the ATMB-2013 model, it is found that it does not work satisfactorily at night, when it performs worse than all the other models. Indeed, it can be seen that during night the Δ values are very high, with low R^2 ($\Delta = 27.0$ km and $R^2 = 0.343$ in quiet conditions, and $\Delta = 28.3$ km and $R^2 = 0.234$ in disturbed conditions). The relatively poor performance of the ATMB-2013 model was already highlighted also by Mengist et al. (2020), who found that the older BSE-1979 formulation provides reasonably better prediction. This is also in line with the results of Krasheninnikov and Leshchenko (2021), who compared BSE-1979 and ATMB-2013 formulations to the Global Dynamic Model of the Ionosphere (GDMI) (Shubin and Gulyaeva, 2021), considered as a further implementation of the SHU-2015 modeling approach based on the re-calibrated sunspot number time series SSN2 for the quiet geomagnetic conditions. The comparison was made considering daily variations of h_mF2 at the IZMIRAN station of Moscow in 2018 by models and independent operator processing of the ionograms with the $N_e(h)$-profile estimation. From their results, the authors noted a significant discrepancy in the model representation of ATMB-2013, concluding that a direct accounting of experimental data for h_mF2 does not give a significant improvement in the accuracy of its representation for this model, at least during low solar activity. However, it should be noted that in the present study the ATMB-2013 model shows a better performance than SHI-1955 and BSE-1979 (both CCIR and UP versions) under quiet daytime conditions.

Finally, it can be noted that the SHI-1955-CCIR does not work properly during the day. In fact, we obtained in quiet daytime conditions RMSE = 66.4 km, $\Delta = 58.8$ km, and $R^2 = 0.19$, while under disturbed daytime conditions RMSE = 57.0 km, $\Delta = 42.3$ km, and $R^2 = 0.105$. This is in line with the conclusions of Perrone et al. (2017), who discouraged the use of such formulation for trend analyses at least under daytime Summer conditions, particularly under solar minimum, due to its strong overestimation. The same point was reported by McNamara (2008), who highlighted that the BSE-1979, and other formulations which consider the ionization below the F2-layer peak, give smaller errors than the original SHI-1955 formula, especially during the day.

Anyway, it should be mentioned that h_mF2 automatically scaled by the Autoscala program (Scotto and Pezzopane, 2000; Scotto, 2009) and obtained by THERION, a method to retrieve thermospheric parameters from ionosonde observations (Perrone and Mikhailov, 2018), gave better results with respect to the SHU-2015 model around noon in a comparison with Millstone Hill ISR data including 60 cases selected in the 2000–2016 period during different seasons and under both solar maximum and minimum conditions (Perrone et al., 2021). However, also the SHU-2015 model demonstrated good accuracy within the same study (with a standard deviation lower than 17 km and a bias of 4.5 km), although the geomagnetic activity under the analyzed days was mainly low and moderate.

4. Conclusions

In this work we studied the performance of the different formulations available in the IRI model for h_mF2 (BSE-1979, AMTB-2013, and SHU-2015), comparing modeled values with those measured by the Incoherent Scatter Radar of Millstone Hill over almost two entire solar cycles, considering separately daytime and night-time hours, and ionospheric quiet and perturbed conditions. The original Shimazaki (SHI-1955) empirical formulation was also included in the study. The SHI-1955 and the BSE-1979 formulas were evaluated using values of M(3000)F2 (and also f_oF2 for BSE-1979) both from global models included in IRI and obtained by the manual scaling of the ionograms, allowing to perform a completely new comparative test involving validated measurements as input of such formulations. From the presented results, some conclusions on the reliability of the various formulas and models can be drawn.

(1) The SHU-2015 works well in basically all conditions. It has very small Δ, which are close to the expected accuracy of h_mF2 determination with the Millstone Hill ISR and always better than those obtainable with the other models.
(2) The SHU-2015 works better even than the formulations updated with ionospheric validated measurements (SHI-1955-UP, BSE-1979-UP), both under night-time and daytime conditions. Anyway, the h_mF2 obtained with the Autoscala program for ionograms autoscaling and the THERION method gave in the past better results with respect to SHU-2015 around noon.
(3) SHI-1955-UP clearly performs better than the same formulation fed by M(3000)F2 from CCIR model (SHI-1955-CCIR) in any condition, while BSE-1979-UP surprisingly behaves worse than BSE-1979-CCIR in terms of Δ and RMSE values, although it generally correlates better with ISR values.
(4) At night, formulations updated with validated measurements (SHI-1955-UP, BSE-1979-UP) show high Δ and high R^2, which indicates the presence of systematic errors.
(5) The AMTB-2013 does not work satisfactorily at night, when it performs worse than all the other models.
(6) The SHI-1955-CCIR does not work properly during the day. Hence, its use is discouraged in such conditions even for trend analyses.

According to these results, it is confirmed that it is advisable to recommend the use of the SHU-2015 as a preferential option of the IRI model, at least in the middle latitudes of the American sector. The presence of systematic errors in SHI-1955-UP and BSE-1979-UP, but high R^2 at night, makes these formulations useful for long-term trend studies using night-time measurements. The BSE-1979 option of the IRI is confirmed to provide reasonably good results, especially during night when conversely AMTB-2013 does not work satisfactorily.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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