E212

A Climate-Informed Probabilistic Typhoon Hazard Framework for Offshore Wind Farm Areas in the Western North Pacific

西北太平洋における洋上風力発電海域を対象とした気候変動を考慮した台風ハザードの確率論的評価枠組み

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This study develops a climate-informed probabilistic typhoon hazard assessment framework aimed at characterizing potential changes in typhoon hazard features under climate change and supporting hazard exposure analysis for offshore wind potential areas. The framework integrates large-scale climate forcing, probabilistic modeling of tropical cyclone generation and evolution, and synthetic typhoon simulation tools to provide a systematic representation of future typhoon hazard scenarios. Within this framework, tropical cyclone genesis is treated as one component of a broader climate-driven hazard modeling chain that links atmospheric conditions to typhoon activity characteristics. The Dynamic Genesis Potential Index (DGPI) is used to represent the modulation of tropical cyclone genesis probability by large-scale climate conditions, while synthetic typhoon tools such as STORM are employed or considered to translate statistical typhoon characteristics into physically realizable typhoon scenarios at the regional scale. Based on this framework, preliminary discussions on typhoon hazard exposure and associated risk implications for the offshore wind industry are also included in this study.

1. Introduction & Motivation

Driven by global energy transition strategies, offshore wind power has become one of the most important pillars of clean energy development (IRENA, 2023; Global Wind Energy Council, 2023). Compared with onshore wind energy, offshore wind power offers advantages such as abundant resources, higher wind stability, and large-scale development potential, leading to rapid expansion from shallow coastal waters to deep-sea and floating wind farm regions (Afridi et al., 2024). Many of these emerging offshore wind developments are located in the Western North Pacific (WNP), the most active tropical cyclone basin in the world (Emanuel, 2021).

Tropical cyclones (TCs) are among the most destructive natural hazards, often accompanied by extreme winds, heavy rainfall, storm surges, and severe flooding, posing significant threats to offshore energy infrastructure. Under climate change, understanding how TC characteristics may evolve has become a critical challenge for offshore wind planning and risk management. Although numerous studies have investigated historical TC variability and future projections, large uncertainties remain, particularly when assessments rely solely on historical statistics or deterministic design assumptions.

2. Research Purpose

While synthetic tropical cyclone models such as STORM (Bloemendaal et al., 2020) have been widely applied to generate long-term typhoon catalogs for hazard analysis, most existing applications primarily focus on reproducing historical statistics or investigating sensitivity to model parameters. The incorporation of large-scale climate forcing into such models for offshore wind‐oriented hazard assessment remains limited. In particular, existing studies rarely provide a systematic framework that explicitly links climate-driven changes in tropical cyclone characteristics to hazard exposure of offshore wind potential areas.

The purpose of this study is to address this gap by embedding synthetic typhoon modeling within a broader climate-informed probabilistic hazard framework tailored for offshore wind applications. Rather than treating synthetic cyclone generation as an isolated modeling task, this study aims to clarify how climate signals should consistently propagate through hazard generation and realization processes. By doing so, the proposed framework seeks to support offshore wind‐specific typhoon hazard exposure analysis and to enhance the applicability of synthetic tropical cyclone models for climate-consistent offshore wind risk assessment.

3. Methodology and model development

A climate-informed probabilistic typhoon hazard framework is developed to link large-scale climate forcing to hazard exposure of offshore wind potential areas. The methodology consists of four interconnected components: climate forcing characterization, probabilistic representation of tropical cyclone generation, synthetic typhoon realization, and exposure-oriented hazard assessment. Climate signals are embedded into the hazard generation process through a probabilistic spatial representation, which provides upstream inputs for synthetic typhoon simulation. The resulting synthetic typhoon scenarios are then used to characterize regional typhoon hazard exposure relevant to offshore wind applications. A schematic overview of the framework is shown in Figure 1.

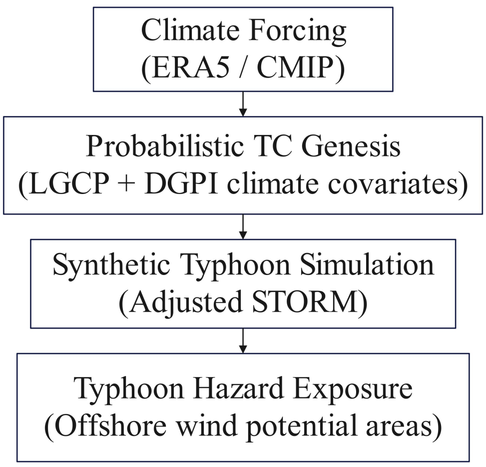


Figure 1. Schematic overview of the proposed climate-informed probabilistic typhoon hazard framework for offshore wind applications.

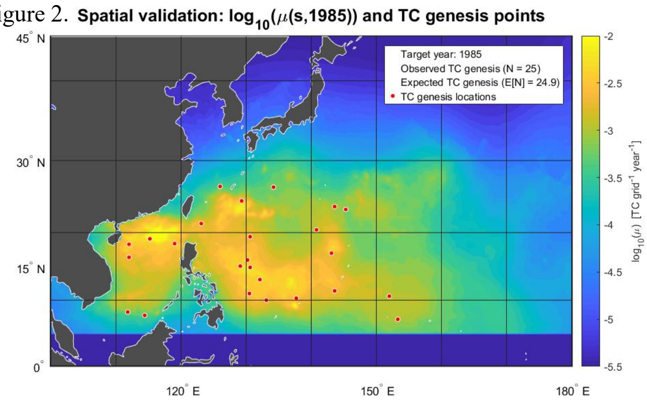
4. Current Results and Future Work

$$\log \mu(s,t) = \log \lambda_{\mathrm{clim}}(s) + \beta_0 + \beta_1 Z_{DGPI}(s,t)$$

Tropical cyclone genesis is represented using a climate-informed probabilistic formulation, in which the genesis intensity $\mu(s,t)$ is decomposed into a long-term spatial baseline $\lambda_{clim}(s)$ and a climate-driven modulation term. The baseline component captures the persistent spatial heterogeneity of historical cyclone formation, while the modulation term reflects the influence of large-scale climate variability through standardized DGPI anomalies $Z_{DGPI(s,t)}$. A global scaling parameter controls the overall genesis level, and the climate sensitivity parameter quantifies the response of genesis intensity to climate forcing.

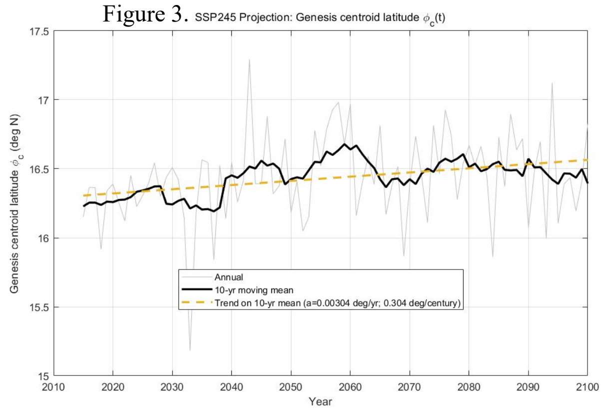
Spatial validation against historical observations shows that the modeled genesis intensity reproduces the main climatological patterns of tropical cyclone formation in the Western North Pacific, with observed genesis locations concentrated in regions of elevated modeled intensity (Figure 2).

Figure 2.



Under the SSP2-4.5 scenario, preliminary projections further illustrate how climate-driven modulation alters the spatial structure of tropical cyclone genesis, as reflected by changes in the mean modulation factor and the latitudinal characteristics of genesis centroids (Figure 3).

Figure 3.



Future work will extend the proposed framework by integrating the climate-informed genesis representation into synthetic typhoon simulation, enabling the generation of climate-consistent typhoon catalogs for the WNP Area. Based on these synthetic scenarios, subsequent analyses will focus on linking typhoon occurrence with wind and wave intensity characteristics relevant to offshore wind systems. This extension will support exposure-oriented typhoon hazard assessment for offshore wind potential areas and provide a basis for future risk-informed offshore wind planning under climate change.