Analysis of Hydroclimatic Extremes in the Great Lakes Basin Under Climate Change Using WRF-Hydro

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ABSTRACT

Floods are among the most frequent and damaging natural hazards, and their characteristics are evolving under climate change. This study investigates projected changes in flood magnitude, frequency, and seasonality across the Great Lakes Basin (GLB), an important freshwater resource of North America. We employed streamflow simulations from the WRF-Hydro model, driven by an ensemble of eight CMIP6 climate models under the SSP5-8.5 scenario. Future projections indicate basin-scale increases in flood magnitudes that are concentrated in the southern and eastern GLB, while northern subbasins show smaller increases or localized decreases. Seasonal analysis reveals pronounced increases in winter floods, especially in northern snow-influenced regions, alongside declining summer floods in the north. These findings highlight a significant reorganization of flood regimes driven by combined effects of intensified precipitation and altered snowmelt dynamics.

KEYWORDS: Climate Change, The Great Lakes Basin, WRF-Hydro, Flood frequency analysis

1 INTRODUCTION

Floods account for roughly 35–40% of weather-related disasters worldwide, causing substantial human and economic losses. Under climate change, flood characteristics such as magnitude, frequency, and seasonality are expected to evolve significantly, posing challenges for flood risk assessment and infrastructure design. The Great Lakes Basin (GLB) exhibits strong hydroclimatic gradients, including snowmelt-dominated regimes in the north and rainfall-dominated regimes in the south. While previous studies have examined parts of the GLB, basin-wide assessments of future flood magnitude, frequency, and seasonality remain scarce. This study addresses these gaps by integrating physically based hydrological simulations from WRF-Hydro and an ensemble of CMIP6 climate projections under a high-emission scenario. The objectives are to quantify projected changes in flood magnitude across the GLB, and assess shifts in the seasonal distribution of floods under future climate conditions.

2 STUDY AREA AND DATA

2.1 Study Area

The study focuses on the Great Lakes Basin, which spans approximately 1.4 million km^2 across the United States and Canada and comprises six major subbasins: Lake Superior, Lake Michigan, Lake Huron, Lake Erie, Lake Ontario, and the St. Lawrence River (Figure 1). The basin experiences a humid continental climate with strong seasonal temperature contrasts and a pronounced north-south gradient in snow influence.

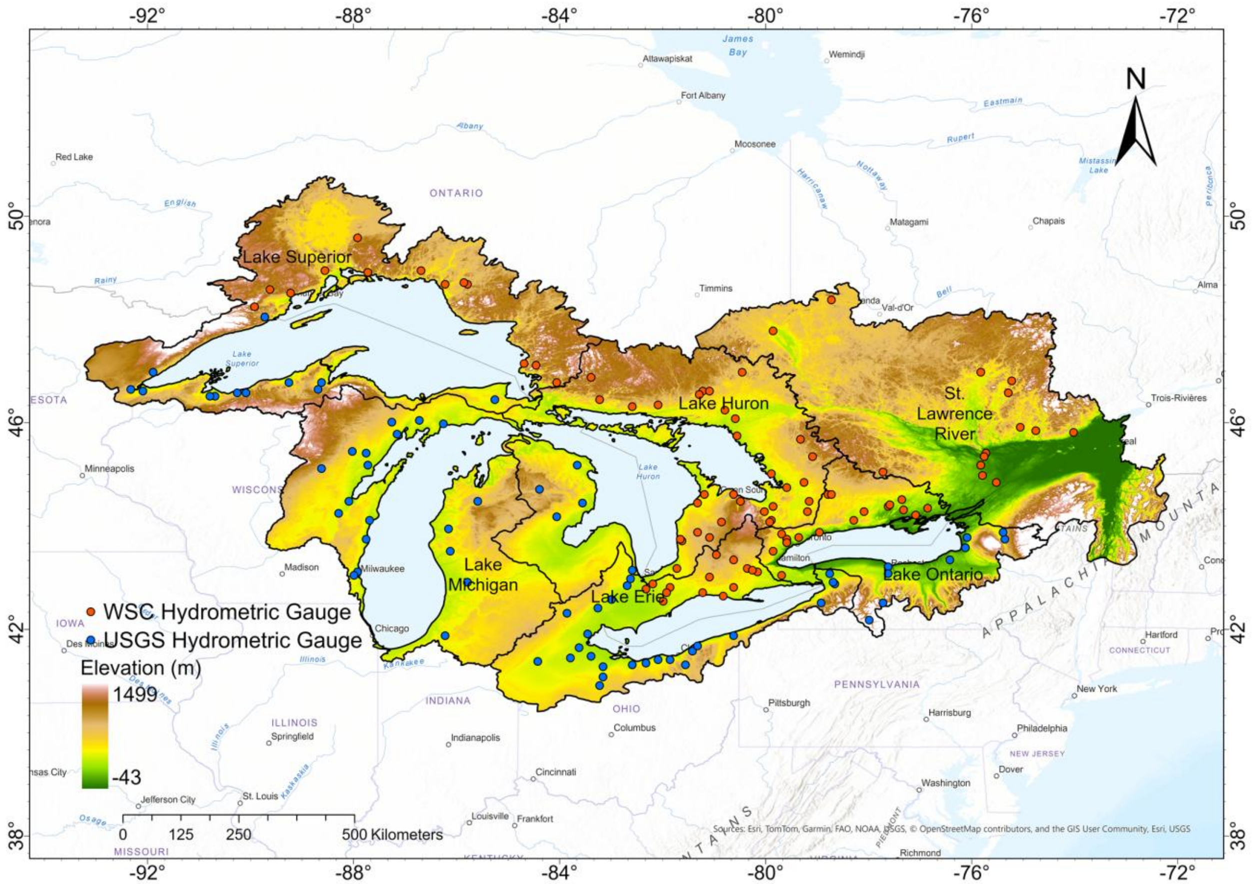

Figure 1: Location and topography of the Great Lakes Basin in North America, and the hydrometric gauges used in this study.

2.2 Hydrometric and Meteorological Data

Daily streamflow observations were obtained from the Water Survey of Canada (WSC) and the United States Geological Survey (USGS). After quality control and data availability screening, which requires at least 30 years of record and at least 90% completeness per year, 160 gauges were retained for analysis.

Meteorological forcing for hydrological simulations during the historical period was derived from the Regional Deterministic Reanalysis System v2 (RDRS-V2 reanalysis), which provides hourly precipitation, temperature, radiation, wind, humidity, and surface pressure fields at high spatial resolution.

2.3 Climate Model Projections

An ensemble of eight CMIP6 Global Climate Models was selected under the SSP5-8.5 scenario. Daily precipitation and temperature variables were bias-corrected and downscaled using the Multivariate Bias Correction (MBCn) method, which preserves inter-variable dependence (Cannon, 2018). Climate simulations span 1960–2100, with historical and future periods defined as 1985–2014 and 2071–2100, respectively.

2.4 Geophysical Data

Land cover, soil texture, and topography were obtained from the North American Land Change Monitoring System (NALCMS), Global Soil Dataset for use in Earth System Models (GSDE), and 2-

minute Gridded Global Relief Data v2 (ETOPO2) datasets and used to parameterize the hydrological model.

3 METHODOLOGY

The WRF-Hydro model (version 5.1.1) was implemented in standalone mode with the Noah-MP land surface model at approximately 3.7 km spatial resolution (Gochis et al., 2020). The model was calibrated and validated against observed streamflow using the Kling-Gupta Efficiency metric. The calibrated model was subsequently driven by bias-corrected CMIP6 climate projections to simulate streamflow for historical and future periods (Rahimimovaghar, 2024).

Multiple statistical distributions, which include GEV, GPD, Log-Pearson III, Metastatistical Extreme Value, and Extended GPD, were employed for flood frequency analysis. A Monte Carlo cross-validation experiment was conducted independently at each gauge. In each of 1000 realizations, a 10-year subset of data was randomly selected for calibration, while the remaining years were used for validation. Model performance was evaluated using a skill score computed for return periods exceeding the calibration length, focusing on extrapolation capability rather than in-sample fit. For each hydrometric gauge, the best-fitting distribution is used for estimating flood quantiles for different return periods.

4 RESULTS

Future projections indicate widespread increases in flood magnitude across the GLB, particularly in southern and eastern subbasins (Figure 2). Ensemble median increases frequently exceed 50% and locally surpass 100% for both 5-year and 100-year floods. Northern subbasins show smaller increases and occasional decreases, especially for more moderate floods. Uncertainty, quantified by the interquartile range across climate models, increases with return period, indicating greater uncertainty for rarer events.

Seasonal flood frequency analysis shows pronounced increases in winter floods (DJF), especially in northern snow-influenced regions (Figure 3). Spring (MAM) and autumn (SON) floods generally increase moderately across most of the basin. In contrast, summer floods (JJA) are projected to decrease in northern subbasins, notably in the Lake Superior and St. Lawrence River basins, while southern regions exhibit smaller changes or increases.

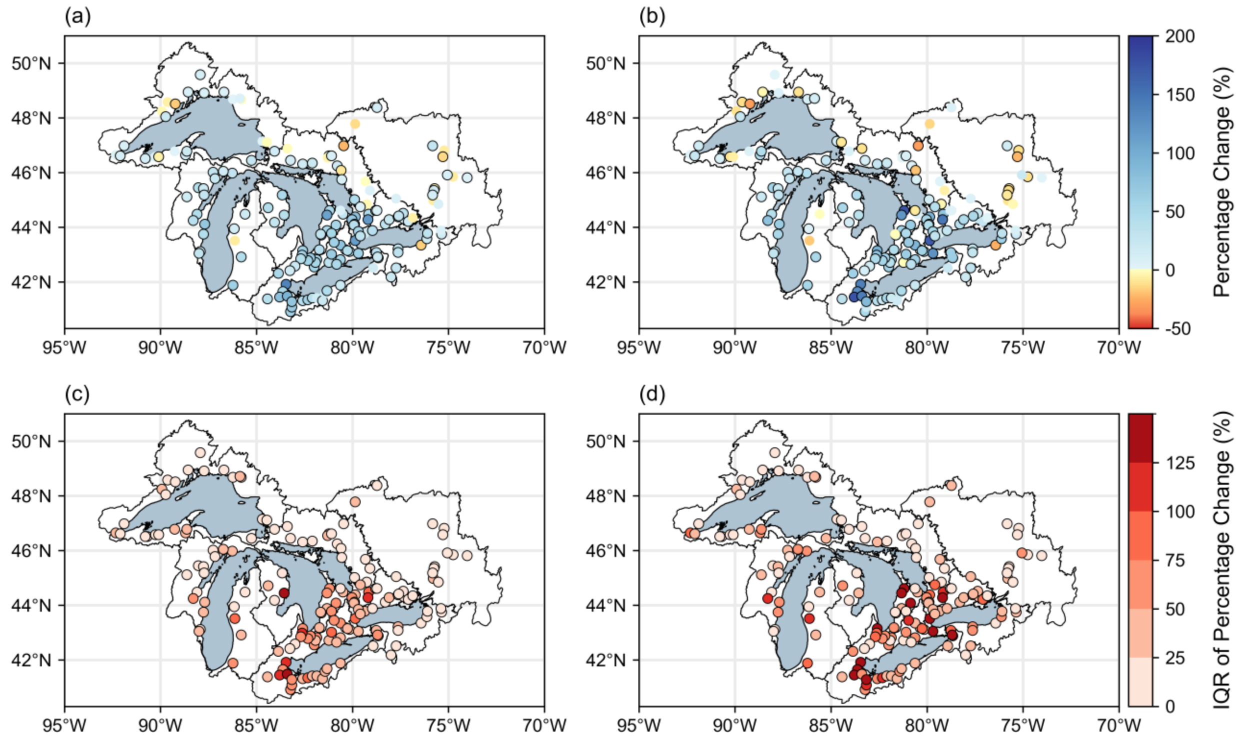

Figure 2: Spatial distribution of projected changes in flood magnitude across the Great Lakes basin. Panels (a) and (b) show the multi-model ensemble median (from 8 GCMs) of the percentage change in flood magnitude between the historical period (1985–2014) and the future period (2071–2100) for the (a) 5-year and (b) 100-year return periods, respectively. Dots outlined in black indicate gauges where the projected change meets the model agreement threshold (≥67% of GCMs). Panels (c) and (d) show the corresponding IQR of percentage change across the 8 GCMs for the (c) 5-year and (d) 100-year return periods.

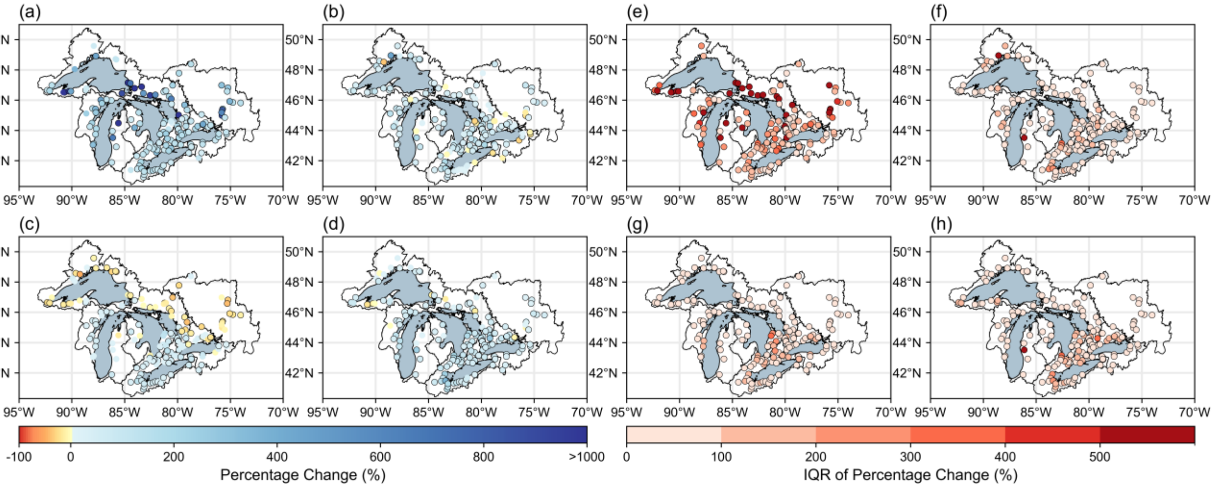

Figure 3: Seasonal projections of changes in the 100-year flood across the Great Lakes basin. Panels (a)–(d) show the multi-model ensemble median (from 8 GCMs) of the percentage change in the 100-year flood between the historical period (1985–2014) and the future period (2071–2100) for the four seasons: (a) DJF, (b) MAM, (c) JJA, and (d) SON. Dots outlined in black indicate gauges where the projected changes meet the model agreement threshold (≥67% of GCMs). Panels (e)–(h) show the corresponding IQR of percentage change across the 8 GCMs for (e) DJF, (f) MAM, (g) JJA, and (h) SON.

5 CONCLUSIONS

This study reveals a substantial reorganization of flood regimes across the Great Lakes Basin under climate change. Projected changes include widespread increases in flood magnitude concentrated in southern and eastern subbasins, with smaller or declining floods in some northern regions. There is a pronounced shift toward more winter-dominated flooding accompanied by declining summer floods in snowmelt-dominated areas. These changes reflect the combined influence of intensified precipitation and altered snowmelt dynamics. Overall, the findings underscore the importance of integrated modeling approaches for flood risk assessment in regions with complex hydroclimatic controls.

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