DOCTORAL THESIS

Flood Hazards in Coastal Areas: Impact of Cyclones and Compound Extremes

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Date of Award:
2022

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A thesis submitted in partial fulfillment of the requirements

for the degree of Doctor of Philosophy

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Abstract

Coastal areas are vulnerable to multiple flood hazards from heavy precipitation and extreme sea levels that are usually associated with cyclones (i.e., tropical cyclones [TCs] and extratropical cyclones [ETCs]). Moreover, the flood risk faced by coastal populations is expected to increase in a warmer future climate due to the accelerating sea level rise and intensifying climate extremes. Therefore, a better understanding of hazards and physical mechanisms of floods in coastal areas is of great significance for flood management and climate change adaptation. This study analyzes the flood hazards in coastal areas by exploring the response of local rainfall totals to the changes in TCs over the coast of China, and comprehensively assessing the compound flood hazards from heavy rainstorm and extreme storm surge across the globe. The spatio-temporal evolution of compound flood hazards during the past decades at the global scale is examined based on long-term observations. Based on the socio-economic damage induced by TCs in Hong Kong, this study also evaluates the impact of compound floods on the society and economy.

The analysis of the changes in TC translation speed indicates that both observations and the multimodel ensemble of Global Climate Model simulations show a significant slowdown of TCs (11% in observations and 10% in simulations, respectively) from 1961 to 2017 over the coast of China. The analyses of long-term observations find a significant increase in the 90th percentile of TC-induced local rainfall totals and significant inverse relationships between TC translation speeds and local rainfall totals over the study period. The study also shows that TCs with lower translation speed and higher rainfall totals occurred more frequently after 1990 in the Pearl River Delta in southern China. The probability analysis indicates that slow-moving TCs are more likely to generate heavy rainfall of higher total amounts than fast-moving TCs. These findings suggest that the slowdown of TCs tends to elevate local rainfall totals and thus impose greater flood risks at the regional scale.

During simultaneous or successive occurrences of precipitation and storm surges, the interplay of the two types of extremes can exacerbate the impact to a greater extent than either of them in isolation. The compound flood hazards from precipitation and storm surges vary across regions of the world because of the various weather

conditions. By analyzing in-*situ* observations of precipitation and storm surges across the globe, it is found that the return periods of compound floods with marginal values exceeding the 98.5th percentile (i.e., equivalent to a joint return period of 12 years if the marginal variables are independent) are < 2 years in most areas, while those in northern Europe are > 8 years due to weaker dependence. The quantitative assessment shows that cyclones (i.e., TCs and ETCs) are the major triggers of compound floods. More than 80% of compound floods in East Asia and > 50% of those in the Gulf of Mexico and northern Australia are associated with TCs, while in northern Europe and the higher latitude coast of North America, ETCs contribute to most compound floods (i.e., 80%). The meteorological patterns characterized by deep low pressure, cyclonic wind, and abundant precipitable water content are conducive to the occurrence of compound floods. Extreme precipitation and extreme storm surges over Europe tend to occur in different months, which explains the relatively lower probability of compound floods in Europe.

Analyzing the past changes in the characteristics of compound flood events is critical to understand the changing flood risks associated with the combination of multiple drivers/hazards. This study examines the evolution of compound flood days (defined using the 90th percentiles) to understand the changing compound flood hazards across the globe. Results show that the annual number of compound flood days increased significantly by 1–4 per decade (α = 0.1) on the east coast of the US and northern Europe, while the annual number of compound flood days decreased significantly in southern Europe and Japan. The increasing trends in precipitation under extreme storm surge and storm surge under extreme precipitation are found extensively across the world except in Japan, suggesting that more intense precipitation appeared when extreme storm surges occurred, and higher storm surge emerged when extreme precipitation occurred. Comparatively, the global fractional contributions of storm surge (i.e., 65%) on changes in compound flood days are higher than that of precipitation (i.e., 35%), demonstrating that storm surge is more likely to dominate the changes in compound flood days.

The relevant methods are applied to Hong Kong to analyze the compound floods from precipitation and extreme sea levels. Results show that the most extreme sea levels are usually accompanied by heavy precipitation and thus may lead to compound floods, while the most extreme precipitation events are not likely to coincide with extreme sea levels. Those most extreme sea levels are associated with TCs, but TCs are not the only weather system that can trigger extreme precipitation in Hong Kong. During past decades, the compound flood hazards in Hong Kong show a significant increasing trend, which is mainly attributed to the mean sea level rise. TCs are the major trigger of compound floods with fractional contributions ranging from 48.8% to 83.8%. The analysis of TC-associated social-economic damage in Hong Kong demonstrates that TCs associated with compound floods are more destructive than those caused single hazards.

This study contributes to providing observational evidence that the slowdown of TCs tends to produce higher local rainfall totals and thus imposes greater flood risks at the regional scale. The findings of spatio-temporal characteristics, the physical mechanisms, and the socio-economic damage of compound floods are important scientific references for engineering design, flood risk management, and formulation of climate change adaptation strategies.

Keywords: Flood hazards; Precipitation; Storm surge; Tropical cyclones; Extratropical cyclones; Compound extremes; Copula; Coastal areas; Climate change