A Systemic Shift towards Hydroclimatic Whiplash in India: Event-Based Evidence of Escalating Dry-Wet Transitions since 1951

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Abstract

This study presents a comprehensive assessment of the evolution of hydroclimatic extremes, dry spells (DS), wet spells (WS), and their rapid transitions (whiplash) across India from 1951 till 2019. A marked reorganization of extremes emerged around the 1980s regime shift, characterized by widespread intensification of WS and a 40 % rise in DS-affected grids experiencing fewer but longer events. Using Event Coincidence Analysis, trigger relationships between extreme DS and WS are quantified, revealing that trigger coincidence rates exceeded 0.8 after the mid-1980s and increased spatially by nearly 49 % over the west coast, Central India, and the Northeast. Disaggregating transitions demonstrated an emerging dominance of dry-to-wet (DTW) behavior, with an increase of ~14 %, reflecting reorganized monsoon feedbacks. Quantification of whiplash severity revealed a 13 % and 8.7 % rise in extreme and severe whiplash frequencies, and a 26.6 % increase in grids exhibiting simultaneous high frequency, duration, and intensity. Spatially, the southwest coast and northern India exhibit ‘persistently high’ risk with no recovery since 1951, while the east coast and central India show ‘emerging’ volatility. Crucially, this intensification translates into a quantifiable ‘climate penalty’ on agriculture: post-2000 wheat yields show persistent negative anomalies with an increase in exposure to extreme whiplash risk, which in turn demands an immediate pivot in adaptation and resource planning.

Short Summary

This study examines how episodes of rapid switches between extreme wet and dry spells have changed across India since 1951. Sudden shifts from dry to wet conditions have become more frequent and intense since the 1980s, spreading to new regions. Some areas now face lasting risk, with no recovery. These changes are already reducing crop yields, showing that growing climate instability is creating real economic losses and demands urgent adaptation.

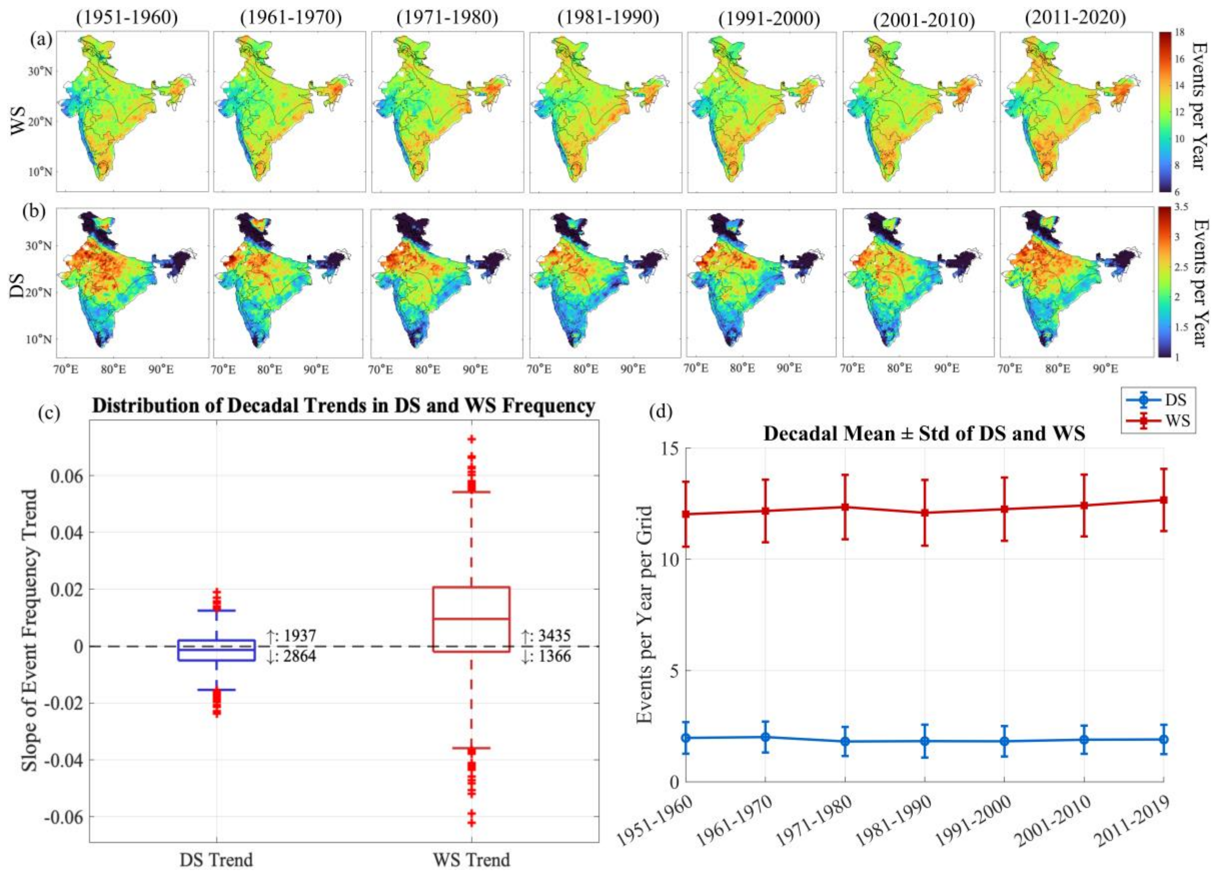

Figure S1: (a) Decadal and spatial evolution of the individual DS and, (b) WS starting from 1951-1960 to 2011-2019, calculated as events per year per decade; (c) Distribution of linear trend slopes in decadal DS and WS frequency across 4801 grids during 1951-2019- positive slope (WS) indicate increasing trends in frequency over time, while negative slope (DS) shows a decreasing trend in frequency over time; (d) Decadal evolution of spatial mean and variability (± 1SD) in DS and WS frequency across India during 1951-2019- while WS shows a consistent rise in mean frequency over the decades, the DS trends remain relatively stable, highlighting an intensifying and spatially variable wetting regime.

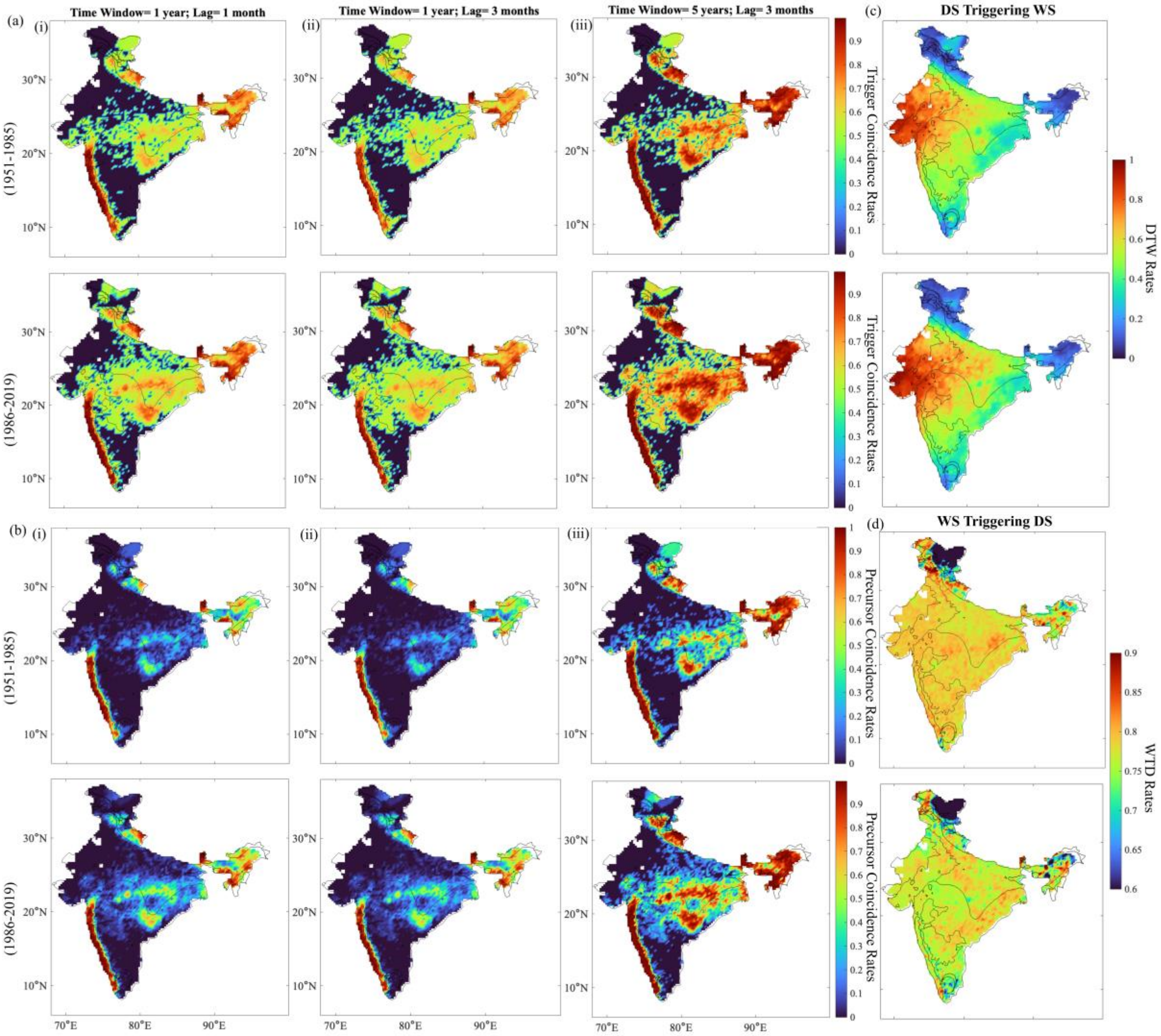

Figure S2: (a) Change in Trigger Coincidence Rates and, (b) Precursor Coincidence Rates with change in ECA metrics: (i) Time Window= 1 year, Lag= 1month, (ii) Time Window= 1 year, Lag= 3 months, (iii) Time Window= 5 years, Lag= 3 months- Trigger rates decreasing with increasing Lag, and increasing with increasing Time Window, with a significant increase during 1986-2019 as compared to 1951-1985; (c) Spatial analysis of DS triggering WS (DTW) and (d) WS triggering DS (WTD) during 1951-1985 and 1986-2019- while DTW shows a prominent spatial footprint which increases during 1986-2019 both in magnitude and spread, WTD though more frequent shrinks in spread during 1986-2019.

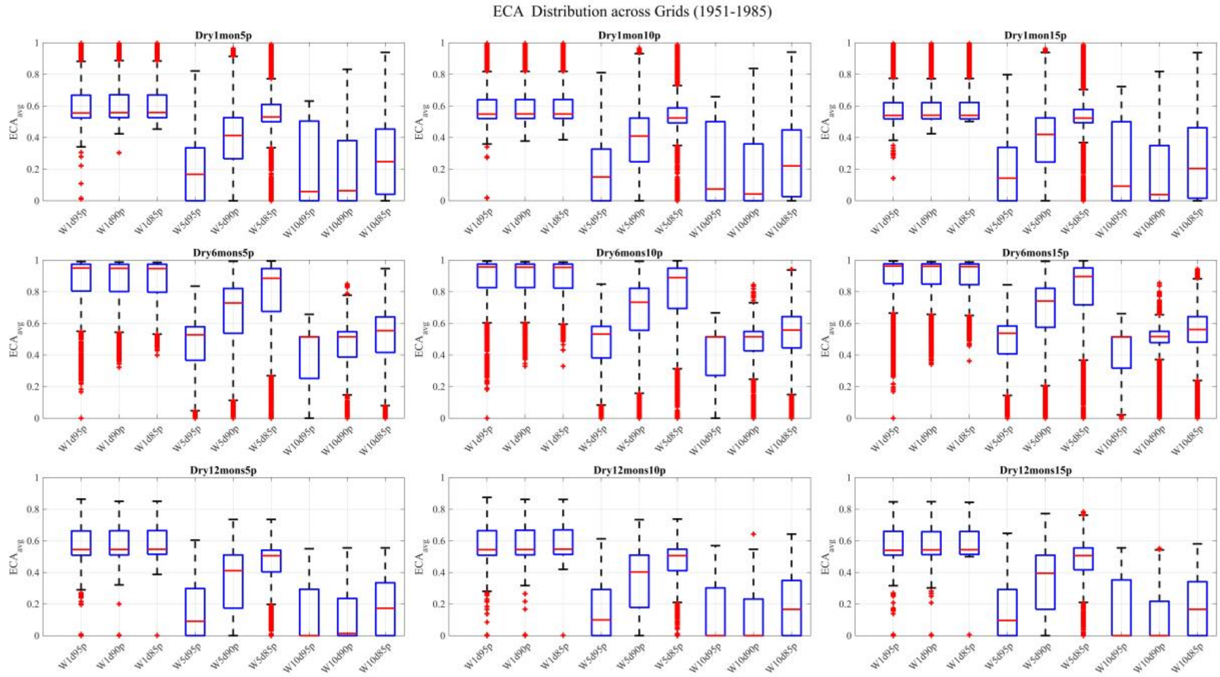

Figure S3: Frequency distribution of 81 compound DS-WS categories during 1951-1985, constructed by varying the duration and intensity of individual DS and WS.

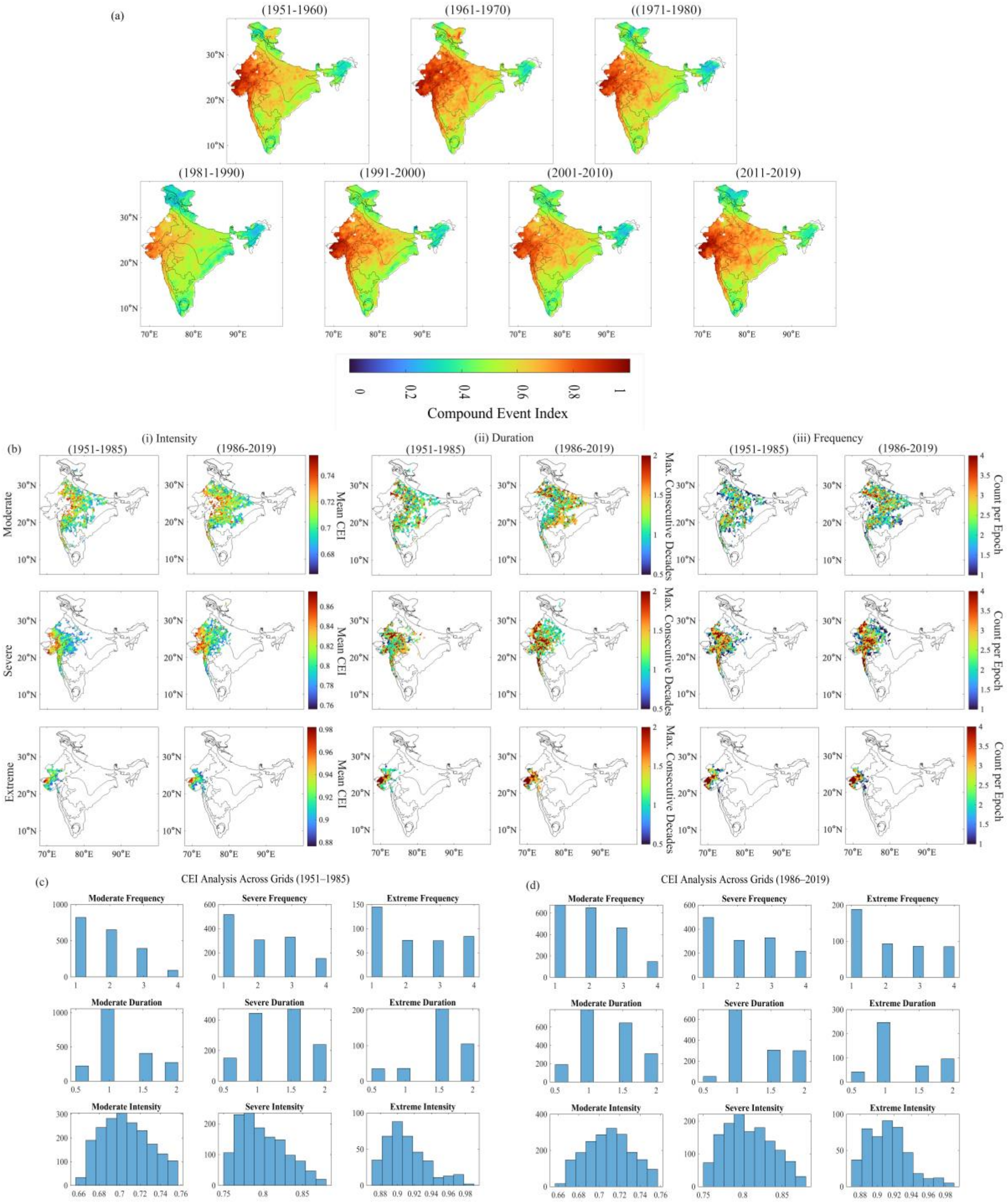

Figure S4: (a) Spatial mapping of decadal normalized CEI revealing a sharp decline in whiplash occurrences and its spatial coverage during 1981-1990, in contrast to the substantial rise after that leading to the highest during 2011-2019; (b) Spatial evolution of the different characteristics- (i) Intensity, (ii) Duration, and (iii) Frequency of the Moderate, Severe, and Extreme Whiplash categories from 1951-1985 to 1986-2019; (c) Grid-wise distribution of Moderate, Severe, and Extreme Whiplash risk characteristics

during 1951-1985 and 1986-2019, showing a comparison of clustering of metrics and emergence of high-risk grids.

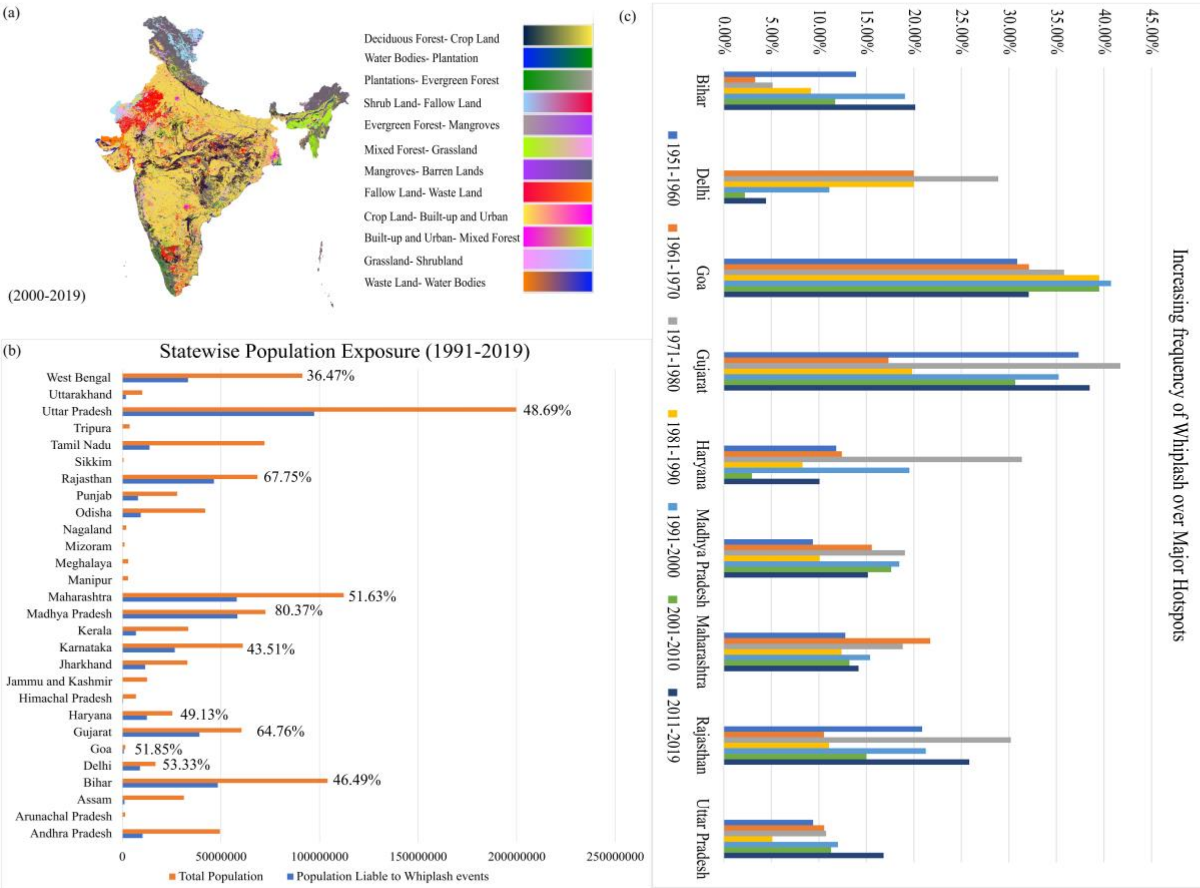

Figure S5: (a) LULC map showing an increased population exposure with an increased built-up region during the most vulnerable decades 1991–2019; (b) State wise population exposure to the whiplash events during 1991–2019 based on percentage of grids over these states vulnerable to the whiplash occurrences; e) Decadal ECA frequency analysis of the states which were the most liable to the whiplash events based on their high population exposures.