Evolution of Hydrological Compound Extremes under Changing Climatic Conditions

Abstract

Hydro-climatic extremes across India are undergoing a profound reorganization under a warming and increasingly non-stationary monsoon system, with major implications for water security, agricultural productivity, and climate resilience. Traditional frameworks based on stationary baselines, aggregated precipitation totals, and linear relationships are increasingly inadequate for resolving the evolving persistence, severity, and cascading behavior of these extremes. This thesis develops a unified, process-consistent analytical framework to investigate the spatiotemporal evolution of droughts, compound drought-heatwave events (CDHWs), hydro-climatic whiplash, and their underlying causal mechanisms across India, while extending key findings to the global terrestrial domain. By integrating non-stationary drought representation, spell-sensitive persistence metrics, event-based transition diagnostics, and a novel non-linear causal architecture, the study advances a regime-aware understanding of how hydro-climatic risks are intensifying, expanding, and bifurcating under climate change.

Across the long observational record, drought characteristics over India reveal clear evidence of structural change. Incorporating a dynamic climatic baseline through the Non-stationary Standardized Precipitation Index (NSPI) substantially improves drought detection relative to stationary formulations, particularly in tropical and semi-arid regions where evolving mean state and variance strongly alter event characterization. The non-linear evolution of these droughts indicates a statistically significant post-1950 rise of nearly 61 to 62 % in intrinsic duration and severity, pointing to a fundamental reorganization of monsoon variability. Spatially, northwestern, western, and eastern India are transitioned toward shorter but more severe droughts, whereas central and southern regions are increasingly characterized by longer but milder drought episodes. These divergent trajectories expose nearly 70 % of India's population to intensifying drought risk, with measurable penalties on cereal productivity, thereby underscoring the necessity of non-stationary drought frameworks for adaptive planning.

The amplification of individual extremes is further manifested in the evolution of compound drought-heatwave events. By explicitly resolving intra-month precipitation spells structure through the Standardized Net Precipitation and Distribution Index (SNEPI), the analysis captures hydrological persistence that remains obscured in conventional aggregated metrics. Over India, this persistence-driven CDHW framework reveals nearly 10 % to 35 % expansion of CDHW-affected areas. A marked hotspot migration from the traditionally arid northwest toward humid southern and eastern regions signifies a regime shift in compound hazard geography, with extreme CDHWs increasing by nearly 25-fold. The persistence signal is not restricted to the Indian domain; at the global scale, a pronounced post-2000 escalation emerges, characterized by ~43 % higher intensity, ~30% longer durations, and nearly doubled frequency. The spatial footprint of affected land nearly doubles, while the seasonal window of occurrence expands beyond boreal summer. Most notably, the transition from short-lived extremes to persistent, multi-month hazard regimes demonstrates that hydrological buffering is weakening globally, transforming CDHWs into sustained systemic risks for food-producing and water-stressed regions.

This erosion of climatic buffering is even more sharply expressed in hydro-climatic whiplash, where rapid transitions between prolonged dry and wet spells are becoming increasingly dominant. Across India, a

marked regime shift emerges around the 1980s, characterized by intensified wet spells, longer dry spells, and a 40 % increase in dry-spell-affected grids experiencing fewer but more persistent events. Event coincidence analysis reveals that trigger coincidence rates between extreme dry and wet spells exceed 0.8 after the mid-1980s, with strong expansion across the west coast, central India, and the northeast. The increasing dominance of dry-to-wet transitions, together with significant rises in severe and extreme whiplash frequencies, indicates a reorganization of monsoon feedbacks toward more volatile and abrupt state changes. Persistent hotspots along the southwest coast and northern India, coupled with post-2000 negative anomalies in wheat yields, demonstrate that this volatility is already imposing a measurable climate penalty on agricultural systems.

The physical mechanisms underlying these rapid transitions are shown to be strongly regime-dependent and fundamentally non-linear. To resolve this complexity, the thesis introduces the Non-linear Physics - constrained Adaptive Causal Evolution (N-PACE) framework, which integrates non-linearity, non-stationarity, and spatial heterogeneity into causal discovery. The results reveal a clear bifurcation in the drivers of whiplash across India. Atmospheric stability, for instance, behaves as a suppressor in humid regions but reverses into a radiative amplifier in arid environments, establishing a “stability inversion” in the physical controls of extremes. In the arid west, a post-1990 thermodynamic takeover is identified, wherein the predictive influence of synoptic circulation weakens and is replaced by instantaneous radiative shocks and collapsing soil-moisture memory, marking a transition from storage-limited to flux-limited hydrology. Conversely, the tropical peninsula exhibits the persistence of comparable forecast skill at long lead times, suggesting the influence of ecological memory in energy-limited systems. By resolving these non-linear causal structures, the framework achieves predictive error reductions approaching 48.7 % in climatically complex regions relative to linear baselines.

Extending the whiplash analysis from the Indian, precipitation-based setting to the global terrestrial domain, the thesis finally develops a globally consistent, impact-relevant diagnostic framework to detect, validate, and characterize hydroclimatic whiplash events across diverse climate zones during 1980–2019. Three whiplash definitions of increasing hydrological complexity are evaluated and validated against observed drought and flood disasters. An integrated cause-effect definition requiring concurrent anomalies in precipitation, runoff, and soil moisture, achieves the highest validation hit rate (~43 %) while detecting fewer but more physically consistent events, indicating superior impact relevance. Approximately 65 % of whiplash-affected regions exhibit statistically significant trigger-response coupling with hydrological water stress, identifying global adaptation-relevant hotspots concentrated across tropical, arid, and monsoon climate zones. These results provide a physically grounded, adaptation-oriented classification of global hydroclimatic vulnerability, offering a diagnostic foundation for prioritizing water-system and river-basin adaptation under increasing compound hazard risk.

Hydro-climatic extremes are not simply intensifying in magnitude; they are reorganizing in persistence, spatial footprint, transition dynamics, and causal anatomy. The convergence of non-stationary drought evolution, persistence-driven compound extremes, accelerating whiplash, and bifurcating physical mechanisms establishes the need for a paradigm shift from stationary, globally averaged diagnostics toward regime-specific, process-aware frameworks. This thesis provides that foundation and offers a unified pathway for next-generation early warning, adaptation, and hydro-climatic risk management under accelerating climate change.