RISE OF THE STORMS:
A TALE OF ALTERING EXTREME PRECIPITATION CHARACTERISTICS IN A WARMING WORLD

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ABSTRACT.

The escalating threat of flooding due to climate change, urbanization, and population growth calls for accurate flood estimation, especially as annual flood losses are projected to reach up to $52 billion by 2050. However, factors like changing precipitation patterns, watershed changes, and model uncertainties complicate future flood estimation. Rising global temperatures not only intensify extreme storms but also alter their spatial and temporal characteristics, yet these changes remain poorly understood across different climate regions, hindering effective hydrological response planning. This study investigates how climate change affects storm spatio-temporal patterns and probable maximum precipitation (PMP) estimates, pinpointing regions most vulnerable to these shifts. The specific three objectives of this study are 1) to understand how the spatial extent of short duration precipitation extreme changes across the globe particularly in response to climate variables like temperature 2) to understand and quantify the changes in combined spatio-temporal characteristics of extreme storms in response to rising temperatures; and 3) to evaluate changes in probable maximum precipitation (PMP) estimates in response to climate change, specifically identifying critical infrastructure—such as dams and nuclear facilities—that may be at increased risk.

In the first objective, a novel grid-based metric called the Spatial Homogeneity (SH) metric is developed to assess the changes in spatial extent of extreme storms of different intensity and across different regions. The study finds that rising temperature results in smaller size extreme storms in the tropics, but larger size storms in the arid regions. It is also found that more intense precipitation events have a smaller spatial extent. Furthermore, larger spatial extent storms were found to be associated with higher total precipitable water, while overall cold vs warm year or overall year around wetness vs dryness of a region had limited impact on the spatial extent of these extreme storms. The results of this study imply that rising temperatures will result in spatially smaller and more intense extreme precipitation storms in the tropics.

Adding a temporal dimension to the Spatial Homogeneity metric, the second objective introduces the Spatio-Temporal Homogeneity (STH) metric to analyze global patterns in the combined spatio-temporal characteristics of short-duration extreme storms. Findings reveal that extreme storms contract in both space and time in the tropics, while expanding in temperate zones as temperatures rise. Additionally, storms in the tropics and southern temperate regions exhibit increased front-loading, whereas northern temperate storms become slightly more rear-loaded. Short-duration (6–12 hours) storms show heightened sensitivity to temperature increases, underscoring the need for region-specific flood management and adaptation strategies.

Finally, the third objective assesses how climate change impacts global PMP estimates, focusing on changes in precipitation efficiency and maximum precipitable water PW_{max}. While precipitation efficiency remains relatively unchanged, PW_{max} has increased up to 40% in certain regions since the 1960s, establishing a conservative baseline for PMP rises. Future climate projections highlight that PMP estimates are expected to continue increasing even further. Furthermore, longer-duration PMPs show the most significant increases, stressing the need to reassess safety standards for large dams in high-risk areas. The study identifies the regions most at risk and highlights the necessity for updated PMP standards and targeted infrastructure adaptation in vulnerable regions.

This dissertation advances our understanding of how climate change is reshaping extreme precipitation characteristics, particularly from a hydrologic flood-generation perspective. By providing refined, climate-adjusted representations of future precipitation patterns, it marks a step toward improved accuracy in future flood and hydrologic response estimation. These insights lay a foundation for more informed flood risk assessments and support the development of targeted, resilient water management strategies essential for adapting to a changing climate.