An Adaptive Dynamic Downscaling Strategy to Obtain Real-time Multi-resolution Wind-field during Evolving Tropical Cyclones to Support Real-Time Risk Forecast of Powerlines

Xiubing Huang
Graduate Student, College of Civil Engineering and Architecture, Zhejiang University, China

Naiyu Wang*
Professor, College of Civil Engineering and Architecture, Zhejiang University, China.
naiyuwang@zju.edu.cn

ABSTRACT: Tropical cyclone (TC) induced high winds often cause significant damages to powerline systems and lead to widespread power failure and socio-economic losses. Meteorological numerical weather prediction during an evolving TC has the potential to enable real-time risk forecast of power systems. However, operational weather forecast only simulates wind-field at mesoscale (i.e.,1~10 km resolution) which is too coarse to be used directly to assess risks of powerlines located in complex terrains. Moreover, micro-scale (10~100 m) wind forecasts realized by dynamic downscaling from mesoscale predictions can only be achieved in existing studies for small domains (<~100 km^2) due to its overwhelming computational demand. This study proposes an adaptive nested dynamic downscaling (ANDD) strategy, which is designed to obtain multi-resolution wind-field forecast in real-time to facilitate risk forecast of powerlines distributed over large region across complex terrains. The obtained wind-field can i) capture critical microscale wind dynamics caused by terrain features by performing dynamic downscaling only to the selected critical domains containing powerline segments suffering high winds; and ii) adapt to the evolution of a TC in real time by proactively and continuously searching for those critical domains based on the latest mesoscale forecasts reflecting the most recent TC evolution. The ANDD strategy is illustrated through the powerline system in Zhejiang Province (105,500 km^2), China, during Typhoon Lekima.

1. INTRODUCTION

Tropical cyclones (TCs) can cause serious damage to electrical power transmission systems, leading to severe economic loses and social disruptions. Compared with a sudden disaster such as an earthquake or Tsunami, a TC evolves gradually while approaching. During this evolution effective risk forecasts of power systems can inform proactive risk mitigation measures, thereby reducing the spatiotemporal range of power failure and the potential socio-economic losses (Sang et al., 2019).

To provide real-time risk forecast of a power transmission system during an evolving TC, it is necessary to capture the dynamic characteristics of the evolving wind-field which serves as the spatiotemporally-varying loading acting on the power system. While parametric wind-field models (e.g. Georgiou, 1986; Vickery et al., 2009) are often used for life-cycle or climate-change types of analyses (Lee and Ellingwood, 2017; Salman et al., 2017) due to their simplified governing equations and relatively low computational cost; meteorological numerical wind prediction (NWP) models, based on more improved physical mechanism (Liu et al., 1997), are used for operational weather forecast worldwide, providing the most suitable wind-field predictions for forecasting risks of power systems in real time. However, the operationally used NWP simulates wind-field at the mesoscale (1~10km) which is too coarse to capture the small-scale (100m~1km) or micro-scale (10~100m) wind dynamics, while such wind dynamics can be critical to risk assessment of transmission towers and conductors located in complex terrains. An accurate damage and risk assessment of a power system require that the operational mesoscale NWP be downscaled to a micro-scale or structural-scale.

The physics-based dynamic downscaling (DD) has been coupled with mesoscale NWP to obtain wind-fields with finer resolutions that can capture small-scale wind dynamics. (Liu et al., 2011; Talbot et al., 2012; Huang et al., 2018). However, such application could only be achieved for small domains (1~10km) in existing studies due to its overwhelming computational demand. The problem at hand deals with regional-scale power transmission systems spanning over large regions (10,000~100,000km^2), which would require unattainable computational resources to obtain micro-scale wind-field predictions over the entire region in real time using DD.

Confronted with the above challenges, this study proposes an Adaptive Nested Dynamic Downscaling (ANDD) strategy to particularly facilitate real-time risk forecast of power transmission systems spanning over complex terrains.

2. ADAPTIVE NESTED DYNAMIC DOWNSCALING (ANDD) STRATEGY

Fig. 1 gives a schematic illustration of the ANDD strategy. The DD operations (either from mesoscale to small-scale or from small-scale to micro-scale) are only performed within their corresponding critical domains (i.e., small-scale domains and micro-scale domains, respectively) which contain towers and conductors sustaining high winds according to the coarser wind-field predictions in each forecast period, shown in the upper portion of Fig. 1. The ANDD strategy proactively and continuously searches for and updates those critical domains during the evolution of a TC according to the latest wind-field forecast that reflects the most recent TC development, shown in the lower portion of Fig.1. The wind-fields of different scales are simulated by NWP models with different resolution capability as discussed in Section 2.1; the nested structures of multi-scale DD domains are determined by the ANDD strategy described further in Section 2.2.

The outcome of the ANDD is a continuously-updated multi-scale adaptive powerline-centric wind-field (APWF) forecast (as illustrated in Section 3) that provides the spatiotemporally-varying load-field acting on the system to facilitate the subsequent risk forecast of regional-scale powerline systems (as illustrated in Section 4) with affordable computational requirements.

2.1. Numerical weather prediction models

Within any NWP models, the governing equations include the conservation of mass, momentum and energy, and the ideal gas law (Bauer et al., 2015). By solving these governing equations, major meteorological variables including wind speed, pressure, density and temperature can be predicted. Typically, these governing equations are nonlinear partial differential equations, and usually cannot be solved exactly through analytical methods. Numerical methods, such as finite difference methods and spectral methods, are often used to obtain approximate solutions (Strikwerda, 2004).

In this study, we employ the Weather Research and Forecasting (WRF), one of the most widely employed regional NWP models (Skamarock et al., 2019), to produce the mesoscale and small-scale wind-fields and employ the large eddy simulation (LES) nested within WRF to simulate microscale wind-fields. The analysis is performed for a predefined forecast period (e.g., 12hrs, 18hrs) with a pre-selected updating frequency (e.g., every 3-hour or 6-hour).

2.2. Framework of the ANDD strategy

As depicted in the upper portion in Fig. 1, the ANDD process obtains the APWF for each forecast period as the following: (i) used WRF to obtain mesoscale wind-field forecast over the entire region of the transmission system (the green-boxed domain) for the duration of forecast period; (ii) generate small-scale domains (blue-boxed) containing powerline segments sustaining high winds (e.g. >20m/s) according to the previous mesoscale wind-field, and the areas of these small-scale domains should be minimized to reduce computational cost; then use WRF again to generate small-scale wind-field within the blue-boxed domains; (iii) further generate micro-scale domains (red-boxed) that contain powerline segments exposed to extra-high winds (e.g. >30m/s) according to the previous small-scale wind-field, and use LES nested in WRF to generate micro-scale wind-field within these red grids.

Through the above process, the resulting compound APWF simultaneously consists of meso-, small- and micro-scale wind subdomains with a nested structure, as in Fig 1, in which subdomains with relatively finer-resolution wind-fields are nested within domains of relatively coarser-resolution wind-fields, with the latter providing the boundary conditions for the former. Such obtained APWF is spatially adaptive to terrain features and to the topology of transmission systems, and is temporally adaptive to the evolution of an approaching TC in real time, as the DD domains are dynamically reconfigured in each forecast period based on the latest mesoscale NWP.

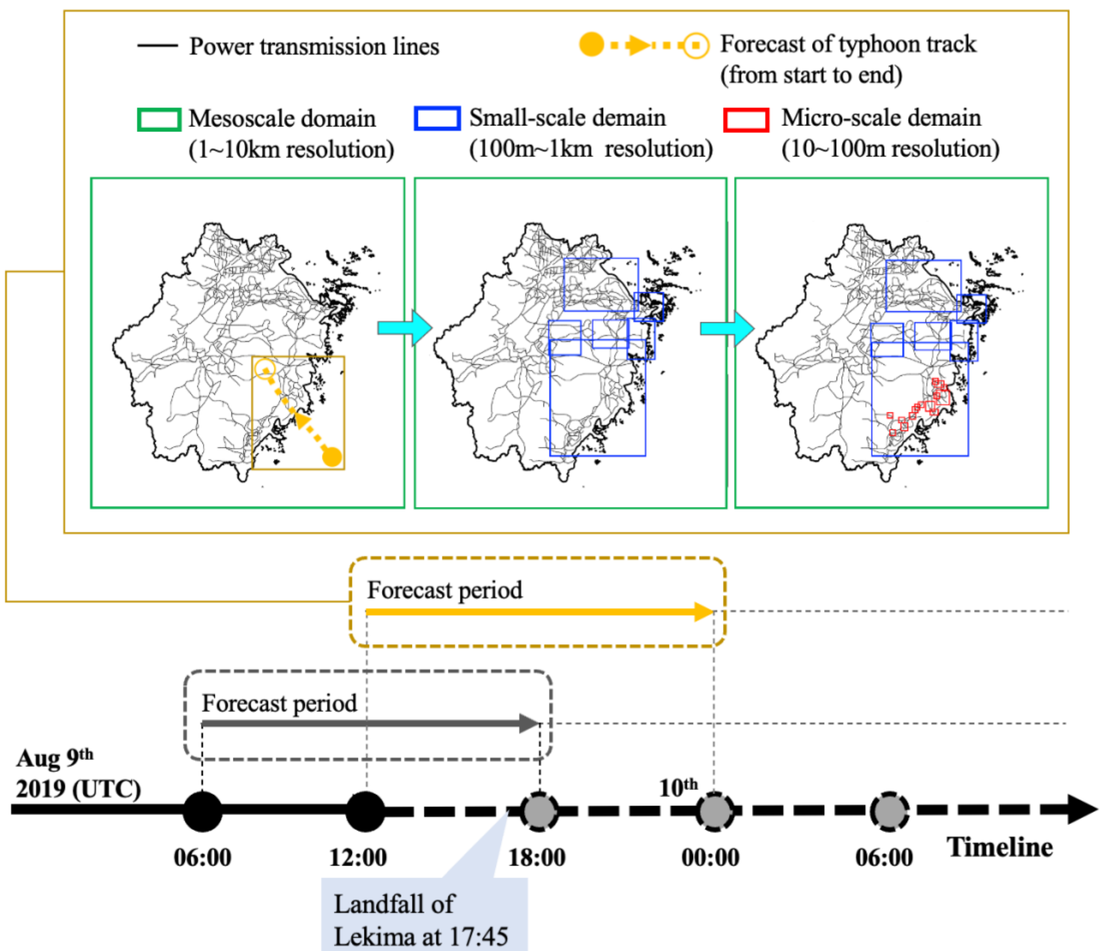

Fig. 1. The process of generating APWF by applying the ANDD strategy (during typhoon Lekima).

3. IMPLIMENRTATION OF THE ANDD TO THE POWER TRANSMISSION SYSTEM IN ZHEJIANG PROVINCE, CHINA, DURING TYPHOON LEKIMA

The 220kV and 500kV power transmission system in Zhejiang Province (105500 km^2), China, is served as a testbed under Typhoon Lekima of 2019 which is one of the strongest typhoons that landed in Zhejiang in the past century (NDRCC, 2019). The topology of the transmission system and Zhejiang elevation map are shown in Fig. 2, indicating a large portion of the system is located in mountains and hills which accounts for nearly 71% of the land surface in Zhejiang.

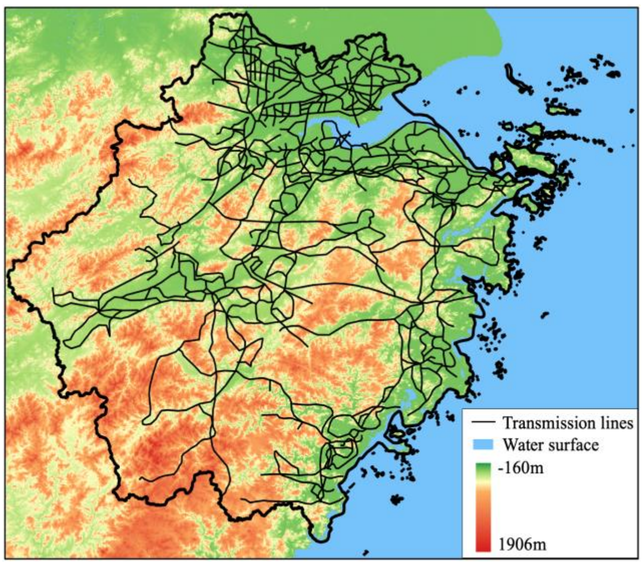

Fig. 2. Elevation map (dataset: ASTER, 1-arc-second) and the transmission system of Zhejiang

Typhoon Lekima landed on the coastal area of Zhejiang at 17:45 UTC on 9 August with maximum sustained wind speed up to 52 m/s near its vortex center, according to the best track data from China Meteorological Administration (CMA). To be consistent with weather forecasts, the powerline risk is forecasted for the future 12-hour period with 6-hour updating frequency. The forecast period of 12:00-24:00 UTC including landing time at 17:45 UTC, shown in Fig.1, is selected to present the analysis result hereafter.

3.1. Model settings of the WRF-LES in ANDD strategy

The three categories of domains used in the ANDD, i.e., mesoscale domain, small-scale domains and micro-scale domains, correspond to resolutions of 1.33km, 443m and 89m, respectively. The model settings used for DD are basically consistent with recommendations by WRF developers (WRF User Guide, 2022) as well as suggested settings in literature (Talbot et al., 2012; Huang et al. 2018). All domains output 10m-above-ground wind fields including 10-minute averaged wind speeds and wind directions.

3.2. The Resulting APWF

Fig. 3 shows the effect of the ANDD using one micro-scale domain (denoted as Area I) as an example. Fig. 3(a) (b) and (c) present the wind-field in Area I, at mesoscale, small-scale and micro-scale, respectively; and Fig. 3(d) (e) and (f) show the corresponding wind-field in the Grid A of 1.33km*1.33km located in Area I. Note that the mesoscale wind-field in Fig. 3(d) only holds one unique value of wind speed/direction for the whole Grid A, while its micro-scale wind-field in Fig. 3(f) manifests significant spatial variations in both wind speed and wind direction.

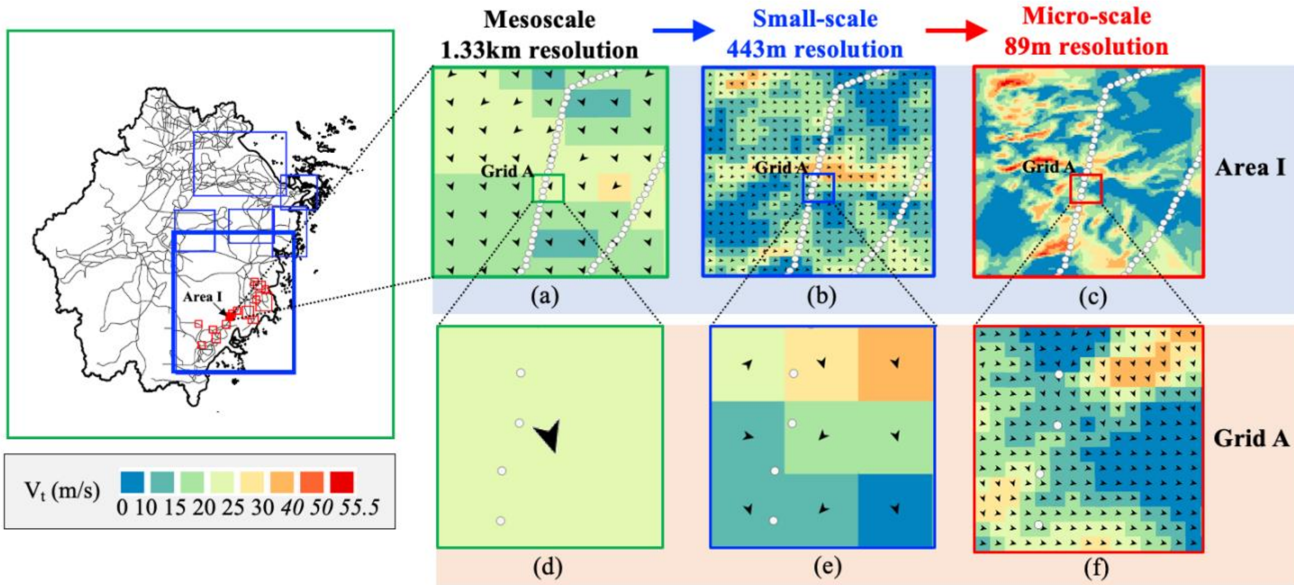

Fig. 3. The 1.33km-resolution mesoscale wind field for (a) Area I and (d) Grid A; the 443m-resolution small-scale wind field for (b) Area I and (e) Grid A; and the 89m-resolution micro-scale wind field for (c) Area I and (f) Grid A; all at landing time.

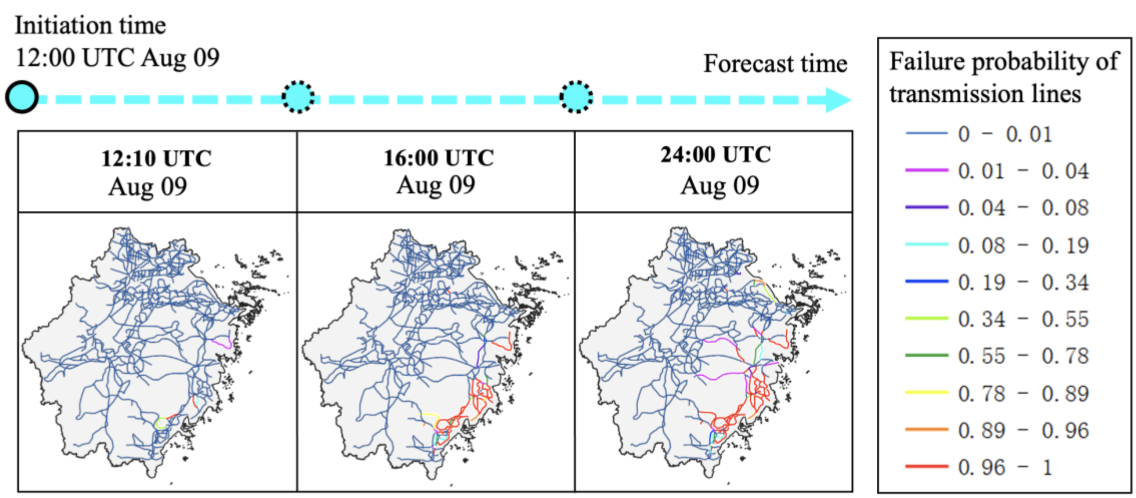

Fig. 4. The failure probabilities of transmission lines for the forecast period of 12:00-24:00 UTC on Aug 9.

4. RISK FORECAST OF POWER TRANSMISSION SYSTEM DURING AN EVOLVING TC

4.1. Risk forecast of power transmission lines

Apply the APWF obtained in Section 3 by ANDD as the wind load acting on the power system, the risk forecast can be performed by using developed fragility curves of load-bearing structures, i.e., towers and conductors. This illustration focuses on the collapse failure mode of towers with buckling of members, as such failure scenarios are common in coastal regions in Zhejiang and are more time-consuming to remedy once occurred.

During a risk forecast period of T (as shown in Fig. 1) under an evolving TC, the failure probability of a tower up to time t, $P_{f,t}$, is:

$$P_{f,t} = \sum_{r \in R} P_{f,t|r} \cdot P(R = r) \quad (1)$$

$$P_{f,t|r} = P_{f,t-1|r} + (1 - P_{f,t-1|r}) \cdot P(r < S_t) \quad (2)$$

where r is a sample of the tower resistance R; $P_{f,t|r}$ is the failure probability of a tower up to time t conditional on $R = r$; S_t is the wind load at time t; the value of $P(r < S_t)$ is obtained by using fragility curves.

Subsequently, the failure (failing to transport electricity) probability of a transmission line (as a series system of conductors and supporting towers) can be estimated by multiplying the failure probabilities of its supporting towers and conductors.

4.2. Risk forecast of Zhejiang power transmission lines during Lekima using the APWF

The total length of the transmission system of the Zhejiang province is approximately 9500 km with 780 transmission lines and 32458 towers. Fig. 4 shows the failure probabilities of the transmission system under the compound APWF (obtained in Section 3) at different times during the forecast period of 12:00 -24:00 UTC on Aug 9. At 12:10 UTC there are two transmission lines starting to show high failure probabilities (i.e., $P_f \geq 0.9$). As Lekima approaches to its landing at 17:45 UTC, the failure probabilities of transmission lines increase rapidly around 16:00 UTC and the failure scenario becomes more serious at 24:00 UTC. Such risk forecast can be revised once the APWF is updated for the next 12-hour forecast period.

5. CONCLUSIONS

To address the incompatibility in resolutions between the operational mesoscale NWP of wind field (the load) and the structural-scale damage analysis of power transmission towers (the load-resisting structures), a computationally-affordable regional application of adaptive nested dynamic downscaling strategy, i.e., ANDD, is proposed to produce powerline-centric multi-scale wind-field forecasts to facilitate effective risk forecasts of large-scale power transmission systems over complex terrains. The implementation of ANDD to Zhejiang transmission system during Lekima reduces the computational cost to 1/58 compared with that of simulating micro-scale wind-filed over the entire domain of Zhejiang Province.

6. ACKNOWLEDGEMENT

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