UNCERTAINTIES AND DRIVERS OF HYDROCLIMATIC EXTREMES UNDER HISTORICAL AND CLIMATE CHANGE SCENARIOS

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ABSTRACT

Hydroclimatic extremes, such as droughts, heatwaves, and their combined occurrence, are becoming more frequent and intense under a changing climate, threatening water resources, agriculture, ecosystems, and human well-being. Improving our understanding of the processes that drive these extremes, and the uncertainties associated with their assessment and future projections, is essential for developing effective climate adaptation strategies. This study investigates the drivers, uncertainties, and future evolution of hydroclimatic extremes across regional and global scales.

The initial part of the study investigates the variability of reference evapotranspiration (ETo) an indicator of atmospheric evaporative demand, across the Indian subcontinent. Historical analysis indicates that ETo showed statistically significant decreasing trends across 61% of the subcontinent despite widespread warming, demonstrating the persistence of the evapotranspiration paradox. Future projections indicate a progressive weakening of the evapotranspiration paradox as temperature-driven atmospheric demand becomes stronger. The thesis then examines how atmospheric evaporative demand and soil moisture (SM) jointly regulate actual evapotranspiration (ET) and how these controls are projected to change under climate warming. The analysis identifies contrasting land–atmosphere interaction regimes, with ET primarily controlled by soil moisture in arid regions and by ETo in humid regions. CMIP6 models capture the large-scale spatial patterns of ET but exhibit substantial inter-model spread and with improved model skill from humid to arid climates. Ensemble reliability is greater in humid regions, and future projections suggest a strengthening influence of soil moisture on ET under climate change.

Recognizing that reliable assessment of hydroclimatic extremes depends on the methods used to quantify them, the thesis evaluates uncertainties associated with drought indices and evapotranspiration formulations. While different drought indices show reasonable agreement under historical conditions, marked divergence emerges toward the end of the 21st century, particularly under high-emission scenarios and in arid and semi-arid regions. The uncertainty analysis shows that drought characterization is sensitive to index structure, ETo formulation, baseline selection, and climate-model spread, with projected drought-category differences reaching up to two drought classes in several regions. These findings underscore the need to explicitly account for methodological uncertainty in drought monitoring, impact assessment, and the design of robust climate adaptation strategies. The thesis further extends the analysis to compound dry and hot events at the global scale using a three-dimensional event-based framework that captures their evolution in space and time. Results identify the Amazon, Central Africa, Northern North America as persistent CDHE hotspots exhibiting high event frequency. The study further investigates intercontinental synchronization using complex-network metrics and evaluates the roles of ENSO, PDO, and anthropogenic warming. The result indicates a weakening ENSO–CDHE linkage and highlight the increasing influence of anthropogenic warming as the dominant driver of CDHE occurrence. The capability of CMIP6 climate models to reproduce historical compound events and project future changes is also evaluated. The models successfully capture the broad characteristics of observed events and consistently project an increase in the frequency of compound dry and hot events during the twenty-first century. The analysis further demonstrates that future projections are influenced not only by differences among climate models but also by the choice of drought and compound-event definitions.

Overall, this study advances the understanding of the physical drivers, land–atmosphere interactions, and methodological uncertainties governing hydroclimatic extremes under historical and future climate conditions. By integrating regional process-based analyses with global assessments of compound extremes, the research provides a comprehensive framework for improving climate risk assessment and supports more informed decision-making for water resource management, drought preparedness, and climate adaptation in an increasingly warming world.

Keywords: Evapotranspiration paradox, Drought, Uncertainty, Compound extreme, Complex network, Climate change