Estimation of extreme wind speed using Typhoon WRF numerical weather prediction (TWRF) model

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Abstract

A numerical weather prediction model (NWP) named Typhoon Weather Research and Forecasting (TWRF), which serves as one of the operational weather prediction models at Central Weather Administration (CWA), is used to re-simulate tropical cyclones (TCs) that affected Taiwan during the year of 2010 - 2024 and to derive historical wind speed grid data and the extreme wind speed of 50-year return period. The accuracy of the modeling results are examined by comparing to the TC track and intensity data from an official typhoon database released by CWA. Verifications of wind speed time series at selected meteorological stations are also performed. The results show that NWP simulation is useful in obtaining spatially wide-range and high-resolution historical wind speed data, and thus is able to estimate extreme wind speed at many places without sufficient observation data. Also, the derived extreme wind speed map shows pronounced topographical effect that hasn't been able to be revealed in conventional methods.

關鍵字: 熱帶氣旋，極限風速，數值天氣預測模型
Keywords: Tropical cyclone, Extreme wind speed, NWP.

1. Introduction

Taiwan Strait is well-known for its wind power and hosts some of the largest offshore wind farms in the world. According to Central Weather Administration (CWA), most of the strong winds ever recorded in this region happened during the passage of tropical cyclones (TCs) (or "typhoons") in summer and autumn seasons. Some other strong wind events occurred in winter during northeast monsoon. Understanding the distribution of extreme wind speeds in this region helps advance the wind energy industry, particularly for wind turbine design considerations which is crucial for estimating construction costs. However, estimating extreme wind speed hasn't been easy. Some conventional methods employ statistical assumptions together with in-situ observations [1, 2]. Due to the insufficiency of observation data in offshore regions, the derived extreme wind speeds tend to underestimate the reality. Other conventional methods utilize Monte Carlo modeling to evaluate the influence of TCs [3-5], but they are largely based on an idealized assumptions on wind-speed distribution around a TC vortex, and thus couldn't account for the complex topographical effects that could severely distort the wind speed distribution as it is often the case for Taiwan Strait [6, 7].

Typhoon Weather Research and Forecasting (TWRF) is a numerical weather prediction model (NWP) based originally on Advanced Research Weather Research and Forecasting (ARW-WRF) but with added numerical procedures to track TC's evolution [8]. TWRF employs nested grids of 15 km resolution in outer Domain 1 (D1), and 3 km resolution in inner Domain 2 (D2), and is currently in optional service at CWA. The advanced developments and high resolution of TWRF model makes it ideal to simulate TC-based historical strong wind conditions.

2. Methodology

2.1 Simulation strategy

The operational version of TWRF model together with input analysis data from NCEP-GFS or NCEP-FV3 is used to simulate every "TC-affected period" during the year of 2010 - 2024. For clarity, a TC-affected period is defined by the time span that includes at least one typhoon warning issued by CWA. To include some modeling varieties, each TC-affected period is covered by multiple "TWRF runs" of fixed 30-hour length each but a 6-hour offset of initial times between adjacent runs. Each TWRF run consists of a 12-hour cold-start process follows by a 30-hour main simulation that outputs wind-speed data at 10 m and 100 m height every hour.

2.2 Data optimization, composition and verification

To optimize data quality, one "best run" among all overlapping runs at each hourly time is selected based on their TC track and intensity errors by comparing to data in CWA Typhoon Databank. First, those runs with track errors within 30 km are selected as candidates. Afterwards, one candidate with smallest intensity error is chosen to be the best run. Collectively, the hourly data coming from all best runs over the entire TC-affected period forms an optimal, composite, wind-speed grid data.

To examine the accuracy of composed data, 3 ~ 4 meteorological stations are selected to verify the modeled wind speeds. These stations come with long history of qualified observational data, and are sitting at geographic locations without severe land friction. Table1 lists the basic information about each station. Hellmann's power-law relationship together with shear exponent of 0.11 suggested in [10] is used to convert the vertical heights of observational data to the model output heights.

Table 1 Basic information of selected observation stations

Station	Pengjiayu	Dongjidao	Hsinchu Buoy	BSMI Wind tower
Location	122.0712E 25.6294N	119.6594E 23.2589N	120.8422E 24.7625N	120.5267E 24.3126N
Station elevation	101.7 m	42.975 m	0 m	0 m
Wind measurement elevation	7.2 m	11.45 m	2 m	38, 67, 100 m
Collection period	2010~2024	2010~2024	2010~2024	2016~2024

2.3 Calculation of extreme wind speed

First, the annual maximum wind speed for a given year is estimated by either considering all TC-affected periods of that year, or includes both TC-affected and non-TC-affected periods. In later case, the non-TC-affected annual maximum wind speed at each grid point is randomly selected from its 3 yearly maximum wind speed values from WRF data during August 2017 - July 2020 excluding TC-affected periods. Next, the 50-year wind speed is calculated using a standard regression formula based on Gumbel distribution method [1], where coefficient α and β are obtained from the probability weighted moment procedure [9].

3. Result

3.1 TC track and intensity errors

Table2 shows the averaged mean errors (simulation minus monitoring) of track and intensity among all simulated TCs in 2010 - 2024. Each TC is classified into one of 3 observed intensity categories outlined in CWA's typhoon Database. The calculation excludes the time during landfall periods where TC positioning is often ambiguous. It can be seen that as TC gets stronger, the track error generally gets smaller but intensity errors become higher. This is mainly because the center of a strong TC is more distinct, making it easier to locate. However, the simulated minimum sea-level pressure (SLP) is based on data on the grid point and thus cannot truly reflect the minimum SLP value of a strong TC. On the other hand, the errors in the simulated near-centered surface maximum wind speeds is smallest for Medium TCs, and the corresponding wind speed for strong (weak) TCs is about 3 m/s lower (higher) than the monitored values.

Table 2 Averaged among all simulated TCs in each intensity category, the mean error (ME) of track, minimum sea-level pressure (SLP), and near-centered surface maximum wind speed. The intensity category is defined using the observed maximum wind-speed during the TC-affected period:

17.2 ~ 32.7 m/s for weak, 32.7 ~ 51 m/s for medium, and 51 m/s or above for strong case.

Affected TCs in 2010 - 2024	ME of track (km)	ME of minimum SLP (hPa)	ME of near-centered surface maximum wind speed (m/s)
Strong	21.70	13.43	-2.99
Medium	28.44	4.33	0.81
Weak	44.11	-0.36	2.95
All cases	31.53	5.49	0.38

3.2 Verification at observation stations

Table3 shows two error measures at each of the observation stations: the average of all mean errors of wind speed among all TC simulation periods (will be abbreviated as AVEE), and the average of all maximum wind speed errors among all TC simulation periods (will be abbreviated as MAXE). It can be seen that the magnitude of both AVEE and MAXE at all selected stations are within 4 m/s, and MAXE are slightly greater than AVEE. However, distinct site characteristics are reflected in the results. At Pengjiayu and Dongjidao station, the modeled wind speeds tend to over-estimate the observed wind speeds, and this is primarily due to the insufficiency of model's resolution in representing these island's terrain height, as higher elevation could introduce stronger land friction that negatively impacts the observed wind speeds. At Hsinchu Buoy and BSMI wind tower, in contrast, the modeled wind speeds tend to under-estimate the observations for somewhat smaller extent (less than 1m/s).

Table 3 Error measures AVEE and MAXE at each stations. The error is calculated using modeled minus observed wind speed at the height of 10 m converted from power-law relationship with exponent 0.11.

Station / Error	Pengjiayu	Dongjidao	Hsinchu Buoy	BSMI Met. (100 m)	BSMI Met. (38 m)
AVEE (m/s)	2.89	1.77	-0.62	-0.51	-0.47
MAXE (m/s)	3.30	2.24	-0.59	-0.66	-0.99

3.3 Extreme wind speed map

Derived from the grid data of annual maximum wind speeds either with or without the inclusion of non-TC-affected data, Figure 1 shows the plane view of 50-year wind at the height of 10 m above surface. It can be seen that the distribution of extreme wind shows strong topographical effect around different sides of Taiwan main island. On both figures, the 50-year winds are relatively smaller at Taiwan Strait than at the eastern-side of the sea area and at Bashi Channel. This is due to the terrain blocking effect as most TCs approach Taiwan from the south-east side. Within Taiwan Strait, there is a local maximum near offshore Hsinchu. At this place, strong wind often occurs when TC is approaching to the north-east coast of Taiwan before landing, where the topography of northern land causes the wind field of the TC to redirect and concentrate into this area. Compare the left and right plot, it can be seen that adding non-TC-affected periods to the data results in an overall smaller extreme wind at Taiwan Strait. This is because for those annual maximum winds that occurred in non-TC-affected periods, for instance, during north-east monsoon, the corresponding wind speeds are mostly mild compared to those generated by TCs. As a result, increasing annual maximum winds at the lower end of the spectrum decreases the odds of an extreme wind. Part (a) of the figure shows that with TC-affected periods only, the 50-year wind speeds at near coast offshore of the Taiwan Strait that hosts many wind farms range from 36 to 44 m/s. Adding non-TC-affected periods decreases this range by 2 to 4 m/s as shown in part (b) of the figure.

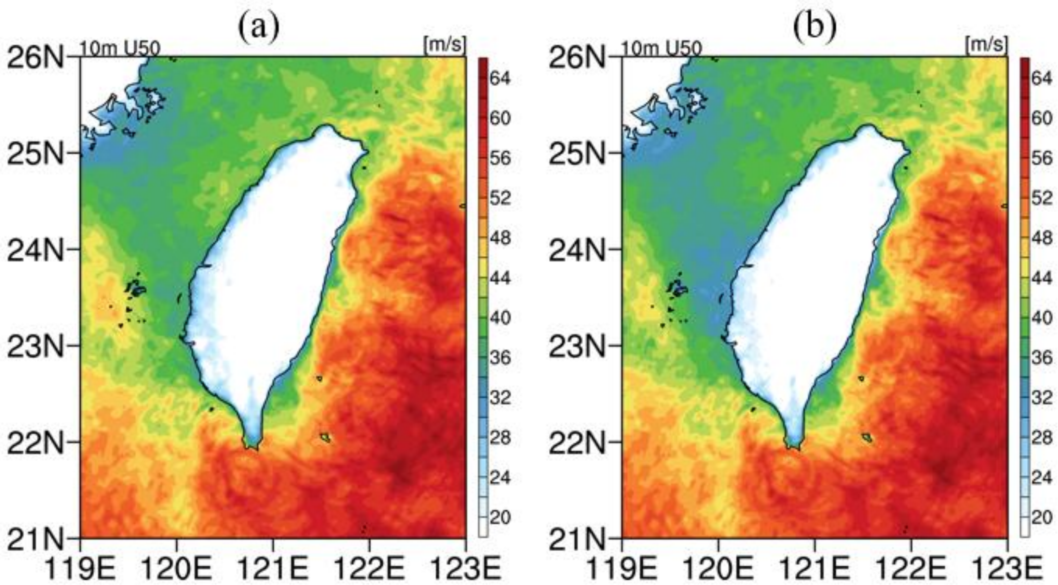

Figure 1 Extreme wind speed of 50-year return period at height of 10 m, derived from (a) all TC-affected periods (b) all TC- and non-TC-affected periods within years of 2010 - 2024.

4. Conclusion

The main findings of this work are as follows. First, with the help of a sophisticated NWP model, the extreme wind speed can be estimated quantitatively at regions without sufficient observation data. Second, the obtained extreme wind speeds exhibit strong geographical effects around different sides of mainland Taiwan that surpass what could have been shown by using other conventional methods. In the main wind farm areas of the Taiwan Strait, the estimated near-surface maximum wind speed is 36 to 44 m/s, which is also the area with lowest maximum wind speeds in all sea areas around Taiwan.

5. Reference

[1] Hansen, B. O. L., Xiaoli Guo; Kelly, Mark C.; Rathmann, Ole Steen; Berg, Jacob; Bechmann, Andreas; Sempreviva, Anna Maria; Ejsing Jørgensen, Hans. "Extreme Wind Calculation Applying Spectral Correction Method – Test and Validation", DTU Wind Energy E, Vol. 0098, 2016.

[2] Mortensen. "Wind resource assessment using the WAsP software", DTU Wind Energy E 0135, 2016.

[3] Holland, G. J. "An Analytic Model of the Wind and Pressure Profiles in Hurricanes", Mon. Wea. Rev. 108, 1980.

[4] Holland, B. A. H. a. G. J. "An updated parametric model of the tropical cyclone", AMS 23rd Conference on Hurricanes and Tropical Meteorology, 1999.

[5] Ott, S. "Extreme Winds in the Western North Pacific", Denmark. Forskningscenter Risoe. Risoe-R 1544, 2006.

[6] Chang, P.-C., et al. "Potential of Offshore Wind Energy and Extreme Wind Speed Forecasting on the West Coast of Taiwan", Energies 8(3): 1685-1700, 2015.

[7] Larsén, X. G., et al. "Recipes for Correcting the Impact of Effective Mesoscale Resolution on the Estimation of Extreme Winds", Journal of Applied Meteorology and Climatology 51(3): 521-533, 2012.

[8] Hsiao, L.-F.; Chen, D.-S.; Hong, J.-S.; Yeh, T.-C.; Fong, C.-T. Improvement of the Numerical Tropical Cyclone Prediction System at the Central Weather Bureau of Taiwan: TWRF (Typhoon WRF). Atmosphere 2020, 11, 657. https://doi.org/10.3390/atmos11060657.

[9] Abild, J. "Application of the wind atlas method to extremes of wind climatology", Denmark. Forskningscenter Risoe. Risoe-R; No. 722(EN), 1994.

[10] Chia-Ren Chu; Yu-Feng Chang. Long-Term Surface Wind Speed Trends over Taiwan between 1961-2008. Chinese version. Meteorological Bulletin. Central Weather Bureau. 2012, 49-1.