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Vertical Wind Profiles in the Mesosphere and Lower Thermosphere Driven by Meteor Radar and Ionospheric Connection Explorer Observations Over the Korean Peninsula

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Key Points:

- Vertical wind profiles above 80 km are derived from meteor radar and Ionospheric Connection Explorer (ICON) observations over Korea
- These observations produce continuous wind profiles at night, but discontinuity exists between two measurements during daytime
- Significant vertical variation in airglow intensity on the dayside can impact wind retrieval from ICON airglow observations

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Abstract

Meteor radar observations provide wind data ranging from 80 to 100 km altitude, while the Michaelson Interferometer for Global High-resolution Thermospheric Imaging (MIGHTI) onboard the Ionospheric Connection Explorer satellite offers wind data above 90 km altitude. This study aims to generate wind profiles in the mesosphere and lower thermosphere by combining the winds derived from meteor radar and MIGHTI observations over the Korean Peninsula from January 2020 to December 2021. The wind profiles derived from the two instruments are continuous at night, but they show discrepancies during the day. The atomic oxygen 557.7 nm (green line) emission intensity measured by MIGHTI peaks at approximately 100 km during the day and 94 km at night. The vertical gradient of the airglow volume emission rate is more pronounced during the day. These differences can cause day-night differences in the MIGHTI wind retrieval accuracy, potentially leading to discrepancies during the day.

Plain Language Summary

This study aims to derive vertical wind profiles in the mesosphere and lower thermosphere (MLT) by integrating wind measurements from different techniques. Neutral winds in the MLT provide a means to study the activity of various atmospheric waves originating from the lower thermosphere and their propagation to the upper thermosphere. The Michelson Interferometer for Global High-resolution Thermospheric Imaging (MIGHTI) instrument onboard the Ionospheric Connection Explorer satellite provides wind measurements above 90 km altitude. A meteor radar in Korea provides wind data in the altitude range of 80–100 km. By combining the MIGHTI and meteor radar observations, we derive extended wind profiles in the MLT. While nighttime winds driven from two different techniques show good agreement, discrepancies exist in daytime winds. Vertical gradients in airglow intensity can affect the wind retrieval from MIGHTI's airglow measurement, and this factor can be one of the sources of daytime discrepancy.

1. Introduction

The mesosphere and lower thermosphere (MLT) region, spanning an altitude range of approximately 70–150 km, is influenced by a variety of atmospheric waves, including planetary waves, atmospheric tides, and gravity waves that originate from lower altitudes. This region coexists with the D- and E-layers of the ionosphere. Neutral winds in the MLT play a crucial role in understanding atmospheric wave activities and their propagation to the upper thermosphere (Fritts & Alexander, 2003). They are equally important for understanding the dynamics and chemical processes in the ionosphere. However, our understanding of MLT winds remains incomplete due to a lack of observations; this region exists at altitudes too high to be directly accessed by ground-based instruments, yet it remains too low to be reached by in situ satellites.

Meteor radars on the ground have been equipped to measure neutral winds and temperature in the lower part of the MLT region (Beard et al., 1997; Beldon & Mitchell, 2010; Day & Mitchell, 2010; Huang et al., 2013; Kam et al., 2021; C. Lee et al., 2021). Meteoroids entering the Earth's atmosphere leave ionization trails, and meteor radars detect backscattering echoes of transmitted radio signals from meteor trails. As the horizontal movement of meteor trails is primarily influenced by the movement of the background atmosphere, the Doppler shifts of the returned signals from meteor trails provide information about local neutral winds. Atmospheric temperature is driven from the measurement of the decay time of the echo power. However, meteor radar measurements are limited to a narrow altitude range of 80–100 km.

The Ionospheric Connection Explorer (ICON) satellite, which was launched on 10 October 2019 and contact was lost on 25 November 2022, represents the most recent mission providing neutral wind measurements in the MLT region and at higher altitudes. Among the four payloads of ICON, the Michelson Interferometer for Global High-resolution Thermospheric Imaging (MIGHTI) instrument provides neutral wind and temperature measurements within the altitude range of 90–300 km. Validation of the MIGHTI wind data has been conducted through comparisons with various ground-based and space-based observations. Harding et al. (2021) reported a strong correlation between the winds driven from MIGHTI and meteor radar observations. However, this comparison focused on the line-of-sight directions rather than horizontal components. Makela et al. (2021) validated the MIGHTI wind data through comparison with the wind measurements by the Fabry–Perot Interferometers at stations in Morocco and the United States. Substantial agreement was found among these observations, but this comparison was limited to nighttime observations. Dhadly et al. (2021) identified similar diurnal wind patterns from the MIGHTI and Thermosphere, Ionosphere, Mesosphere Energetics & Dynamics (TIMED)/Doppler Interferometer (TIDI) observations. However, the comparison was incomplete due to a systematic bias in the TIDI data in a specific direction. Chen et al. (2022) derived the vertical wind profiles in the MLT region by combining the MIGHTI and meteor radar wind data over China. In their results, the winds derived from the two measurements at night exhibited better agreement compared to those derived from the measurements during the day. The validations in previous studies indicate that wind measurements by MIGHTI are comparable to those obtained from other instruments, albeit the magnitudes of deviations vary with geographic and geophysical conditions. These deviations may arise from spatial gradients in the airglow and winds, as well as differences in viewing geometries of different techniques (Makela et al., 2021).

A meteor radar in Korea, located at Daejeon (longitude: 127.1°E, latitude: 36.2°N), has been operated since October 2017 by the Korea Astronomy and Space Science Institute (KASI) (Kam et al., 2021). The period of KASI meteor radar (KASI-MR) observations overlaps that of MIGHTI observations, and this study derives vertical wind profiles in the MLT region by combining the observations of the two instruments. This study also aims to provide additional evidence for the day-night differences in agreement between MIGHTI and meteor radar winds, as previously identified in observations over China (Chen et al., 2022). Among the sources contributing to the day-night difference, we discuss the effect of vertical gradients in the airglow intensity on the retrieval of winds from MIGHTI airglow observations.

2. MIGHTI and KASI-MR Data Description

MIGHTI comprises two identical sensors, labeled A and B, which are positioned with 90° offsets in the direction of the northern limb (Englert et al., 2017, 2023). Through the limb scanning technique, MIGHTI observes the volume emission rates (VERs) of atomic oxygen (OI) 557.7 nm (green) and 630.0 nm (red) lines, covering altitudes ranging roughly from 88 to 300 km. The VER profiles are the inverted fringe amplitude (Makela et al., 2021). Although VERs are not completely calibrated, the absolute values of VER are not crucial for this study because we focus on the relative intensities between altitudes. Doppler shifts in these spectral lines result from the bulk motion of atomic oxygen, from which neutral winds are inferred using MIGHTI's Doppler shift measurements (Harding et al., 2017, 2021). Our analysis employs Level 2.2 Version 5 MIGHTI data collected between January 2020 and December 2021, exclusively utilizing high-quality data (data quality = 1). Specifically, MIGHTI data for comparison with KASI-MR wind data are constrained to the vicinity of the Korean Peninsula, within the latitude range of 31.2°–41.2°N and longitude range of 122.1°−132.1°E. Only the winds driven from airglows in the green line (557.7 nm) are used, as our focus is the winds in the lower MLT region.

KASI-MR consists of one transmitter and five receiver antennas. The central frequency and transmitting peak power are 40.8 MHz and 24 kW, respectively. While KASI-MR detects meteor trails within the altitude range of 80–100 km, wind measurements are considered reliable at altitudes of approximately 82–96 km due to the inadequate number of meteor echoes outside this altitude range for accurate wind retrieval.

Figure 1a illustrates the longitude and latitude ranges encompassing the MIGHTI data employed in this study. The location of the meteor radar is marked by a red star symbol, while the available MIGHTI data points on 14 August 2021 are marked by black dots. The times of MIGHTI observations are in the format hour:minute:second. The

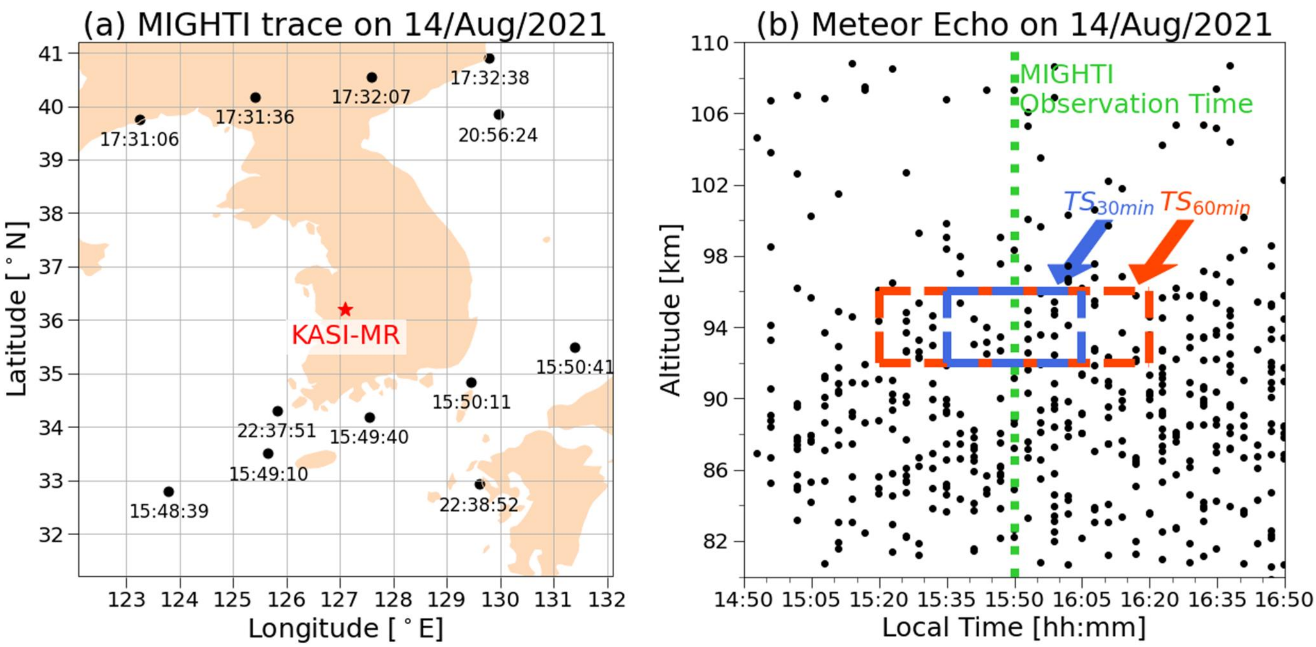

Figure 1. Illustration of MIGHTI and KASI-MR data. (a) ICON/MIGHTI data (black dots) on 14 August 2021 used for comparison with KASI-MR data. The MIGHTI observation times are Korean Standard Time (KST) in the format hour:minute:second. The KASI-MR location is marked by a red star symbol. (b) Distribution of meteor echoes detected by KASI-MR around one of the MIGHTI observation times (15:50 KST). As an illustrative example, the KASI-MR wind velocities at 94 km altitude are calculated using the data within the blue (30-min time segments, TS_{30min}) and red (60-min time segment, TS_{60min}) boxes for comparison with the MIGHTI winds at 15:50 KST.

provided time is in Korean Standard Time (KST), which is 9 hr ahead of Universal Time. Figure 1b shows the distribution of KASI-MR data at approximately 15:50 KST.

MIGHTI winds are derived from airglow observations conducted for 30 s during the daytime and 60 s during the nighttime. To make a comparison with MIGHTI winds, we calculate wind velocities using KASI-MR data within 4-km altitude bins spaced every two km. These data are collected over various time segments: 10, 20, 30, 40, 50, and 60 min, all centered on a MIGHTI observation time. As an illustrative instance, wind velocities at 94 km altitude and 15:50 KST are calculated using data confined within the blue and red boxes, corresponding to 30- and 60-min segments, respectively. The computation of wind velocities across different time segments serves to evaluate the temporal variations in winds within a local region.

Cardinal winds of KASI-MR are estimated from the line-of-sight wind speed of each echo for a specific time such as 30- or 60-min. The error in KASI-MR winds means the standard deviation of the line-of-sight wind speed of each echo used to estimate the cardinal wind of KASI-MR. On the other hand, the uncertainty arises from the systematic error when MIGHTI cardinal winds are estimated. Therefore, the errors in KASI-MR winds and MIGHTI winds do not provide identical information on the uncertainty of winds. Hence, we did not display the uncertainty of winds and utilized only "'Good Quality" data to reduce potential uncertainties in wind measurements.

3. Results and Discussion

Our results obtained from case studies and statistical analyses are presented in Figure 2. The vertical profiles of daytime zonal and meridional winds derived from the MIGHTI and KASI-MR observations are compared in Figure 2a. The MIGHTI observation time is 15:49:40 KST on 14 August 2021. MIGHTI data are shown with black dots and lines, and the KASI-MR winds derived for different time segments are distinguished by colors. Nighttime winds observed at 01:20:49 KST (MIGHTI observation time) on 9 August 2021 are shown in Figure 2b using the same format. The KASI-MR winds for different time segments overlap, indicating that the variation in winds over a 30-min period in the local region is not significant. Vertical shears in horizontal winds are more clearly discernible through the combination of the MIGHTI and KASI-MR wind data compared to utilizing data

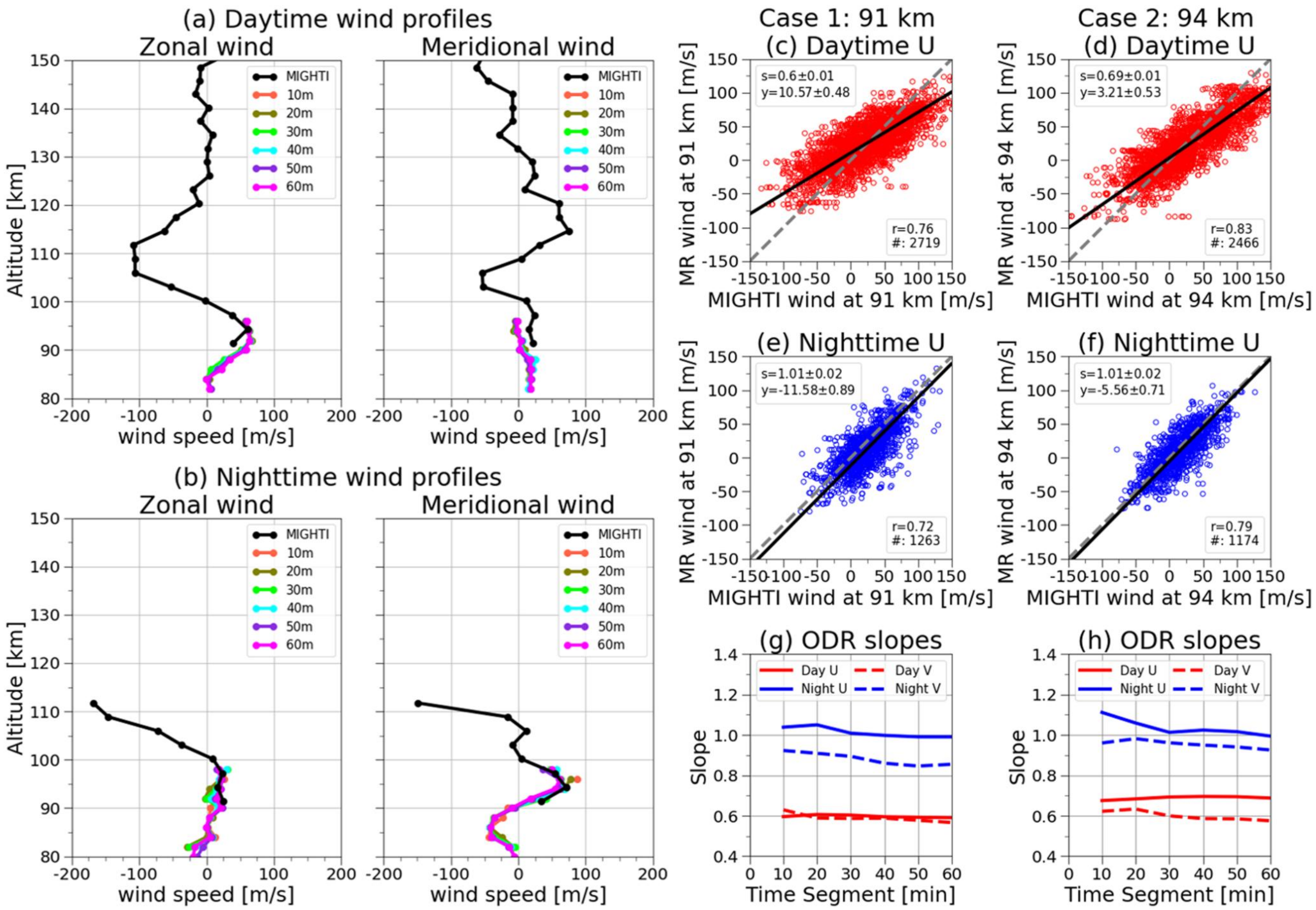

Figure 2. Comparison of MIGHTI and KASI-MR wind data. (a) Daytime (15:49:40 Korean Standard Time (KST)) wind profiles on 14 August 2021. MIGHTI zonal and meridional winds are shown as black dots. KASI-MR winds derived from the data collected during different time segments are distinguished by colors. (b) Nighttime (01:20:49 KST) wind profiles on 9 August 2021 using the same format. (c and d) Comparison of MIGHTI and KASI-MR daytime zonal winds at 91 and 94 km altitudes. See the text for the definitions of the parameters in the plots. (e and f) Comparison of nighttime zonal winds with the same format. (g and h) orthogonal distance regression slopes between MIGHTI and KASI-MR winds at 91 and 94 km altitudes. KASI-MR winds are calculated for 6 time segments. Zonal and meridional winds are differentiated by line styles (U: solid line, V: dashed line), and daytime and nighttime winds are distinguished by colors (daytime: red, nighttime: blue).

from a single instrument. Our focus lies in examining the continuity of the winds at altitudes where the two observations overlap. The MIGHTI and KASI-MR winds exhibit good agreement at night, yielding continuous vertical wind profiles. During the day, we can observe vertically extended wind patterns from the MIGHTI and KASI-MR data, but discrepancies exist between the two observations. The difference in agreement between the two observations during the day and night is a common characteristic identified in observations on other days.

The relationship between the MIGHTI and KASI-MR winds is investigated by applying the Pearson correlation and orthogonal distance regression (ODR) methods to all data acquired from January 2020 to December 2021. The investigation is conducted for data at two altitudes: 91 km (Case 1) and 94 km (Case 2). For the purpose of statistical analysis, the data are divided into two time zones: daytime and nighttime. Daytime is defined as the period from 2 hr after sunrise to 2 hr before sunset KST, while nighttime is defined as the period from 2 hr after sunset to 2 hr before sunrise KST. The periods of daytime and nighttime vary throughout the year due to the changing sunset and sunrise times.

The results for the two cases are shown in Figures 2c–2h. The upper panels (c and d) present daytime zonal winds (U), and the middle panels (e and f) present nighttime zonal winds at 91 and 94 km. In each plot, the data points in the 30-min segment are represented as colored circles. The solid black line is the linear fitting line, with "*s*" denoting the ODR slope, "*y*" indicating the *y*-axis intercept of the fitting line, "*r*" representing the Pearson correlation coefficient, and "#" indicating the data count in the plot. For the daytime data, the range of variation in

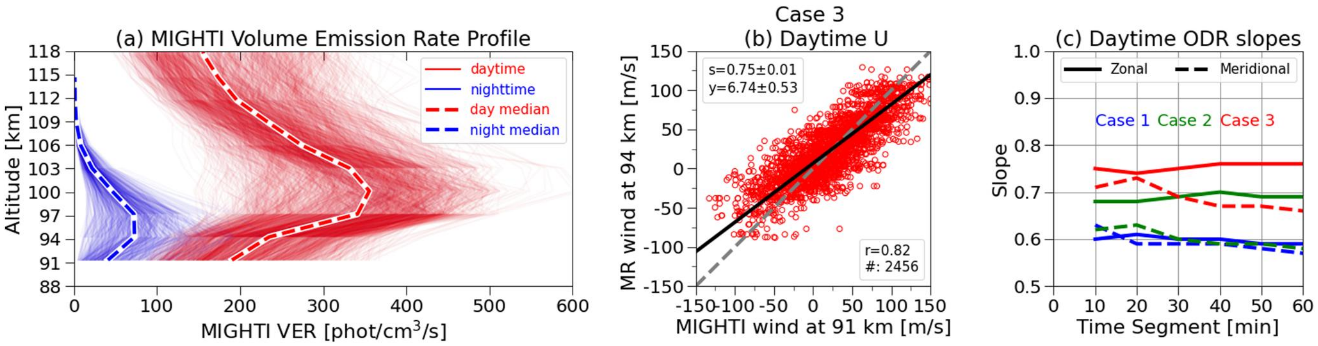

Figure 3. Investigation of the effect of vertical gradients in the volume emission rate on the daytime wind retrieval from MIGHTI observations. (a) Vertical profiles of daytime (red) and nighttime (blue) airglow intensity (OI 557.7 nm) measured by MIGHTI from January 2020 to December 2021. The thin lines are the profiles obtained at each MIGHTI observation time, and dashed lines are the median intensities. (b) Comparison of the MIGHTI zonal winds at 91 km altitude and KASI-MR zonal winds at 94 km altitude. (c) Orthogonal distance regression slopes for three cases as a function of time segments. Zonal and meridional winds are distinguished by line styles (U: solid line, V: dashed line), and cases are distinguished by colors (Case 1: blue, Case 2: green, Case 3: red).

MIGHTI winds is greater than that of KASI-MR winds, contributing to a slope less than 1 in the fitting line. During nighttime, the MIGHTI and KASI-MR winds exhibit a strong correlation, as demonstrated by the slope values approaching 1. From a similar investigation for meridional winds (V), the same underlying characteristics were identified. The lower panels (g–h) present the ODR slopes (s) for both zonal and meridional winds obtained from data collected during different time segments. Zonal and meridional winds are differentiated by line styles (U: solid line, V: dashed line), and daytime and nighttime winds are distinguished by colors (daytime: red, nighttime: blue). The results remain consistent across various time segments, aligning with the observations presented in Figures 2a and 2b.

Our results reveal substantial agreement between the MIGHTI and KASI-MR nighttime winds. This finding indicates that combining the wind data from these two instruments yields dependable vertical wind profiles in the MLT region. However, for daytime winds, persistent and systematic discrepancies exist between the two sets of observations. The difference in agreement between the MIGHTI and MR winds during the day and night is a recognized phenomenon observed at different locations. Besides, we also confirm the MIGHTI winds are larger than the meteor radar winds like other results in Chen et al. (2022) and Harding et al. (2021). Our observations further contribute to this understanding by providing additional evidence for the day-night difference.

The heights of meteor echoes can be precisely determined from MR observations (Holdsworth, 2005; Holdsworth et al., 2004). Conversely, wind retrieval from MIGHTI airglow observations can be influenced by variations in airglow intensity over time, altitude, longitude, and latitude (Gao et al., 2012; Wu et al., 2020). Figure 3a displays the daytime (red) and nighttime (blue) VERs of the OI 557.7 nm line. These profiles encompass all MIGHTI data utilized in this study. The dashed lines represent median VERs obtained by binning the data at a 3 km resolution. The day-night difference in the VER profiles provides insight into interpreting the observed day-night differences in agreement between the MIGHTI and MR winds. The VER at a specific altitude from MIGHTI's limb scanning is a measure of the emission occurring along the line-of-sight within a defined altitude range. Any irregularities within the emission along the line-of-sight or within the altitude range can influence the wind retrieval at that particular altitude. The vertical gradient in the VER during daytime is much greater than that during nighttime. Consequently, the impact of the emissions originating from various altitudes on the wind retrieval at a specific altitude can be considerably more pronounced during daytime than during nighttime. At night, the influence of emissions from other altitudes on the wind retrieval at an altitude of approximately 94 km is not significant because the VER has the maximum value around this altitude. However, on the dayside, the wind retrieval below 100 km altitude can be influenced by emissions from higher altitudes, as the VER peak occurs at approximately 100 km altitude.

In an attempt to assess the influence of the vertical VER gradient on wind retrieval, Case 3 involves a comparison between MIGHTI winds at 91 km altitude and KASI-MR winds at 94 km altitude. In this scenario, the assumption is made that the MIGHTI winds at 91 km altitude provide a more accurate representation of actual winds at 94 km altitude than the MIGHTI winds directly collected at 94 km altitude. This assumption is based on the strong emissions originating from higher altitudes, which can significantly impact the measurements taken at 94 km altitude.

Figure 3b shows the relationship between the MIGHTI zonal winds at 91 km altitude and KASI-MR zonal winds at 94 km altitude in 30-min segments during daytime. Their relationship is slightly enhanced compared to that in Case 2 shown in Figure 2. To facilitate comparison with other cases, the slopes (s) obtained from three cases are presented together in Figure 3c. The line styles distinguish zonal and meridional winds (U: solid line, V: dashed line), and the colors differentiate the cases (Case 1: blue, Case 2: green, Case 3: red). The correlation between MIGHTI and KASI-MR winds displays an ascending trend from Case 1 to Case 3. The enhancement in correlation observed in Case 2 (94 km), as compared to Case 1 (91 km), could suggest a more pronounced influence of emissions from different altitudes when the VER at a given altitude is low. The enhanced correlation observed in Case 3, surpassing Case 2, potentially lends support to our aforementioned assumption. While a comparison between MIGHTI winds at 94 km and KASI-MR winds at higher altitudes (e.g., 97 km) could offer additional insights, the limited availability of KASI-MR echo data at higher altitudes inhibits us from conducting such an investigation. For such reasons, we do not know what altitude's VER has the most impact on the MIGHTI winds at an altitude of 91 km (specifically, the VER at 94 km or higher).

4. Conclusion

We evaluated the production of reliable vertical profiles of horizontal winds in the MLT region by combining wind measurements from the ICON/MIGHTI and KASI-MR instruments. The investigation utilized the MIGHTI (green line) and KASI-MR data spanning January 2020 to December 2021. MIGHTI data, employed for comparison with KASI-MR wind data, were constrained within ±5° in both longitude and latitude from the KASI-MR location (127.1°E, 36.2°N). While MIGHTI and KASI-MR winds exhibit strong agreement during the night, discrepancies in the two data sets arise during the day. The disparity in agreement between MIGHTI and MR winds during daytime and nighttime is a recognized phenomenon. However, our observations contribute to a deeper understanding of this phenomenon by providing additional evidence.

The vertical gradients in airglow intensity can serve as potential sources of daytime discrepancies between the two data sets. Our experimental test, built upon this assumption, improves the agreement between the two data sets. However, it accounts for only a partial explanation for daytime discrepancies; the correlation for daytime data remains noticeably lower than that for nighttime data. Should significant spatial wind variation exist within the local region during daytime, this factor could also contribute to the observed discrepancies between the MIGHTI and KASI-MR winds.

Data Availability Statement

Korea Astronomy and Space Science Institute (KASI) meteor radar wind data are available from J. Lee (2023). The ICON-MIGHTI data are processed in the ICON Science Data center at UCB and available at https://icon.ssl.berkeley.edu/Data.

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