INTENSITY IDENTIFICATION OF TYPHOON HAIKUI (1211) DURING THE LANDING STAGE

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ABSTRACT

In daily typhoon operation, identifying the intensity of typhoons is always a contentious problem, which can be attributed to the absence of direct observational data when typhoons are present on the ocean. When typhoons move to the offshore region, where many automatic weather stations (AWSs) are present, utilizing automatic observations in non-standard conditions is a good way of identifying the intensity or wind of a typhoon. Before identification, AWS data should be conversed or revised based on statistical experiences from a multilayer wind tower.

In this study, the intensity of Haikui (1211) at the landing stage (from 08071200 UTC to 08071920 UTC) is revised carefully. Calculating the wind conversion coefficient between different heights from a 300m multilayer tower observation, the wind data caught by two offshore AWSs were converted to the standard wind of 10 meters and used to identify the intensity of the landing Haikui. The maximum surface wind of Haikui in the landing period was about 45 m/s to 48 m/s and then reduced to 40 m/s to 42 m/s approximately just before landing.

On the basis of the discussion in this study, the AWS data in a non-standard environment can be utilized to determine the surface wind at 10 m height by arithmetic conversion. This implies that we should pay more attention and patient to the wind data observed in offshore island AWSs during typhoon identification.

Keywords: typhoon intensity identification, automatic weather station data, surface wind conversion

1. Introduction

In 2012, 25 tropical cyclones occurred over the West Pacific, in which 6 of them landed on China. Among these 6 landed typhoons, the 11th typhoon “Haikui” (1211) is one of the most severe threats to mainland China and caused several hazardous disasters including heavy precipitation, windstorms, and storm surges. Haikui was born in Central Pacific (about 140.7°N, 23.2°N) at 08030000 UTC and landed on Xiangshan in Zhejiang Province, China at 08071920 UTC. Haikui was graded “severe typhoon” according to the National Meteorological Center of China Meteorology Agency (NMC-CMA). The major characteristics of Haikui during its life period included generation in the high latitude area, rapid intensification just before landing, and stagnation after landing, which induced persistent rainstorm in Southeast China. However, the intensity of Haikui, particularly during landing stage, was evaluated differently by different typhoon operation centers, including China Meteorogical Administration (CMA), Japan Meteorology Agency (JMA), and Joint Typhoon Warning Center (JTWC) of United States. The intensity identification result of Haikui in the landing ranged from 48 m/s, which was estimated by NMC-CMA), to 33 m/s, which was estimated by JTWC prior to landfall. The differences among tracks from different reports are quite minimal, as shown in Fig. 1. However, the criteria of typhoon intensity referred by different operation centers are different, e.g., 2-min average wind speed is used by CMA, 1-min average wind speed is used by JTWC, and 10-min average wind speed is used by JMA. Given these different criteria considered by operation centers, the forecast reports of the operation centers are incompatible and would lead to operation problems. The primary purpose of this study is to verify the intensity of Typhoon Haikui at landing stage by examining observational data especially to the AWS data . The capability of anemometers of AWSs, particularly the stations located in islands or mountains gathering wind data at a height of dozens of meters, was doubted in determining the

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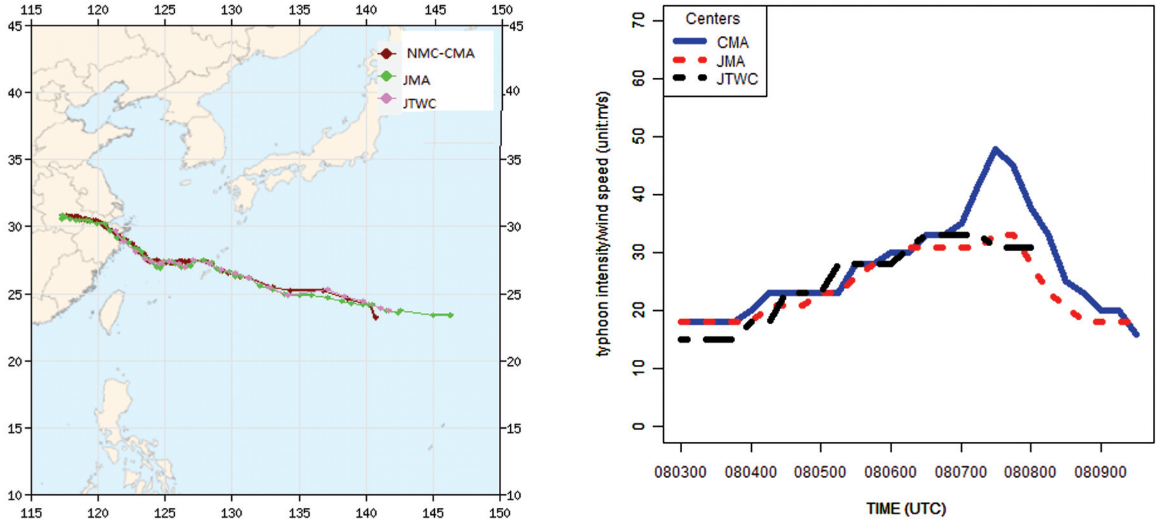

FIG. 1. Track (left) and intensity (right) information of Haikui from different operation centers.

position of typhoons because the environment of AWSs is not uniform and standard. To clarify this problem of AWSs, this study will try to explore the utility of near-surface anemometer AWS data in the flow chart of operation typhoon positionand will discuss the potential of AWSs on offshore islands in indentifying typhoon intensity during landfall.

This study will briefly review the landfall process lifetime of Haikui by weather diagnosis and radar analysis in the third section after introduce the data used in this study in the section 2e. In Sections 4, we will diagnose the evolution of Haikui before landing and then verify the intensity by surface observations. A brief summary will be given in the last section.

2. Introduction of Dataset and Method

The data used in this study include final analysis dataset from CFSRV2 (Saha et al.2010), Doppler radar data collected by Ningbo radar (about 30.070°N, 121.509°E, 458.40 m in altitude), and black body temperature from the multifunctional transport satellite of JMA. The near-surface wind-observation data came from the tallest power energy tower (PET) in the world, which is located in Liangmaoshan Island of Ningbo (29.95°N, 122.03°E, 24.5 m in altitude, as shown in Fig. 2b). Ningbo is an area frequently affected by typhoons during summer and has two AWSs (Dongji Island at about 121.93°E, 28.72°N, 76 m in altitude; Dachen island at about 121.90°E, 28.45°N, 86 m in altitude, as shown in Figs. 2c–2d). PET and AWSs were deployed on separated islands to gather wind accurately (Figs. 2b–2d). Multilayer two-dimensional wind anemometers in the PET were installed at 32, 89, 212, and 298 m above ground level at a 10 Hz time resolution. The wind anemometers were utilized in this study mostly in 1 min resolution. The average wind data of AWSs in Dongji and Dachen are 2 min. The track and intensity information for Haikui in this paper came from the CMA forecast result. The typhoon reports of JMA and JTWC and the satellite objective report of NSMC-CMA were also used in the discussion on the intensity of Haikui before landing (Figs. 1a to 1b).

3. Review of the Hakui's landfall

a. Weather diagnosis of the landfall

At 08060000 UTC, Haikui arrived at the conjunction area between continent subtropical high (CSH) and West Pacific subtropical high (WPSH) and slowed (figures omitted) its western movement. Two high-pressure systems (including CSH and WPSH) and two low systems (Haikui and Asia trough located in the Japan islands) formed a typical saddle shape of geopotential field. This type of weather situation is weak and would slow down the movement of Haikui.

At 08070000 UTC, the structure of Haikui is not compact and symmetric (Figs. 3a–b). After Haikui gradually moved closer to mainland China, the friction impact of the islands and terrains was enhanced, which has a negative effect on the development and persistence of Haikui. However, in the subsequent 12 h to 36 h before landing, the cloud of Haikui became more condensed. According to the report of NMC-CMA (Figs. 4a–4b), the typhoon strengthened and became a severe typhoon with maximum intensity of 48 m/s. This phenomenon can be caused by the interaction of the typhoon with the enhanced southwest monsoon and lower troposphere monsoon trough of low-pressure systems, as represented by the green solid line in Fig. 4. The persistent southwest monsoon transported abundant moisture into the internal circulation, which is quite favorable to the inten-

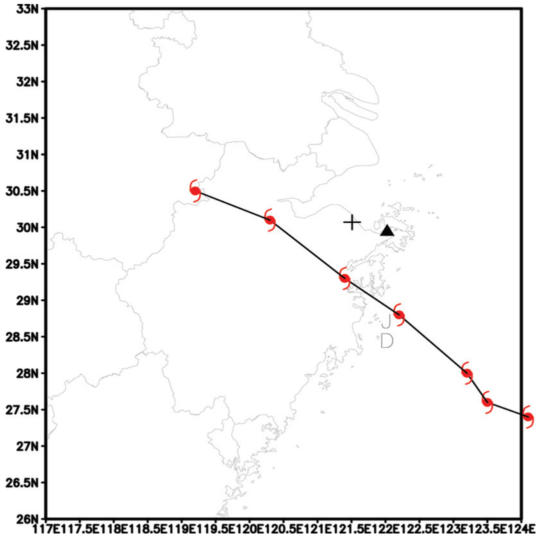

Fig. 2a. Track of Haikui at the landing stage (+ denotes Ningbo Radar, ▲ denotes PET in Liangmaoshan Island, J denotes the AWS in Dongji Island AWS, D denotes the AWS in Dachen Island).

Fig. 2b. Air photo of a PET in Liangmaoshan Island.

Fig. 2c. Satellite photo of AWS in Dongji Island (the yellow signal denotes the position of AWS).

Fig. 2d. Satellite photo of AWS in Dachen Island (the yellow signal denotes the position of AWS).

sification of the typhoon. Different operation centers have different opinions regarding the intensity of Haikui in this stage. For instance, JMA and JTWC determined that Haikui is a severe tropical storm with maximum surface wind at about 30 m/s to 33m/s (Fig. 1b), whereas NMC-CMA judged the intensity to be 48 m/s. To verify the intensity of Haikui, we will diagnose the structure and intensity of Haiku by radar and wind data in the next two sections.

b. Evolution of Haikui during landfall stage according to radar data

At about 1200 UTC of 7 August, the spiral rainband of Haikui began to touch the coastline of Zhejiang Province and hit the east of Zhejiang, as observed by the Ningbo radar (Fig. 4). The maximum reflectivity of the radar is about 40 dBz to 45 dBz. After 3 h, the eyewall, which was caught by the Ningbo radar, evolved an asymmetric structure. The main convective region was located in the northwest part of Haikui, which is near the Ningbo radar station and Liangmaoshan Island. At 08071802 UTC, which is approximately 1 h before landing, the structure of the typhoon began to dissipate gradually. The weakened

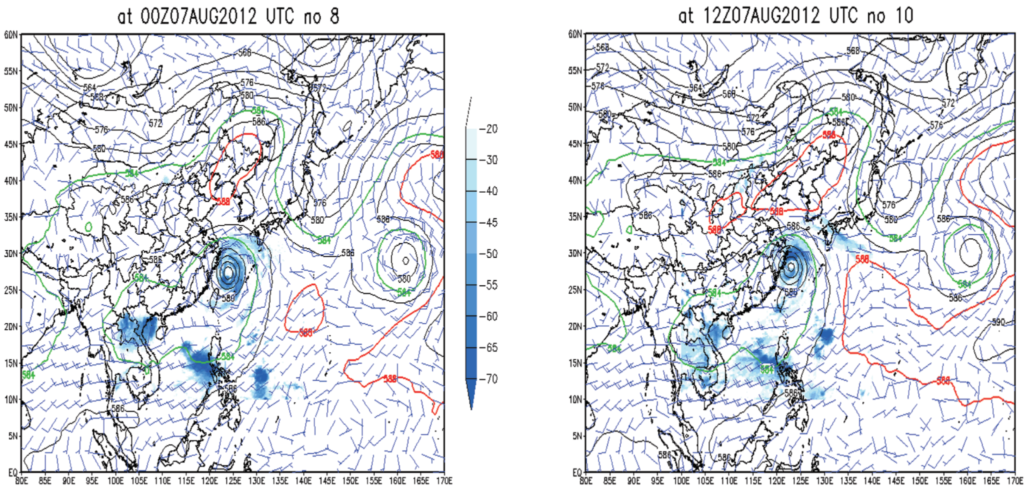

FIG. 3a. 08070000 UTC. **FIG. 3b**. 08071200 UTC.

500 hPa geopotential height (unit: 10 m) and 850 hPa wind field (m/s) analysis and black body temperature by MTSAT Satellite (unit: °C).

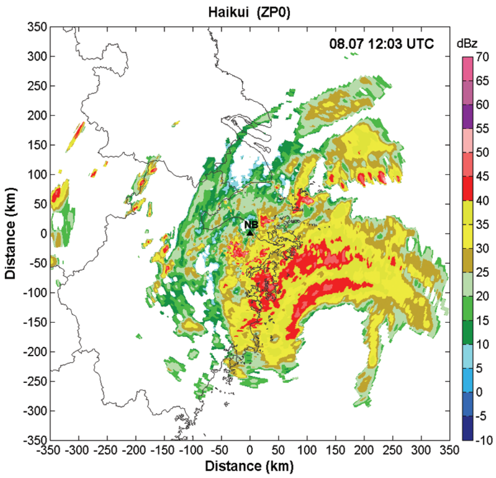

FIG. 4a. Reflectivity of Ningbo radar at 08071203 UTC (unit: dBz).

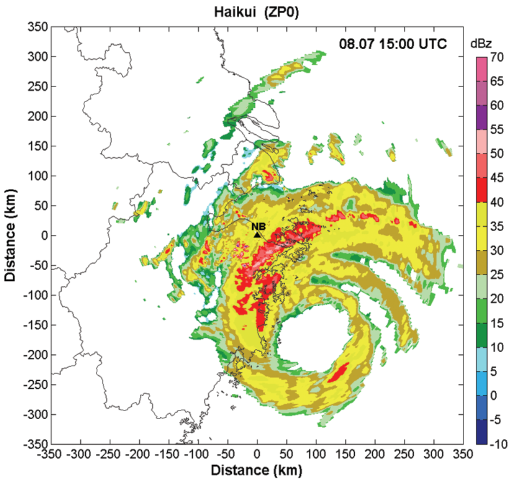

FIG. 4b. Reflectivity of Ningbo radar at 08071500 UTC (unit: dBz).

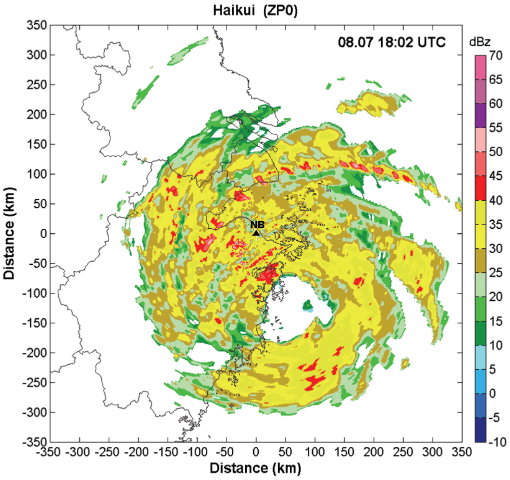

FIG. 4c. Reflectivity of Ningbo radar at 08071802 UTC (unit: dBz).

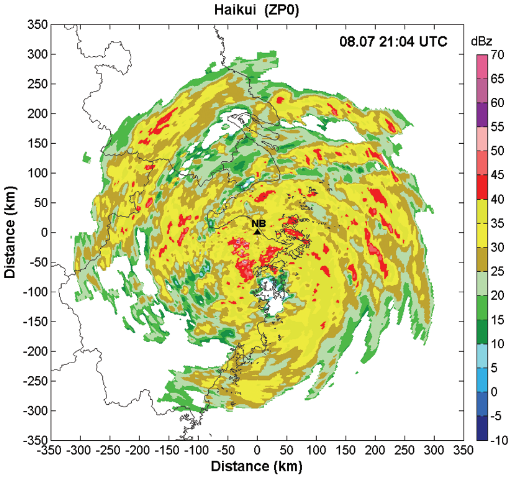

FIG. 4d. Reflectivity of Ningbo radar at 08072104 UTC (unit: dBz)

convection in Haikui implies that the intensity of the typhoon is reduced gradually.

The diagnosis result of the development of Haikui by radar data agrees with the tendency reports by different operation centers (Table 1). Except the result of JTWC, most reports denote that the maximum intensity occurred at 08071200 UTC. By comparing the radar figures in 1500 and 1800 UTC (Figs. 4b–4c), the convection of the typhoon was reduced and the structure of the main body of Haikui began to loosen. Even in this weakening situation, Haikui retained a complete eyewall until landing. This evolution tendency caught by Ningbo radar implied that the reports of CMA and JMA, which identify that Haikui kept a maximum intensity until landfall, are more reasonable compared with the reports of other centers. However, to obtain the intensity of Haikui, careful wind verification on the basis of surface weather station is necessary.

4. Intensity identification of Haikui by near-surfaces data

To identify the intensity of Haikui by AWSs and PET data and to verify the intensity difference among different operation centers (NMC-CMA, JMA, and JTWC), at least three questions should be answered. 1) Can the wind data of AWSs and PET determine the intensity of Haikui during the landing stage? 2) How could we compare wind grade in different observation standards from different countries? 3) Could we identify the intensity by AWSs in non-standard height? Among these questions, the third question is the most fundamental. In this section, these questions will be discussed to clarify the feasibility of the AWS data in typhoon identification. In the last part of this section, we will identify the intensity of Haikui at the landing stage.

a. Qualification of AWSs to identify Haikui

Dongji and Dachen are about 28.4 and 45.3 km far from the center of Haikui, respectively, just before landing at 08071800 UTC (Fig. 2a). The AWSs in Dongji and Dachen are both near the track of Haikui (Fig. 2a). The influence of Dongji and Dachen on the AWSs started from 08071200 UTC to 08072100 UTC (Fig. 5).

By observing the AWSs data (Fig. 6), we can determine that strong wind persisted for about 12 h from 08071200 UTC to 08080000 UTC. The maximum wind observed in Dongji exceeded 42 m/s and persisted from 08071500UTC to 08071800UTC. Afterward, the wind of Dongji decreased at about 10 m/s and then increased again in a few hours. The wind of Dachen showed a similar but smaller amplitude tendency with that of Dongji. This rapid change of wind of AWSs is caused by the eyewall of Haikui passing through Dongji and Dachen at about 080718 UTC, as shown in Fig. 5. This relative position between AWSs and Haikui and the variation of wind in the two AWSs showed that the maximum wind region of Haikui passed the AWSs before landing (Figs. 5 and 6a–6b). Therefore, the wind data of the two offshore AWSs have the potential to identify the intensity of Haikui especially before landing.

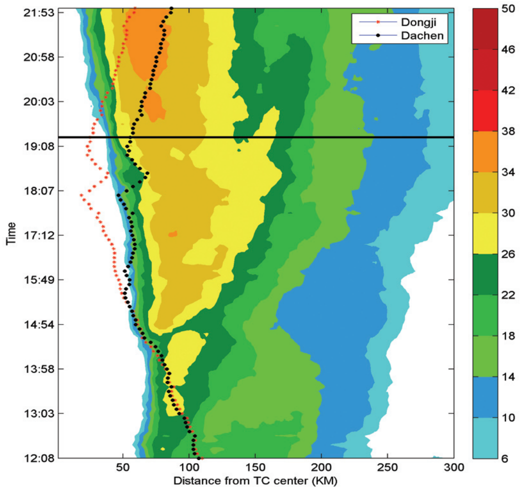

Fig. 5. Relative distance of AWSs to Haikui at different times. Black (red) dot: the Dongji (Dachen) station; color shaded: mean radial radar reflectivity (unit: dBz); black solid line denotes the landfall time of Haikui.

b. Conversion of wind data between different average time-scales

The observed normal surface wind is different in different countries. The time average scales of wind observation used by CMA, JMA, and JTWC are 2, 10, and 1 min, respectively. This difference in time scale always leads to different results even when using the same wind process.

Table 1. Intensity of different centers (unit: m/s) (/denotes no data; red solid italic numbers denote maximum intensity of the same report).

	Time(UTC)					
Centers	070000	070600	071200	071800	080000	080600
NMC-CMA	35	42	***48***	45	38	33
JMA	31	31	***33***	***33***	28	23
JTWC	***33***	***33***	31	31	31	/

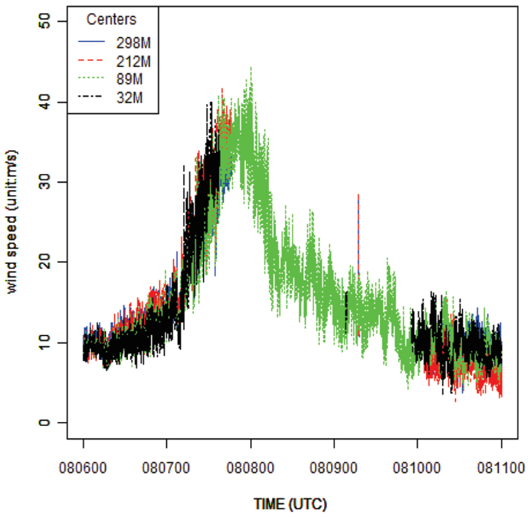

FIG. 6a. 1 min average wind at different PET heights (blue solid line: 29 m; red dash line: 212 m; green dot line: 89 m; black dash dot line: 32 m).

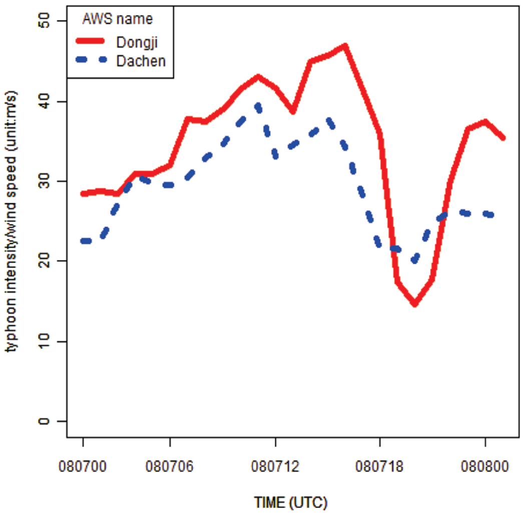

FIG. 6b. 2 min average wind by AWSs of Dongji (red solid line) and Dachen (blue dash line) during Haikui landfall.

To compare the wind observation from different countries, a coefficient is defined to convert the wind value into different time average scales. According to the results of previous studies, the classical "conversion coefficient" between 1 and 10 min is about 0.871 (Deacon 1955, 1965; Atkinson and Holliday 1977). A recent study indicated that the conversion coefficient should vary from 0.83 to 0.95 (Harper et al. 2010) in different underlying surfaces. The wind conversion factor between 2 and 10 min varied from 0.95 to 0.98.

By calculating the observational data of PET in Liangmaoshan Island, we determined that the average wind conversion factors among 1, 2, and 10 min (Table 2) are similar with that of the result of Harper (2010).

c. Conversion of wind data within standard and observation heights of AWSs

The mostly frequently used dataset in identifying typhoons located on the ocean surface comes from satellite or radar images because standard surface stations or AWSs are always absent. The identification of marine typhoons is always based on indirect methods such as the Dvorak technique (Dvorak 1975, 1984). The relationship between surface wind speed and remote observation is established by mathematical estimations based on experiences and pervious data (Dvorak 1984). Thus, the environment and structure of typhoons vary for each case, and remote data are not uniform because satellites and radars in typhoon monitoring always differ in location and precision. These factors cause difficulty in utilizing mathematical estimation in typhoon identification and produce errors in data identification procedures. This situation leads typhoon forecasters to use direct observation datasets such as automatic surface observations in operations.

TABLE 2. Wind speed conversion coefficient in different time average of PET during the landfall of Typhoon Haikui

	1 min	2 min	10 min
1 min	1	/	/
2 min	0.972	1	/
10 min	0.905	0.952	1

By contrast, the reliability and reference value of AWSs, particularly AWSs in non-standard environment conditions, is always questioned in typhoon operation, identification, and prediction. The observation environmental factors of AWSs are not always uniform and qualified. For example, the elevation amplitudes of the two AWSs used in this study are 86 and 76 m, which are much higher than the standard elevation of 10 m for operation intensity identification. Given that wind varies with different heights for friction, wind data from amplitudes less than 10 m is not comparable or convincing in the intensity identification of typhoons and should not be referred to directly without careful revision.

The reliability of the two kinds of datasets for offshore typhoon identification, namely, the direct but not perfect wind observation data and the uniform but indirect remote data is always discussed. Considering that the Dvorak technique has been discussed in numerous studies, wind data in different heights during the landfall of Typhoon Haikui is diagnosed to evaluate the representativeness of wind observations at varying height intervals and near-surface typhoon layers and to qualify the conversion relationship of non-standard wind observations to standard surface wind observations in the boundary layer of the typhoon.

PET wind data was utilized to verify the conversion coefficient in different heights. According to radar observation (Figs. 4a to 4d), the severe convection that affected Liangmaoshan Island and Ningbo City lasted from 08071200UTC to 08071800UTC. The PET of Liangmaoshan Island is approximately 129.9 km away from Haikui at 08071800UTC and approximately 101.3 km away from the landing place of Haikui (Fig. 2a). The PET and AWSs located at the offshore islands of Zhejiang have similar geographical conditions (Figs. 2b to 2d). Given that the underlying surface and wind environment are identical, the wind conversion relation between different heights from PET can be utilized to converse the wind of AWSs in Dongji and Dachen.

The main body of Typhoon Haikui went through the multilayer PET in Liangmaoshan Island from 071200 UTC to 080900UTC, thus resulting in persistent gales for hours (Figs. 2a and 6a). From the dataset collected from PET during the typhoon period in Fig. 6a, the 89 m wind records is the only consequent high-quality dataset among the four layer observations. Data in other heights could not pass through quality control continuously, particularly during the most severe time of Typhoon Haikui (08071200UTC to 08100000UTC) (Figs. 6a and Table 3). Nevertheless, the anemometers in the other three levels still collected large amounts of wind variations.

Wind ratio (WRO) denotes (Eq. 1) the relative scale between different levels and is utilized to quantize the decay of wind with the height decrease in near-surface typhoon boundaries. By using WRO, we estimated the variation tendency and converted the wind data in the target height from the collected data.

$$\mathrm{WRO} = \left|V_{L1}\right| / \left|V_{L2}\right| \tag{1}$$

A comparison of the discontinuous observation and continuous 89 m wind data (Fig. 6) reveals that the wind relationship between different levels and 89 m is quasi-linear and the most frequent wind ratio between levels is from 0.5 to 1.5 (Figs. 7a to 7d). The average wind ratio between 89 and 32 m is approximately 0.955 from Table.4.

The average WRO between 32 and 89 m is 0.955; this result implies that wind in 89 m is generally larger than the wind in 32 m by approximately 4.5% (Table 4). Wind in 212 and 298 m are larger than the wind in 32 m by approximately 11.5% and 13.0%, respectively. Generally, the average WRO between PET levels imply that the wind decreases slowly than expected for Typhoon Haikui.

On the contrary, this quasi-uninform tendency of the wind in near-surface typhoon boundary layers is similar to the observation result of Wurman and Winslow (1998, WW98 hereafter). In their study, wind in different heights is uniform, particularly in near-surface tropical cyclones. Under this consideration, the difference between two levels in near-surface typhoons is overestimated in traditional knowledge, and the 10 m wind surface can be converted or estimated from the observation in higher detail.

In this study, the amplitudes of two AWSs located in Dongji and Dachen islands are 76 and 86 m. The height difference between the standard observation height (10 m) and AWSs elevation is 66 and 76 m, respectively. These two numbers are both fairly similar to the height difference between the lowest two levels (32 and 89 m) of PET in Liangmaoshan Island. The PET and AWSs in this study are all located at the offshore islands of Zhejiang Province. These near-surface wind-measuring instruments are proximate to each other. Furthermore, the PET and AWSs in this study are similar in the synoptic factors of underlying surfaces and influences of Typhoon Haikui. The similarities of the synoptic environments and height differences mentioned above imply that utilizing data from offshore island AWSs to identify the intensity of Typhoon Haikui is possible. Therefore, we can reconstruct the wind data in standard 10 m height from the original AWSs data by using the references of the conversion relationship from the experiences in the 32 and 98 m PET. Employing AWSs data to diagnose the intensity of Typhoon Haikui is possible by using a simple math method under the reference of near-surface multilayer wind anemograph in PET.

d. *Intensity Identification of Typhoon Hakui Landing by AWSs*

AWS wind data, particularly the converted data by

TABLE 3. Valid wind data in different PET heights during Haikui Landfall (√ donate data valid/ donate data missing)

	6th	7th	8th	9th	10th	11th
32 M	√	√	\	\	\	√
89 M	√	√	√	√	√	√
212 M	√	√	\	\	\	√
298 M	√	√	\	\	\	√

TABLE 4. Average wind speed conversion coefficient between different PET heights during the landfall of Typhoon Haikui

	Height			
Height	32 M	89 M	212 M	298 M
32 M	1	/	/	/
89 M	0.955	1	/	/
212 M	0.885	0.982	1	/
298 M	0.870	0.970	0.976	1

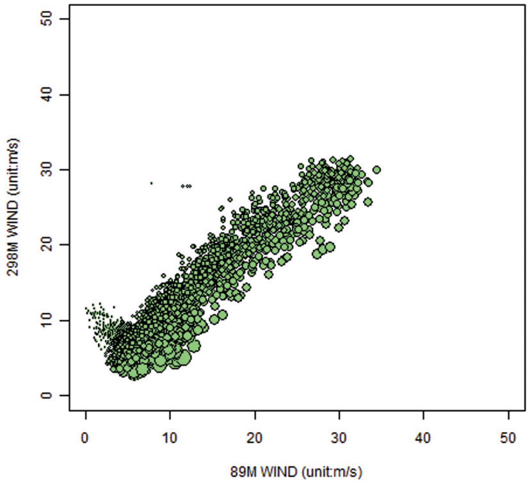

FIG. 7a. Distribution of wind in 89 and 298 m; the size of the circle denotes the relative wind ratio.

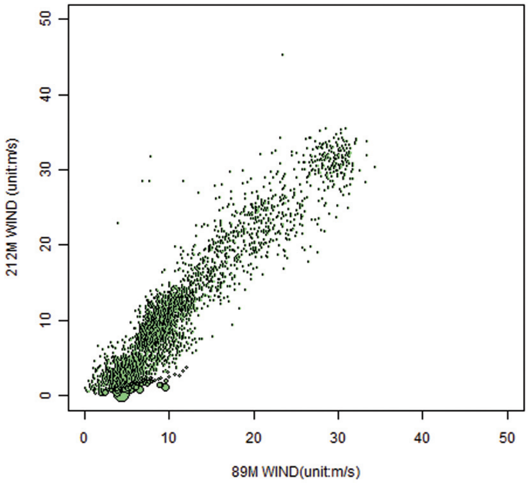

FIG. 7b. Distribution of wind in 89 and 212 m; the size of the circle denotes the relative wind ratio.

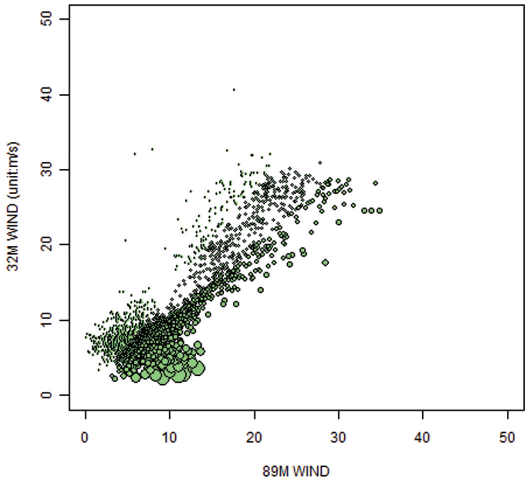

FIG. 7c. Distribution of wind in 89 and 32 m; the size of the circle denotes the relative wind ratio.

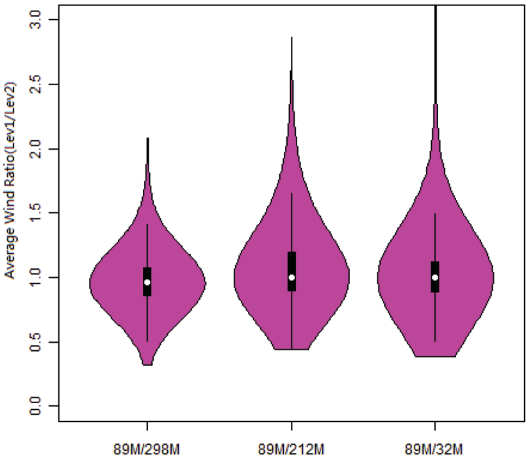

FIG. 7d. Violin distribution of wind ratio between different levels. The pink shaded area denotes the wind ratio density distribution; the black boxplot denotes the maximum, medium, and down quartiles and the minimum wind ratios between levels.

experimental statistics from PET data, can be utilized to identify the intensity of Typhoon Haikui just before landing with acceptable precision.

According to Tables 2 and 4, original wind data from Dongji and Dachen were converted to the wind with 10 m height within 1, 2, and 10 min (Figs. 8a to 8b). From the converted results, the conversed 10 m wind in 1, 2, and 10 min average of Dongji is 46.1, 44.2, and 42.7 m/s at 08071600UTC respectively (Fig. 8a). The maximum wind in Dachen, which is slightly farther from Haikui than Dongji in different time scales (1, 2, and 10 min) all exceeds 35 m/s (Fig. 8b).

Dongji and Dachen are located at the left semi-circle of Haiui when landing (Fig. 2a). Thus, the wind speeds of Dongji and Dachen are offset by the movement of Typhoon Haikui (Fig. 9). Typhoon intensity is defined as the maximum near-center surface wind. In weather operations, the wind observation and wind movement speed should be combined to rebuild the typhoon intensity (Eq. 2).

$$\vec{V}_F = \vec{V}_{LO} + \vec{V}_t \tag{2}$$

$\vec{V}_t$ is the movement velocity of Typhoon Haiui, and $\vec{V}_{LO}$ is the observation wind speed in the left semi-circle of Typhoon Haikui.

This fluctuation in wind speed for several hours means that the maximum wind speed of Typhoon Haikui should be caught by the two AWSs. Considering the discount of

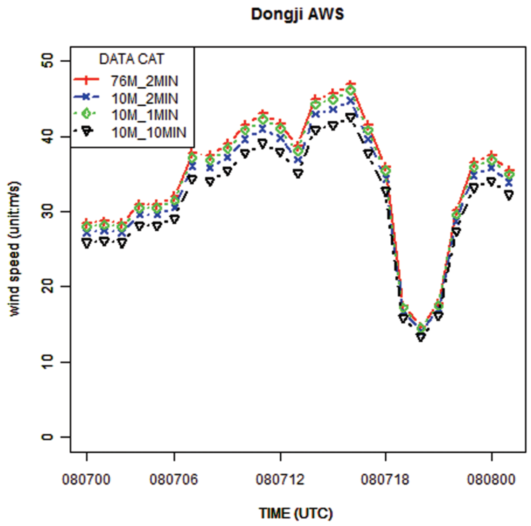

Fig. 8a. Different wind catalog in Daongji AWS

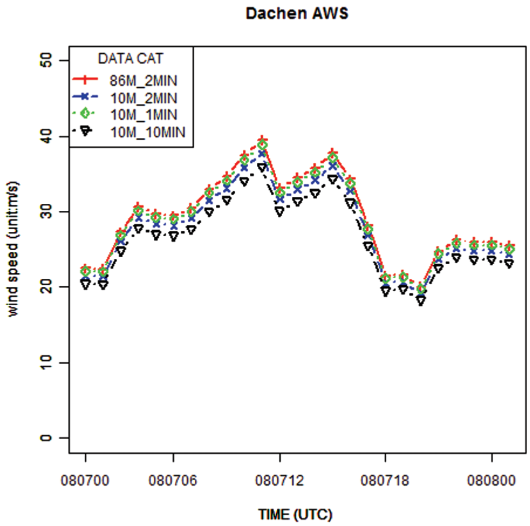

Fig. 8b. Different wind catalog in Dachen AWS

Red Solid Line: original data in 2 min average; Blue dash Line: converted 10 m wind in 2 min average; Green Dash Line: converted 10 m wind in 1 min average; Black dot dash Line: converted 10 m wind in 10 min average.

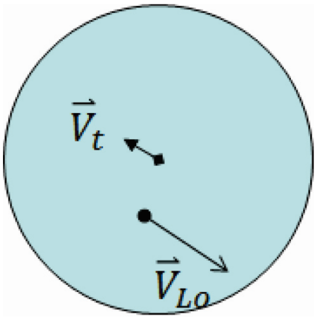

Fig. 9. Relative velocity of observation wind speed and typhoon movement.

the movement of Typhoon Haikui and the possible conversion error between different heights, maximum surface wind is approximately 45 m/s to 48 m/s and Typhoon Haikui at 08071800UTC should be a severe typhoon. Furthermore, the wind observed at Dongji and Dachen increased before 08071500UTC and decreased gradually after 08071800UTC. Thus, the maximum surface wind of Typhoon Haikui persisted for about 40 m/s to 42 m/s for a few hours when landing at 08071920 UTC.

5. Summary

In typhoon operations, the identification of typhoon intensity is always a contentious problem because of the absence of direct observational data. This dilemma forces typhoon forecasters and researchers to identify typhoon intensities based on indirect datasets (e.g., satellite images) and experimental methods (e.g., Dvroak technique). However, when typhoons move to offshore islands, wherein most AWSs are located, forecasters and researchers can better utilize automatic observation data even though most AWSs are in a non-standard observation environment. Before employing these non-standard data, new observation methods or data, including the multilayer wind tower (e.g., PET data in this study), should be used to convert non-standard wind data into standard wind data in 10 m. This study helps accumulate experiences or build mathematical formulas to convert original AWS data to standard data reasonable and accurately.

In this study, the intensity of Typhoon Haikui (1211) in the landing stage is carefully investigated. A multilayer tower observation dataset near the path of Typhoon Haikui is used to build an experimental conversion estimation of wind between different heights in the near-surface layer of typhoon. The difference in different time-average scales is also discussed and verified. By wind conversion coefficient based the PET data, two AWSs that passed by the eyewall of Typhoon Haikui were converted, and the intensity of Typhoon Haikui was identified. After conversion, the maximum surface wind of Typhoon Haikui is approximately 45 m/s to 48 m/s from 08071200UTC to 08071800UTC and is reduced to approximately 40 m/s to 42 m/s before landing.

From the result of this paper, the decrease in the amplitude of wind with height in the typhoon eyewall is much smaller than that in traditional knowledge. This is likely due to the result of WW98 who stated that a severe wind speed of approximately 50 m to 100 m in near-surface tropical cyclones is very close to the surface observation (Fig. 6 in their paper). From this perspective, the wind in the height of dozens of meters will be very close the standard surface data and decreases linearly.

According to the beforehand discussion, AWSs data in non-standard environments can be used for detecting the surface wind in 10 m height after some arithmetic conversion based on a multilayer observation. To typhoon identification, researchers should focus more on AWSs located in offshore islands and the conversion coefficient in different height originated from a single tower observation. These conversion coefficients should be verified by more datasets and further studies.

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