FORECASTING MULTI-HAZARD SCENARIOS WITH ENSEMBLE TROPICAL CYCLONE FORECASTS

Md. Rezuanul Islam, Institute of Engineering Innovation, The University of Tokyo, fahiemislam@gmail.com
Le Duc, Institute of Engineering Innovation, The University of Tokyo, leduc@sogo.t.u-tokyo.ac.jp
Yohei Sawada, Institute of Engineering Innovation, The University of Tokyo, yohei.sawada@sogo.t.u-tokyo.ac.jp

INTRODUCTION

Multi-hazard events resulting from tropical cyclones (TC) involve the simultaneous or sequential occurrence of various destructive disasters, including storm surges, heavy rainfall, and strong winds, which collectively pose significant threats to society (Needham et al., 2015; Takagi et al., 2022). While ensemble forecasts are widely employed in TC prediction, their potential for comprehensively assessing multi-hazard scenarios has been ignored (Titley et al., 2019). In this study, we introduce Pareto optimization based an innovative, efficient, and practical framework for analyzing multi-hazard scenarios, utilizing large ensemble TC forecasts comprising 1000 members to evaluate storm surge, rainfall, and wind-related risks. To exemplify the applicability of our approach, we conducted simulations for TC Hagibis that hit Central Japan in 2019 using the non-hydrostatic model from the Japan Meteorological Agency (JMA). The resulting atmospheric predictions served as inputs for modeling storm surges, rainfall patterns, and wind hazards. We anticipate that this assessment framework will empower forecasters, disaster management authorities, and communities to make well-informed decisions and enhance their resilience in the face of TC-related impacts.

DATA AND METHOD

The atmospheric ensemble forecasts of TC Hagibis were obtained by running JMA's former operational limited-area model called NHM (non-hydrostatic model; Saito et al., 2006). We utilized a state-of-the-art data assimilation system with 1000 ensemble members, called the four-dimensional variational-ensemble assimilation technique (4DEnVAR; Kobayashi et al., 2020) in this study. Here, we opted for a 39h forecast horizon because JMA's operational Meso-scale Ensemble Prediction System (MEPS) also generates 39h forecasts at 6-hour intervals. A statistical storm surge model called storm surge hazard potential index (SSHPI; Islam et al. 2021, 2023a) was used to compute ensemble peak storm surge heights in four tide gauges (i.e., Harumi, Chiba, Yokohama, and Mera) covering Tokyo Bay. To provide primary flood risk information of TC Hagibis, this study emphasized the assessment of areal extreme precipitation. Specifically, we scrutinized the maximum *N*-hour river basin-averaged accumulated rainfall (BAAR; Arakawa, Tone, and Tama river), an important metric that accounts for flood travel time and serves as a fundamental proxy for extreme flood events. For wind-related hazards, we analyzed gust wind for four locations (i.e., Haneda, Edogawa, Yokohama, and Kyonan). Finally, we conducted multi-objective optimization to select ensemble forecast members that reasonably characterize the potential worst/optimum multi-hazard scenarios for a particular location (e.g., Tokyo Bay) by computing the Pareto frontier. The Pareto frontier captures the trade-offs between objectives. It is the set of all Pareto-optimum solutions where a single Pareto optimal solution denotes a solution that is not dominated by any other solution. TC Hagibis and storm surge ensemble forecasts, and Pareto optimality and assessing multi-scenarios are described in detail in Islam et al. (2023b). Rather than repeating the equations and explanations here, we refer the readers to this companion paper.

RESULTS

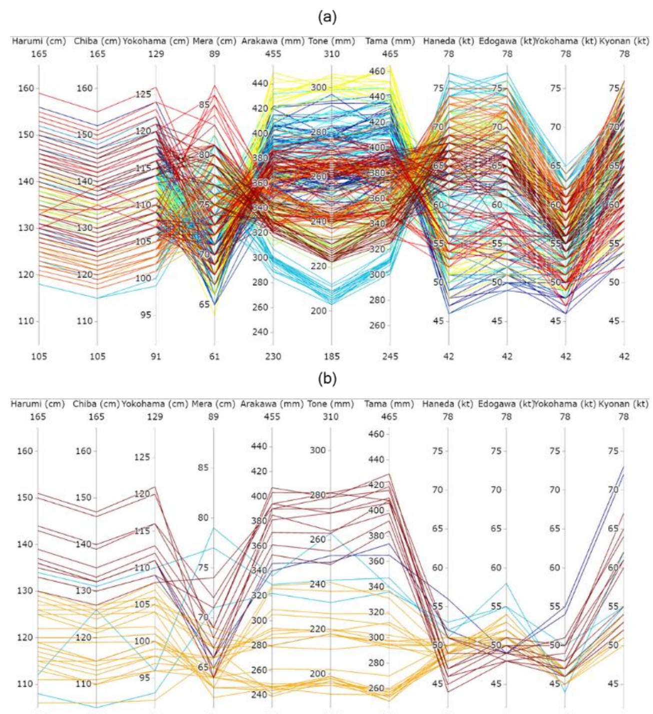

Figure 1 – Forecasted Pareto optimal multi-hazard scenarios for Tokyo Bay and its' surrounding area due to TC Hagibis (a) worst predictions for storm surge, river flooding, and wind hazards; (b) optimum predictions for storm surge, river flooding, and wind hazards.

Our findings reveal that Pareto-optimized solutions derived from multi-hazard forecasts can depict the potential worst (maximum) and optimal (minimum) multi-hazard situations while showcasing complex trade-offs among different hazard types and geographical locations (Figure 1). For instance, ensemble members that produce the most severe storm surges may not necessarily be associated with heavy rainfall in river basins. Similarly, members generating heavy rainfall in one river basin may not produce the same intensity of rainfall in neighboring river basins. Our study underscores the pivotal role of selecting appropriate hazard indicators, such as 39-hour and 48-hour accumulated rainfall, to accurately assess the compound flood hazards resulting from intense rainfall and storm surges. Notably, factors like rainfall rate and the time lag between the rainfall centroid and peak storm surge emerge as robust predictors in this evaluation. Furthermore, our findings emphasize the importance of conducting a comprehensive assessment of Pareto optimal solutions to elucidate the impact of meteorological variables, including TC track, intensity, and size, on both the worst and optimum multi-hazard scenarios.

CONCLUSIONS AND DISCUSSION

The variability in multi-hazard intensity induced by TCs along and in proximity to coastlines poses a considerable challenge for decision-makers tasked with formulating effective evacuation strategies. To tackle this issue, we have demonstrated that opting Pareto optimized forecasts can unveil a spectrum of trade-off scenarios encompassing various coastal regions. The importance of evaluating trade-offs through Pareto optimization has long been recognized in the context of sustainable development goals and the management of ecosystem services (Flecker et al., 2022). However, its application in disaster-risk management is noticeably lacking. Pareto optimal solutions serve as an effective initial filter for identifying ensemble multi-scenario forecasts. This information can be visually presented to enhance the comprehension of forecast uncertainty regarding worst and best-case scenarios. Subsequently, a targeted warning signal can be issued within a forecast window (e.g., 39-hour lead time). If there exists diversity in the trade-offs between hazard outcomes among Pareto frontiers, the warning signal can be tailored further for specific locations.

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