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Comparing Ionospheric MUF using IRI16 Model with Mid-Latitude Ionosonde Observations and Associated with Strong Geomagnetic Storms

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Abstract

High frequency (HF) radio wave propagation depends on the ionosphere status which is changed with the time of day, season, and solar activity conditions. In this research, ionosonde observations were used to calculate the values of maximum usable frequency (MUF) the ionospheric F2- layer during strong geomagnetic storms (Dst ≤ -100 nT) which were compared with the predicted MUF for the same layer by using IRI-16 model. Data from years 2015 and 2017, during which five strong geomagnetic storms occurred, were selected from two Japanese ionosonde stations (Kokubunji and Wakkanai) located at the mid-latitude region. The results of the present work do not show a good correlation between the observed and predicted MUF values for F2- layer during the selected events of strong geomagnetic storms at these stations. Thus, there is a further need to improve the IRI-16 model for better matching with the observations during strong geomagnetic storms.

Keywords: Geomagnetic storms, Ionosphere, IRI-16 model, Maximum Usable Frequency.

مقارنة التردد الاقصى القابل للاستعمال (MUF) بأستخدام أنموذج IRI-16 مع ارصاد الايونوسوند الواقعة على خطوط العرض الوسطى المرتبطة بالعواصف الجيومغناطيسية القوية

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الخلاصه

يعتمد انتشار الموجات الراديوية عالية التردد (HF) على حالة الأيونوسفير التي تتغير مع مرور الوقت من اليوم والفصل وحالة النشاط الشمسي. في هذا البحث، تم حساب قيم التردد الأقصى القابل للاستخدام (MUF) للطبقة F2 من الأيونوسفير خلال العواصف الجيومغناطيسية القوية (Dst-100 nT) باستخدام ارصادات الأيونوسوند ، ومقارنتها بالتردد MUF المتنبأ بها لنفس الطبقة باستخدام نموذج IRI-16 . تم اختيار عامي 2015 و 2017 لهذه الدراسة والتي حدثت فيها خمس عواصف جيومغناطيسية قوية ولمحطتين يابانيتين (Kokubunji و Wakkanai) والواقعة ضمن مناطق خطوط العرض الوسطى. لا تظهر نتائج العمل الحالي علاقة جيدة بين قيم MUF المرصودة والمتنبأ بها للطبقة F2 خلال العواصف الجيومغناطيسية القوية المختارة وللمنطقتين اللتين تم اختيارهما. وعليه فأنه هنالك حاجة إضافية إلى أدخال تحسينات على أنموذج IRI-16 ليتوافق مع الملاحظات أثناء العواصف الجيومغناطيسية القوية.

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1. Introduction

The HF (3-30 MHz) radio wave is very important in communications because it has low cost and can be sent over long distances, with stations that are easy to set up. However, the propagation of this wave through the medium, such as the ionosphere layers, becomes complicated because of issues of absorption and interference [1-3]. The F2 layer of the ionosphere is responsible for radio communications due to its presence throughout the day. Therefore, this layer carries approximately all nighttime radio wave propagation all over the world for long distances, depending on the height of the layer [4, 5]. There are daily, seasonally, and annually changes in the ionization of this layer, leading to variations in electron density (Ne) and its height. Also, the ionization in this layer varies with the geographic coordination, depending mainly on the latitude [6, 7]. Several researchers have made attempts to explore the relationship between solar activity and ionosphere parameters [8-10]. Other researchers studied the ionosphere conditions with geomagnetic storms. Lakshmi *et al*., in 1997, found a rapid collapse in midnight ionospheric F layer electron density during severe geomagnetic storms [11]. Kouris and Fotiadis [12-14] conducted many types of research related to daily and hourly variability of ionospheric parameters and their variation with the latitude.

Najat, in 2009, compared some observed ionospheric parameters with the predicted values obtained from the international reference ionosphere (IRI) model for Japan's mid-latitudes region and reported no correlation relations [15]. Kotova *et al*., in 2016, studied the ionospheric variation with space weather changes and found an influence of stratosphere heating on the radio wave propagation, leading to attenuation in the HF signal in the daytime for the ionospheric equator region [16]. An international project by the committee on space research (COSPAR) was released to develop the IRI model and the results were published by reports of Adeniyi [17], Bilitza and Reinisch [18], and Krasheninnikov and Egorov [19]. In the past three years, several improved IRI models provided the prediction of ionospheric parameters for given date, time, location, solar activity, and geomagnetic conditions [20]. Comparisons were made between the modified theoretical model and observations [21]. There was a mismatch for some ionospheric coefficients in some regions of the world, at different latitudes, and during geomagnetic storms [22]. Therefore, in this research, the efficiency of IRI-16 model during strong geomagnetic storms (Dst < -100 nT) is studied. We took into account the available data from stations in mid-latitudes, using the ionosphere parameter of the MUF, for its importance in communication.

2. Calculating MUF from observations

The MUF is defined as the highest frequency that could be used to permit acceptable performance for radio circuits between two terminals at a specific time [23]. The MUF is very important in communication for determining the perfectly high frequency to be used between two regions under specific working conditions, including the type of antenna and the type of power [24]. This parameter can be calculated for the F layer by multiplying the critical frequency (foF_2) by the propagation factor for the same layer M (3000) F2, which is a very important parameter in ionosphere application that represents the optimum frequency received at a distance of 3000 km to broadcast a HF signal [25]. This parameter can be obtained from the ionosonde data of the vertical incidence ionogram [26]. Using the standard method, equation (1) is applied to calculate MUF for F_2-layer:

$$\text{MUF F2} = \text{foF2} \times \text{M(3000)F2} \quad (1)$$

where foF2 is the critical frequency for F2 layer and $M(3000)F_2$ is the propagation factor. The F2 layer's maximum usable frequency (MUF F2) in particular varies annually, seasonally, and with the solar cycle [27].

3. Geomagnetic Storm

The ionization gases (plasma clouds) from the Sun reach the space in the solar system and they are named as Coronal Mass Ejections (CME). They lead to disturbing the magnetic field lines of Earth, causing geomagnetic storms [28]. Occasionally, due to high solar activity, a stream of high energy solar wind is produced, which strikes Earth's magnetic field. This leads to the occurrence of geomagnetic storms accompanied by disturbances in the Earth's ionosphere that last for several hours, or sometime for two days, depending on the strength and type of the storm [29,30], which affects the propagation of HF radio wave [31,32].

4. Statistical Methodology

The statistics used in this study were selected to reveal possible model biases and whether the model follows the trend of the observed data. They were also applied to determine the accuracy of the model output. The cross-correlation error represents the difference between a predicted value (P) and an observed value (O). The statistics used in this study include Spearman's rank correlation coefficient (r_s), expressed in equation (2). This coefficient has a value between 1 and -1. A value of 1 indicates a perfect positive correlation, a value of -1 indicates a perfect negative correlation, and a value near zero indicates poor correlation. The equation for r_s is given below [33, 34]

$$r_s = \frac{SS_{PO}}{\sqrt{SS_{PP}SS_{OO}}} \quad (2)$$

where:

$$SS_{PO} = \sum_{i=1}^{n} P_i O_i - \frac{(\sum_{i=1}^{n} P_i \sum_{i=1}^{n} O_i)}{n} \quad (3)$$

$$SS_{PP} = \sum_{i=1}^{n} P_i^2 - \frac{(\sum_{i=1}^{n} P_i)^2}{n} \quad (4)$$

$$SS_{OO} = \sum_{i=1}^{n} O_i^2 - \frac{(\sum_{i=1}^{n} O_i)^2}{n} \quad (5)$$

In the above equations, n is the total number of pairs (predicted and observed) of values, and (i) refers to a specific value within a group.

5. Data selection and analysis

The primary source of observations data in this research is the ionosonde stations in Japan site (http://wdc.nict.go.jp) for ionosphere parameters. These are the long-range data recorded for the hourly and daily values of foF_2 (in MHz) and propagation factor M (3000) F2. For geomagnetic activity data, the hourly/daily sunspot number and the hourly/ daily values of geomagnetic storms indices (Dst) in nano Tesla (nT) are taken from NASA (ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC_DATA/INDICES/DST/). Two ionosonde stations are selected (as available from the site), located in the mid-latitude regions of Kokubunji and Wakkanai, Table-1 presents the geographic coordinates of these stations. For this study, two years are selected (2015 and 2017), during which five strong geomagnetic storms occurred (Dst $\leq$ -100), three in 2015 and two in 2017. Figure-1 shows the data of the hourly geomagnetic storm index Dst (nT) for the two years of study. A description of the five events that occurred during these years is provided in Table-2. Figure-2 presents data of the solar cycle 24, during which the two years selected for this study occurred.

Table 1-Geographic coordinates of stations from which data selected for this research

Ionosonde station name	Geographic Latitude (in degree)	Geographic Longitude (in degree)
Kokubunji	35.7° N	139.5° E
Wakkanai	45.4° N	141.7° E

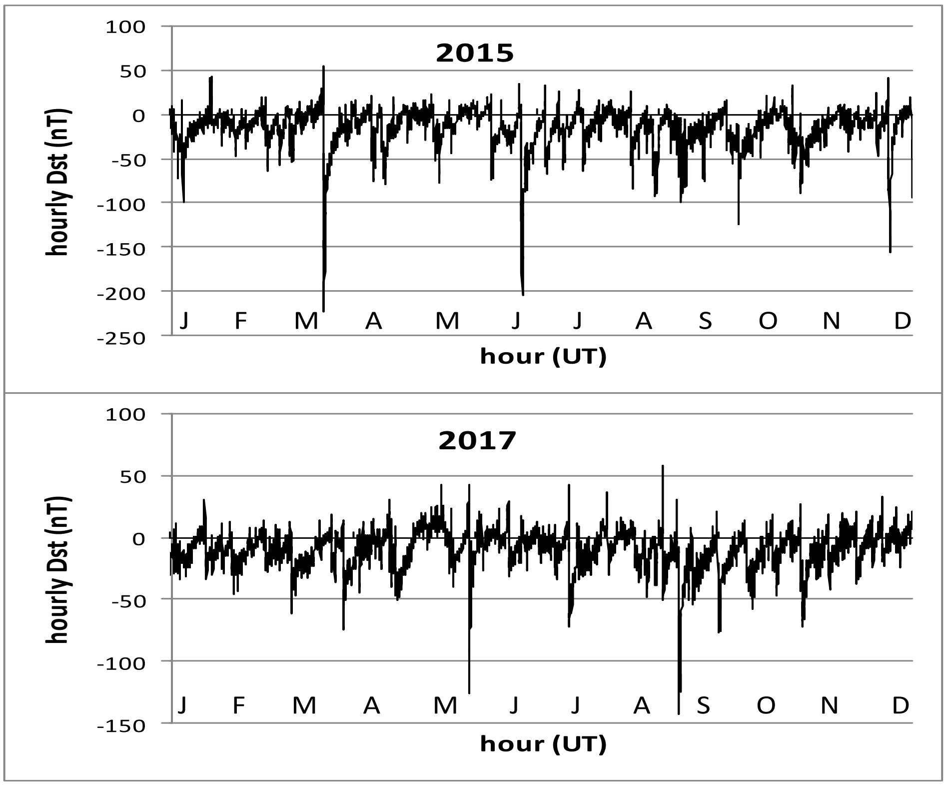

Figure 1-Hourly geomagnetic storm index Dst (nT) for years 2015 and 2017.

Table 2-Strong geomagnetic storms occurred in years 2015 and 2017

Event no	Year	month	day	hour	Type
1	2015	6	23	1-17	Strong
2	2015	10	7	19-23	Strong
3	2015	12	21-22	17-10	Strong
4	2017	5	28	5-8	Strong
5	2017	9	8	13-21	Strong

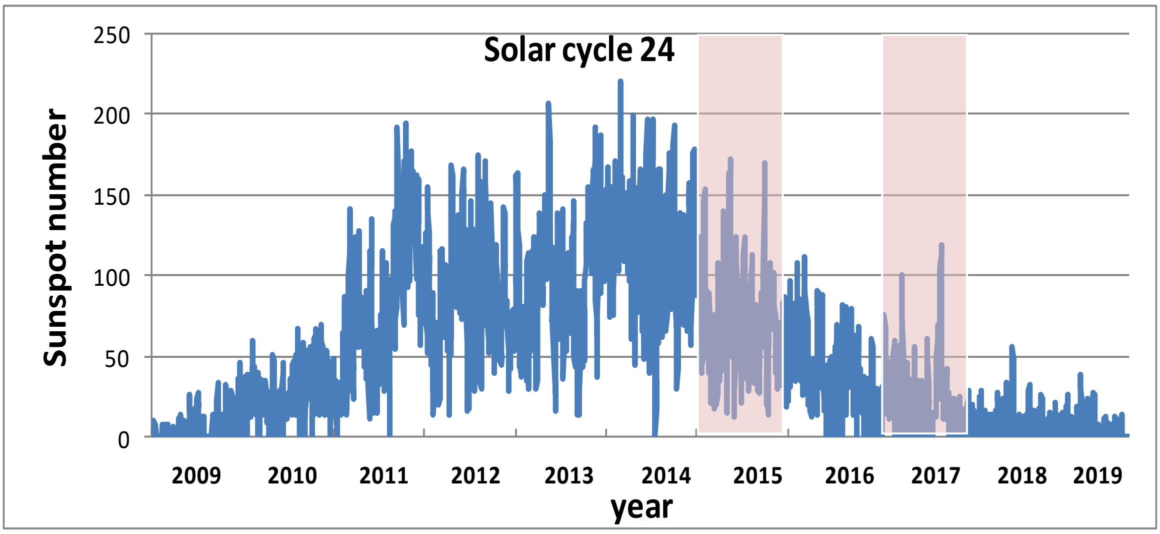

Figure 2-The solar cycle 24 through the sunspot number.

6. Results and Discussion

In the initial step, attempts were made to calculate the values of MUF from observations, which were verified with the predicted MUF values using IRI-16 model (http://omniweb.gsfc.nasa.gov/for/dxl.html). Figures- (3-7) show the hourly predicted (blue) and observed (red) MUF values, using the hourly Dst-index, for the time intervals of two days before, during, and two days after the storm. Since the values of MUF depend mainly on those of foF2, as confirmed by their direct relation in Equation 1, the observations demonstrated that their day values were greater than night values.

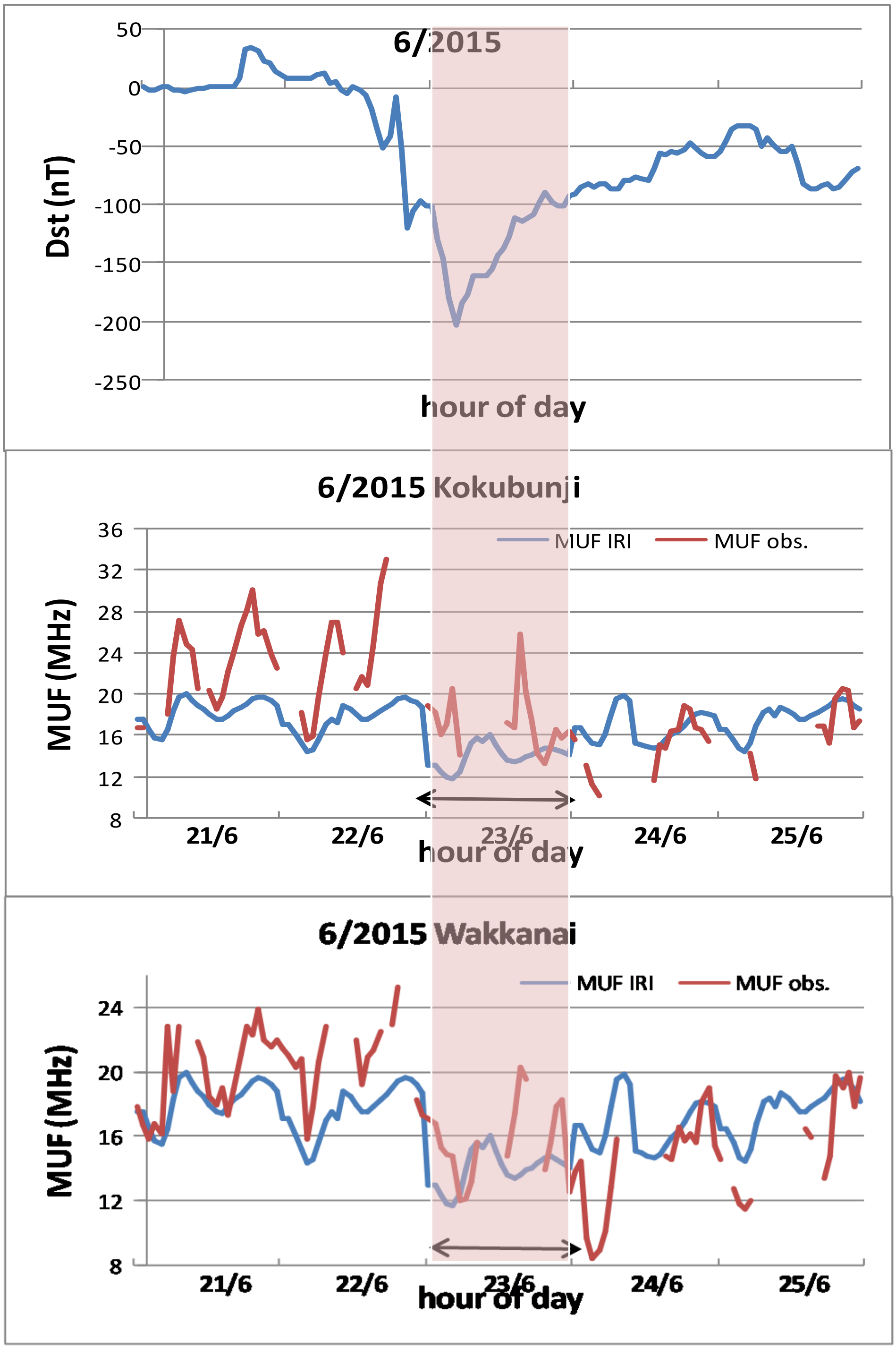

Figure 3- Hourly predicted (blue) and observed (red) MUF before, during, and after the storm of 23 Jun 2015.

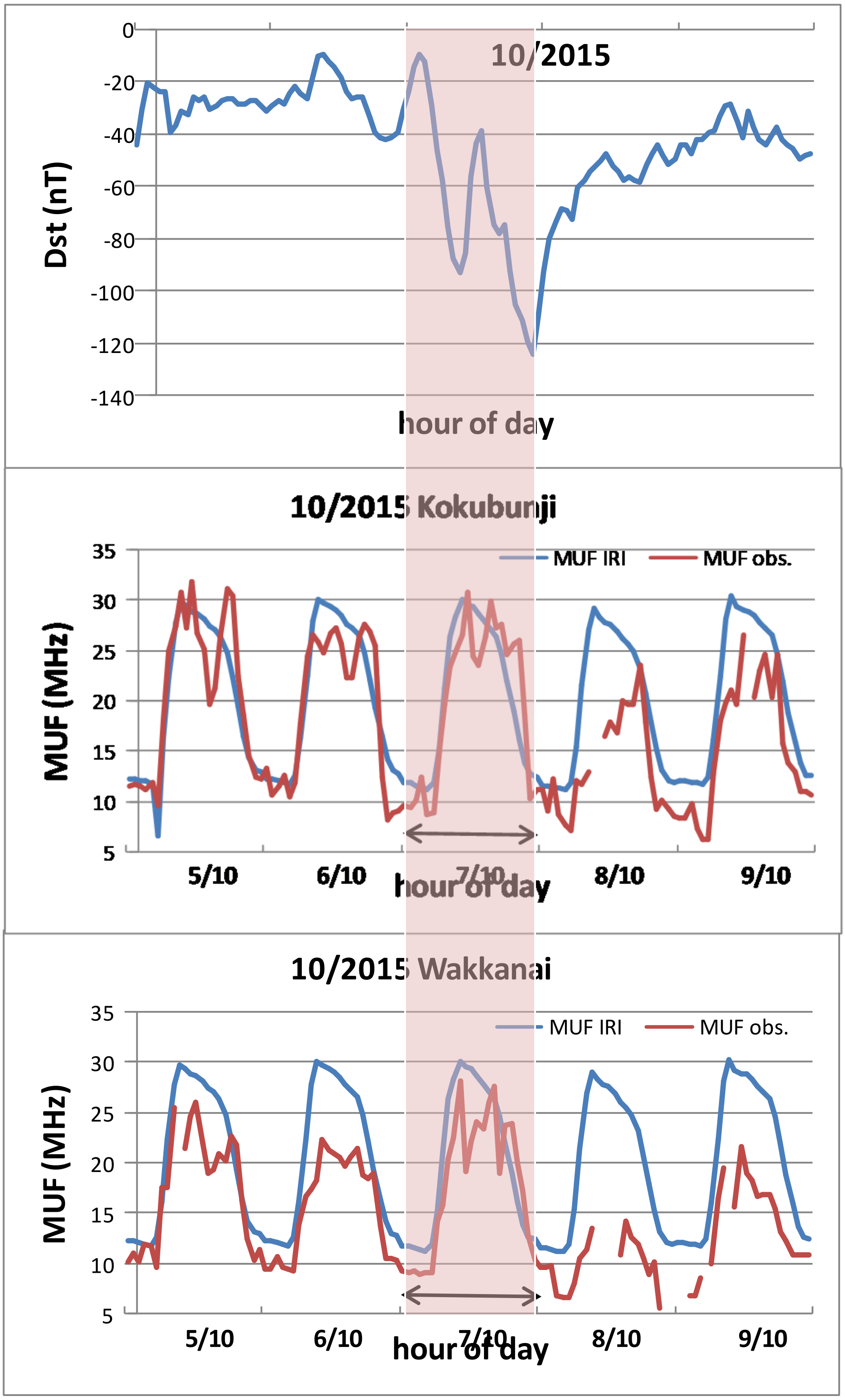

Figure 4-Hourly predicted (blue) and observed (red) MUF before, during, and after the storm of 7 October 2015

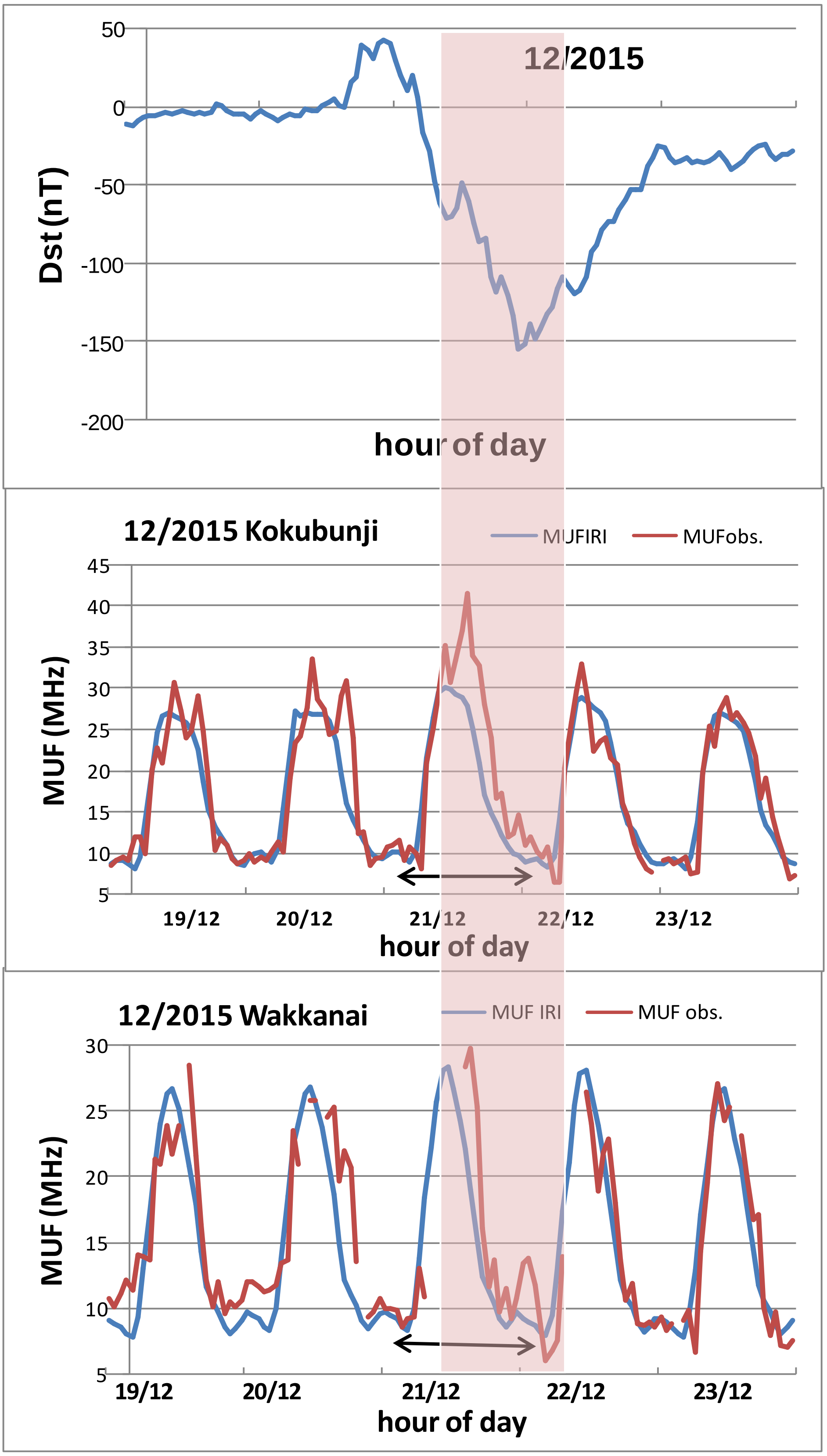

Figure 5-Hourly predicted (blue) and observed (red) MUF before, during the storm of 21-22 December 2015 and after.

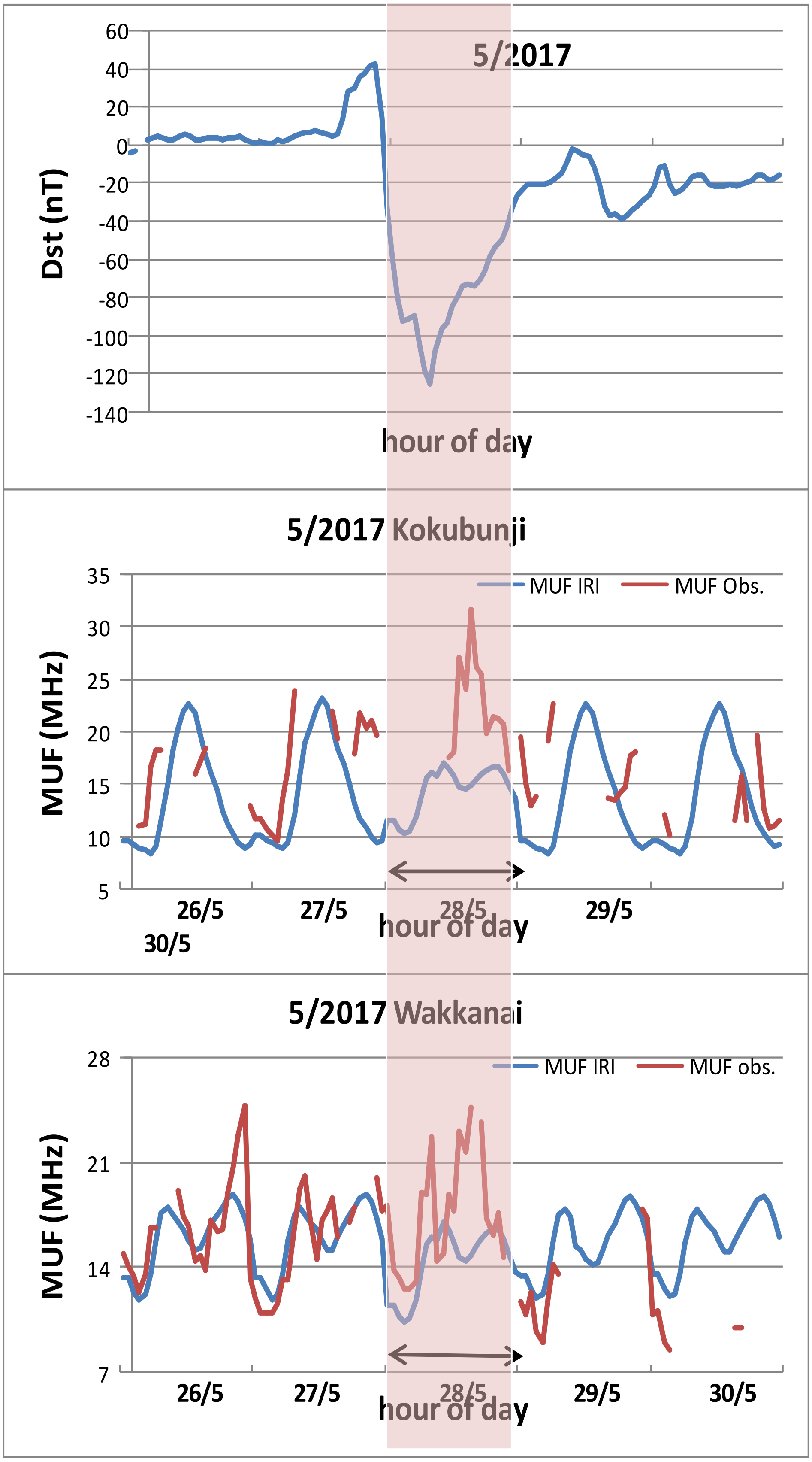

Figure 6-Hourly predicted (blue) and observed (red) MUF before, during the storm of 28 May 2017 and after.

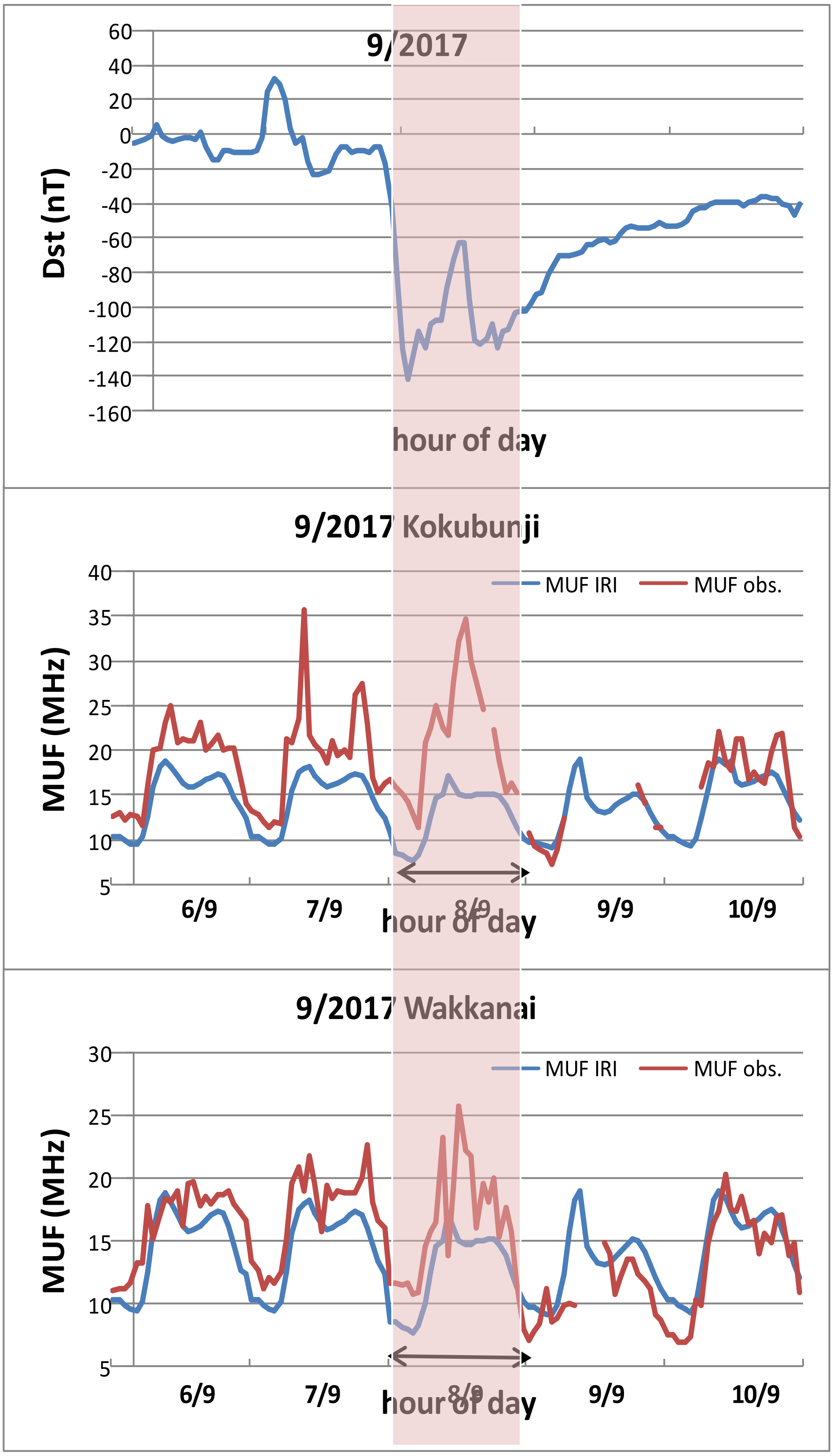

Figure 7-Hourly predicted (blue) and observed (red) MUF before, during the storm of 8 September 2017 and after.

The maximum MUF value was recorded at day time (approximately 40 MHz) in event 3 (21 of December 2015), in which the Dst value was about -150 nT. However, a minimum value of approximately 5 MHz was recorded in the night time of the same event. The propagation of HF varied through the seasons. The atmosphere was denser and colder in winter, e.g. December, as observed in event 3. This makes the height of the ionosphere layers lower to the Earth, with greater ionization or higher electron density (Ne). Also in winter, the Sun is closer to the Earth in the daytime, which causes more ionization and higher electron density in the ionosphere. Because of that, the daytime value of MUF in December was higher than that in the other months during the selected events. At night time, the recombination became faster in the F2 layer, causing a decrease in the values of MUF. Because of longer evenings in winter (December), the F2 layer has a longer time to lose its ionizations. When the day approached the sunrise and before dawn, the MUF fell to its lowest value (5 MHz) or lower in the quiet conditions.

By observing the MUF values of 2015 and 2017, no clear difference was found, because the two years are in the descent of the solar cycle 24, as shown in Figure- 2. In the minimum solar cycle (minimum sunspot), the Sun's chromosphere became quiet and the UV emissions became low, causing a decreased ionization of the ionospheric F2 layer and, accordingly, it’s a decreased value of MUF.

The results show a mismatch between observed and predicted values of MUF during the day, in which the strong geomagnetic storms occurred, and for the two latitudes selected (Kokubunji and Wakkanai). We also found non-linear relations between the observed and predicted values along the five events taken. For comparison, a statistical method was applied, which is the most important step in this research because it showed the validity or efficiency of the IRI-16 model in the mid-latitude region during strong geomagnetic storms. By using equation (2), the cross correlation between the observed and predicted values calculated for the five events and two latitudes indicated that the best correlation appears in events 2 and 3, reaching approximately 0.9. However, the lowest correlation was recorded in events 1 and 4. Therefore, it is necessary to improve the model to match the observations during strong geomagnetic storms.

Table 3-Cross-correlation between predicted and observed MUF values

Event no	Date of storms			Stations	
	Day	Month	Year	Kokubonji	Wakkanai
				CCR	CCR
1	23	6	2015	-0.27986	0.046176
2	7	10	2015	0.880482	0.866454
3	21	12	2015	0.8974	0.793362
4	28	5	2017	0.233332	0.466814
5	8	9	2017	0.738912	0.752648

7. Conclusions

The purpose of using the theoretical model (IRI) is to secure HF communication if it is blacked out, especially during geomagnetic storms, in which the ionospheric F2 layer is disturbed. From the results of the model, we can conclude that there is no linear relation between the observed and predicted values of MUF during strong geomagnetic storms and for the two mid-latitudes selected. The statistical cross-correlation between predicted and observed MUF values shows a low correlation. Thus, it is necessary to enhance the model to be suited with the observations during storm time.

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