Validation of MIGHTI/ICON Atmospheric Wind Observations over China Region Based on Meteor Radar and Horizontal Wind Model (HWM14)

Zhou Chen 1, Yi Liu 1,*, Zhitaod Du 2, Zhiqiang Fan 2, Haiyang Sun 2 and Chen Zhou 1

1 Department of Space Physics, School of Electronic Information, Wuhan University, Wuhan 430072, China; zhouchen_whu@whu.edu.cn (Z.C.); chenzhou@whu.edu.cn (C.Z.)
2 Beijing Institute of Applied Meteorology, Beijing 100101, China; 18610106762@163.com (Z.D.); zqlan2016@sina.com (Z.F.); sunshy@163.com (H.S.)
* Correspondence: liuyiwhuhan@whu.edu.cn

Abstract: The Michelson Interferometer for Global High-resolution Thermospheric Imaging (MIGHTI) on board the ICON satellite provides effective measurement of horizontal winds in the mesosphere and lower thermosphere (MLT) region. In order to verify the measurement accuracy of the horizontal wind, this study uses the measurements of the meteor radar in Wuhan and the simulation results of a horizontal wind field model (HWM14) to compare and analyze the measurement results of MIGHTI/ICON in the whole year of 2020. The comparative analysis indicated that two datasets from MIGHTI/ICON and meteor radar are strongly correlated (r = 0.65, 0.76) with an RMS difference of 39.21 m/s (30.31 m/s). The consistency for meridional wind from MIGHTI/ICON, meteor radar, and HWM14 is worse than that of zonal wind. The accuracy of horizontal wind observations is influenced by altitude, diurnal, and seasonal patterns.

Keywords: MIGHTI/ICON; meteor radar; HWM14; horizontal wind measurement

1. Introduction

Atmospheric winds play an important role in determining the state and evolution of the atmosphere and ionosphere by participating in various chemical changes and physical processes in the mesosphere and lower thermosphere (MLT) region [1]. Atmospheric winds can push plasma drift by wind-driven electromotive forces and control the exchange of energy between atmospheric waves from the lower atmosphere and upper atmosphere in the MLT region [2]. Thus, an accurate measurement of atmospheric winds in the MLT region is important to facilitate our better understanding of the near-Earth space environment. Currently, atmospheric winds have been generally measured by ground-based instruments, including meteor radar [3–6], lidar [7,8], medium-frequency radar [9–11], passive optical instrumentation, etc.

Among the ground-based instruments, meteor radar has the advantage of 24 h continuous observation with height coverage from 70 to 110 km, which provides favorable conditions for analyzing the characteristic parameters of long-period atmospheric waves, such as tidal waves and planetary waves in the MLT region [8,12]. However, poor spatial coverage for ground-based instruments results in an inability to provide global distribution of atmospheric winds. Space-borne instruments can overcome these limitations and provide a global measurement of atmospheric winds. For example, the High-Resolution Doppler Imager (HRDI) and the Wind Imaging Interferometer (WINDI) onboard the UARS satellite first measure atmospheric winds within the height ranges of 50–115 km and 90–180 km by observing the Doppler shift characteristics of O2 airglow emission and O airglow emission, respectively [13]. The High-Resolution Doppler Imager on the Thermosphere Ionosphere Mesosphere Energetics and Dynamics Doppler Interferometer (TIDI), launched in 2001, has
been monitoring MLT winds for two decades and has collected the most comprehensive global information on neutral winds [14]. The wind observations have been cross-validated by using ground-based instruments and there is no statistically significant difference for horizontal winds [13,14], which indicates that space-borne instruments can also provide an accurate wind measurement.

A new global atmospheric wind dataset can be now obtained from the Ionospheric Connection Explorer (ICON) launched in 2019. The Michelson Interferometer for Global High-resolution Thermospheric Imaging (MIGHTI) onboard the ICON can view airglow emissions from OI 557.7 and 630.0 nm to determine Doppler wind [15–17]. A series of cross-comparisons of ICON wind observations with ground-based and space-borne instruments have been carried out by recent research [14,18,19]. Makela et al. presented MIGHTI/ICON and ground-based Fabry–Perot interferometer measurements of the nocturnal thermospheric neutral wind and showed consistency within 10 m/s [18]. Harding et al. showed a strong correlation (r = 0.82) between ICON-MIGHTI and specular meteor radars for coincident wind measurements with an average error of 4.5 m/s [19]. The agreement of MIGHTI/ICON and TIMED/TIDI atmospheric wind measurements in the MLT region has also been shown in Dhadly et al. [14]. However, no study has yet considered the consistency of meteor radar and MIGHTI/ICON measurements of neutral wind in the MLT region on the basis of a full year of detection data. Here, we focus on the cross-validation of MIGHTI/ICON and meteor radar horizontal winds around Wuhan in 2020. The simulated results of Horizontal Wind Model 14 (HWM14) are also used to find the inconsistencies between MIGHTI/ICON measurements and HWM14 simulations.

This work is organized as follows. In Section 2, we introduce MIGHTI/ICON, meteor radar, and HWM14 in turn. In Section 3, we analyze the results at the example and statistical levels, respectively. We present the discussion process and conclusion in Section 4.

2. Dataset

ICON is the newest member of NASA’s Heliophysics satellite constellation with a 27-degree inclination orbit at about 600 km, which is tasked with better understanding the relationship between Earth’s atmosphere and the space environment [20]. To determine the height distribution of atmospheric winds and temperatures in the Earth’s upper atmosphere, MIGHTI is carried on board the ICON satellite [15]. MIGHTI consists of two sensors with orthogonal fields of view, MIGHTI-A with a 45° azimuthal line of sight to the spacecraft velocity vector and MIGHTI-B with a 135° azimuthal line of sight to the spacecraft velocity vector. In this view, MIGHTI makes two vertical line-of-sight wind speed measurements of the same physical space while the spacecraft passes [17]. Doppler shifts of two airglow emission lines of oxygen, one green (557.7 nm) and one red (630.0 nm), are measured to retrieve the horizontal winds [16,21]. The details of MIGHTI/ICON are discussed by Englert et al. [15]. MIGHTI measurement requirements for a single field of view of wind are provided in Table 1. In this study, the cardinal vector wind data from MIGHTI in 2020 are used in cross-comparison analysis.

| Altitude Range (km) | Day | Night | Vertical Resolution (km) | Along Track Resolution (km) | Wind Velocity Precision (m/s) |
|---------------------|-----|-------|--------------------------|-----------------------------|-------------------------------|
| 90–105              | x   | x     | 5                        | 500                         | 8.7                           |
| 105–170             | x   |       | 5                        | 500                         | 10                            |
| 170–200             | x   |       | 30                       | 500                         | 10                            |
| 200–300             | x   | x     | 30                       | 500                         | 8.7                           |

In this work, we used meteor radar wind measurements in 2020 at Wuhan (30°40′ N, 114°30′ E). Horizontal winds (zonal wind and meridional wind) from 70 to 110 km were available from meteor radar with 2 km height resolution and 1 h time resolution.
HWM14 is the latest version for HWM series which has been updated in the thermosphere with new observations. Updated results provide an improved, time-dependent, observation-based, global empirical model for the general circulation of the upper atmosphere and the horizontal winds of migrating tides. In general agreement with existing theoretical knowledge of the thermospheric general circulation, additional studies have shown that the empirical wind field is consistent with the ionospheric plasma distribution and electric field pattern [22–25]. The details of HWM14 are shown in Drob et al. [23]. The simulated results of horizontal winds at Wuhan were used in this study.

3. Results and Discussion

3.1. Case Study

In this study, the following formulae are used to determine the coincident wind observations from MIGHTI/ICON and meteor radar:

\[ |t_{ICON} - t_{Meteor}| \leq 1 \text{ h} \]  
\[ |Lat_{ICON} - Lat_{Meteor}| \leq 3^\circ \text{ and } |Lon_{ICON} - Lon_{Meteor}| \leq 3^\circ \]

where \( t_{ICON}, Lat_{ICON}, \text{ and } Lon_{ICON} \) are wind observation time, latitude, and longitude of MIGHTI/ICON, respectively. \( t_{Meteor}, Lat_{Meteor}, \text{ and } Lon_{Meteor} \) are wind observation time, latitude, and longitude of meteor radar, respectively.

To investigate the measuring accuracy of horizontal winds for MIGHTI/ICON, we used the horizontal winds obtained by meteor radar as a reference. It should be noted that the retrieved wind from meteor radar 1 h observations is a spatial average of true wind within the range of \( 200 \times 200 \text{ km} \) [5]. Figure 1 shows the coincident wind observations from MIGHTI/ICON and meteor radar on 7–8 October 2020. The analysis of Figure 1 shows that: firstly, since the measurement time and horizontal position of MIGHTI/ICON and meteor radar are not the same, the horizontal winds have certain deviations, the root-mean-square (RMS) differences for meridional wind and zonal wind in Figure 1a are 27.56 and 27.85 m/s, and the RMS differences in Figure 1b are 20.34 and 59.22 m/s; secondly, although there are deviations in the horizontal wind measurements for MIGHTI/ICON and meteor radar, they have the same trends in the distribution of height; and thirdly, the horizontal wind measurements for MIGHTI/ICON and meteor radar are more consistent at 90–100 km than those at 100–110 km.

In a qualitative sense, the horizontal wind measurements by MIGHTI/ICON and meteor radar overlap at 90–100 km. However, at 100–110 km, these differences exceed 50 m/s. The reason for this discrepancy may be that the horizontal wind measurement accuracy of meteor radar above 100 km has some errors [6].
3.2. Statistical Study

To estimate the precision of horizontal winds derived by MIGHTI/ICON, using the method described above, we statistically compared the thermospheric horizontal wind measurements obtained by MIGHTI/ICON, meteor radar, and HWM14 in the whole year of 2020. Since the meteor radar detects at a resolution of 2 km over 70–110 km in altitude and the MIGHTI/ICON detects at a resolution of 2.9 km over 90–110 km, we performed three spline interpolations of the MIGHTI/ICON detection data over 90–110 km in altitude. Then, the horizontal wind data for MIGHTI/ICON, meteor radar, and HWM14 in the altitude range of 90–100 km were used for comparative analysis.

We adopted the method of statistical comparison of geophysical data using multiple instruments with different accuracies proposed by Hocking et al. [26]. We denote the MIGHTI/ICON data sets as \( \{ x_i \} \) and the meteor radar data sets as \( \{ y_j \} \) from two instruments that measure the same physical quantity but have different sensitivities to its variabilities. The variability that both instruments can detect is denoted by \( v_i \) and \( g_0 v_j \) for the two instruments, respectively, where \( g_0 \) is a measure of the relative amplitude of the variability in two measurements.
\[ x_i = v_i + \delta x_i \] (3)
\[ y_i = g_0v_i + \delta y_i \] (4)
\[ \delta x_i \sim N(0, \sigma^2_x) \] (5)
\[ \delta y_i \sim N(0, \sigma^2_y) \] (6)

The calculation gives us the variance values \( s^2_x \) and \( s^2_y \) for \( x_i \) and \( y_i \), and the covariance value \( s^2_{xy} \). It is easy to obtain the correlation coefficient \( r \) and the functional relations between \( g_0 \) and \( \sigma_x \) and \( \sigma_y \) as:

\[ r = \frac{s_{xy}}{s_xs_y} \] (7)
\[ g_0 = \frac{s^2_{xy}}{s^2_x - \sigma^2_x} \] (8)
\[ g_0 = \frac{s^2_y - \sigma^2_y}{s^2_{xy}} \] (9)

Table 2 shows the correlation coefficients of the meridional and zonal winds obtained from MIGHTI/ICON and meteor radar at different altitudes. The correlation coefficients decrease with height, and the measurement deviation between MIGHTI/ICON and meteor radar increases with height. Due to the poor data quality for wind measurement from the meteor radar above 100 km, we only compared coincident thermospheric neutral wind data at 94, 96, and 98 km from MIGHTI/ICON and meteor radar at Wuhan.

Table 2. The correlation coefficients of the meridional and zonal winds obtained from MIGHTI/ICON and meteor radar at different altitudes.

| Height (km) | Number of Samples | Meridional Wind Correlation Coefficient | Zonal Wind Correlation Coefficient |
|------------|------------------|---------------------------------------|-----------------------------------|
| 94 km      | 709              | 0.65                                  | 0.79                              |
| 96 km      | 697              | 0.66                                  | 0.78                              |
| 98 km      | 636              | 0.63                                  | 0.70                              |
| 100 km     | 502              | 0.48                                  | 0.48                              |

Figure 2 shows the functional relations described by Equations (8) and (9). They show the relationship between the three variables \( g_0 \), \( \sigma_{\text{MIGHTI/ICON}} \), and \( \sigma_{\text{meteor radar}} \). The intersects of the curves with the \( y \)-axis are \( g_{\text{MIGHTI/ICON}} \) and \( g_{\text{meteor radar}} \), with \( g_{\text{meteor radar}} \) always larger than \( g_{\text{MIGHTI/ICON}} \), which means the MIGHTI/ICON dataset corresponds to a larger error. Comparing the changes in the four curves, we find that the change in \( g_{\text{MIGHTI/ICON}} \) with \( \sigma_y \) for the meridional winds is flatter, suggesting a greater error in the MIGHTI/ICON observations of the meridional winds.

Figure 3 shows scatter plots of the horizontal wind measurements from MIGHTI/ICON, meteor radar, and HWM14. Each data point indicates that it is from the same altitude and time. It is obvious from the Figure 3a that there is a strong correlation between horizontal wind measurements from MIGHTI/ICON and meteor radar. The correlation coefficients (fitting slopes) for meridional wind and zonal wind are about 0.65 (0.87) and 0.76 (0.85), respectively. Figure 3b compares the MIGHTI/ICON wind to HWM14 wind. The poor correlation with the maximum correlation coefficient of approximately 0.57 is found in Figure 3b. The fitting slopes for meridional wind and zonal wind are, respectively, 1.40 and 1.31, suggesting that the magnitude of horizontal winds obtained from HWM14 was relatively small.
Figure 2. Relations between \( g_0 \) and the errors \( \sigma \) for meridional wind and zonal wind at 94–98 km. The left column shows the meridional winds and the right column shows the zonal winds.

Figure 3. Scatter diagram of horizontal wind measurements from MIGHTI/ICON, meteor radar, and HWM14. The left side is for meridional winds, and the right side is for zonal winds. (a) MIGHTI/ICON-Meteor Radar; (b) MIGHTI/ICON-HWM14.

Figure 4 shows the distributions of the difference among the horizontal wind measurements from MIGHTI/ICON, meteor radar, and HWM14. The distributions of horizontal wind differences appear normal and peak around 0 m/s. The RMS differences are
39.21 and 46.44 m/s for meridional winds and 30.31 and 37.65 m/s for zonal winds in Figure 4a,b, respectively.

Figure 4 shows the distributions of the difference among the horizontal wind measurements from MIGHTI/ICON, meteor radar, and HWM14. The distributions of horizontal wind differences appear normal and peak around 0 m/s. The RMS differences are 39.21 and 46.44 m/s for meridional winds and 30.31 and 37.65 m/s for zonal winds in Figure 4a,b, respectively.

Figure 5 shows the distributions of the speed ratio and direction difference among the horizontal wind measurements from MIGHTI/ICON, meteor radar, and HWM14. The average of the radar/MIGHTI wind speed ratio is 1.08 and direction difference is $-1.36^\circ$ in Figure 5a. Similarly, the average of the HWM14/MIGHTI wind speed ratio is 0.57 and direction difference is $-3.11^\circ$ in Figure 5b.

Comparing the results shown above, it could be seen that the consistency of zonal wind measurements from MIGHTI/ICON and meteor radar is better than that of meridional wind measurements, which may be caused by the orbit configuration of the ICON satellite [14]. The measurement of meridional wind from MIGHTI/ICON is naturally less accurate than that of zonal wind due to the north–south motion of the ICON satellite around Wuhan. In addition, the consistency of zonal wind measurements between MIGHTI/ICON and HWM14 is also better than that of meridional wind measurements, which is agreement with the results of previous studies [25,27]. Tang et al. compared the horizontal wind measurements obtained by meteor radar and HWM14 and found that the consistency of meridional wind between model prediction and radar observation is worse than that of the zonal wind [25]. Taiwo et al. compared results from HWM14 with a Fabry–Perot interferometer (FPI) located in Sutherland, South Africa, and found a better
agreement between FPI measured winds and HWM14 modeled winds for the meridional component compared to the zonal component [27].

Figure 5. The distributions of the speed ratio and direction difference among the horizontal wind measurements from MIGHTI/ICON, meteor radar, and HWM14. The left side is for speed ratio, and the right side is for direction difference. (a) Meteor Radar-MIGHTI/ICON; (b) HWM14-MIGHTI/ICON.

In addition to the above-mentioned reasons for the satellite trajectories, another reason is that the meridional winds in the MLT region are significantly longitudinally dependent, which means that HWM14 cannot accurately predict the meridional winds based only on the limited longitude input [9,10,28,29]. The cause of this disagreement is not clear up to now. For example, Hu et al. studied MLT winds with MF radars in Wuhan (30° N, 114° E) and in Yamagawa (31° N, 131° E), and found the longitudinal variations in atmospheric gravity waves forcing may contribute to the differences in the mean winds and tides between Wuhan and Yamagawa [10]. Jacobi et al. studied mid-latitude MLT winds over Europe and Canada and found that the zonal prevailing winds in winter show partly opposite behavior at different longitudes, which may be explained by a stationary planetary wave (SPW) influence [29].

3.3. Day/Night Differences

To investigate the differences in measurement accuracy of MIGHTI/ICON during day and night, Figure 6 shows the scatter plots of the horizontal wind measurements from MIGHTI/ICON and meteor radar during day and night. It is obvious from Figure 6a that the correlation of meridional winds from MIGHTI/ICON and meteor radar is better at night than that during the day. The correlation coefficients (fitting slopes) for day and
night are about 0.60 (0.51) and 0.67 (0.53), respectively. Figure 6b compares the zonal wind measurements from MIGHTI/ICON and meteor radar during the day and night. Similarly, the consistency of the data measured at night is better than that during the day, the correlation coefficients (fitting slopes) for day and night are about 0.73 (0.59) and 0.89 (0.68), respectively.

Figure 6. Scatter diagram of horizontal wind measurements from MIGHTI/ICON and meteor radar. The left side is daytime measurement, and the right side is night measurement. (a) Meridional wind; (b) zonal wind.

By processing the data as before, we obtained 818 sets of data measured during the daytime and 1224 sets of data measured at night, where the daytime is from 06:00 to 18:00 and the rest of the time is considered as night. Comparing the correlation coefficients of horizontal winds from MIGHTI/ICON and meteor radar observations, we find a better agreement at night than during the day, and this difference is reflected in both meridional and zonal winds. Similar results were also observed by Harding et al., who compared MIGHTI-A/B with meteor radar results in day/night mode [19]. In this regard, we speculate that the difference in the measurement patterns taken by MIGHTI during the day and night is the reason. For example, the exposure is 30 s instead of 60 s in day mode, and the aperture is stopped at 15% of the nighttime aperture [15,19].

Additionally, we calculated fitted slopes in all four cases in Figure 6 and found that the wind field measurements by MIGHTI/ICON are larger than those by meteor radar, which is reflected in both day/night mode and meridional/zonal winds. This is also effectively illustrated by the ratio of velocities plotted in Figure 5. This difference in horizontal wind measurement is shown in previous comparisons of both satellite-based soundings and ground-based observations [30,31]. Hasebe et al. compared MLT wind velocities measured...
by the High-Resolution Doppler Imager (HRDI) on board the Upper-Atmosphere Research Satellite (UARS) and meteor radars located at Shigaraki, Japan, and Jakarta, Indonesia [30]. The median of the speed ratio (HRDI/radar) is 1.379 in the meteor mode for the Shigaraki MU radar. Wu et al. compared the TIDI meridional winds with meteor radar measurements at Maui. The meteor data show smaller diurnal tide amplitude than that shown in the TIDI data [31].

3.4. Seasonal Differences

It is well known that the horizontal winds not only have day and night variations, but also change with the seasons [25]. Figure 7 shows the monthly mean variation in horizontal winds observed by MIGHTI/ICON and meteor radar. The monthly mean zonal wind is mainly eastward in summer and prevailing westward in winter, and the southward monthly mean meridional wind is dominant in Wuhan. Similar seasonal variations in horizontal winds obtained by Wuhan meteor radar were also shown in Zhao et al. [32]. In Figure 7, we find an excellent correlation (r = 0.96) between the zonal winds, which are generally consistent in terms of trend and amplitude, but some differences in some months in the meridional winds result in a poor correlation (r = 0.66), which could be explained by the orbit configuration of the ICON satellite [14].

![Figure 7](image)

Figure 7. The monthly variations in monthly average of horizontal winds. The error bars are the standard deviation of the monthly average of horizontal winds. The left column shows the meridional winds and the right column shows the zonal winds.

In Figure 8, we further plotted the scatter plots of MIGHTI/ICON and meteor radar measurements of horizontal winds with seasonal variations. The MIGHTI/ICON and meteor radar measurements all show a good consistency in different seasons, and the consistency of both is better in spring and autumn than that in summer and winter. The reasons may be that the existence of strong shears of horizontal winds and intermittent gravity waves could cause violent local horizontal wind variations, particularly in the winter MLT region at mid-latitudes, which can result in the discrepancy between MIGHTI/ICON and meteor radar due to the instrument biases [32,33].
Figure 8. Scatter diagram of horizontal wind measurements from MIGHTI/ICON and meteor radar. The left side is meridional wind, and the right side is zonal wind. From top to bottom: Spring (January, February, and March), summer (April, May, and June), autumn (July, August, and September), and winter (October, November, and December).
4. Conclusions

This study first introduced the horizontal wind measurements by MIGHTI/ICON, meteor radar and the HWM14 model, and then validated the horizontal wind measurement accuracy of MIGHTI/ICON based on the measurement results of a meteor radar at Wuhan station and the simulation results of HWM14. The statistical analysis led to the following conclusions:

1. According to the statistical analysis of measurement results of MIGHTI/ICON, meteor radar, and HWM14 model, the measurement accuracy of zonal wind \((r = 0.76, 0.57)\) from MIGHTI/ICON is better than that of meridional wind \((r = 0.65, 0.45)\).

2. MIGHTI/ICON horizontal wind measurement accuracy at 95–100 km is better than that at 100–110 km. The reason may be that the horizontal wind measurement accuracy from the meteor radar at 100–110 km is more inaccurate.

3. Comparing the correlation coefficients between MIGHTI/ICON and meteor radar observations of horizontal wind, we find a better agreement at night \((r = 0.67, 0.77)\) than during the day \((r = 0.60, 0.68)\), and the consistency is better in spring and autumn than that in summer and winter.

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Data Availability Statement: The Meteor radar data used in this study are from the website of world data center for Geophysics, Beijjing: http://wdc.geophys.ac.cn/index.asp (accessed on 1 January 2022). This analysis used v04 of the Level 2.2 ICON-MIGHTI data, which is available at the Space Physics Data Facility (https://spdf.gsfc.nasa.gov/pub/data/icon/12/ (accessed on 1 January 2022)).

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