Abstract

Climate change is fundamentally reshaping hydroclimatic regimes worldwide, with profound implications for water resources, agriculture, ecosystems, and urban infrastructure. A critical manifestation of this transformation involves shifts in aridity regimes, which govern land-atmosphere interactions that modulate the characteristics of hydroclimatic extremes, including catastrophic flash floods triggered by extreme precipitation and flash droughts from rapid soil drying. With continued global warming, future events are likely to intensify further, driving regime transitions with profound implications for ecosystems, agricultural productivity, and critical infrastructure. These transformations are particularly concerning for India, given its high population density, climatic diversity, and primary dependence on monsoon precipitation for agriculture. Given the pressing nature of these issues, a comprehensive spatio-temporal assessment of hydroclimatic regime shifts is crucial. To address these research gaps, the studies undertaken in this thesis focus on examining the past and future shifts in the spatio-temporal dynamics of aridity, assessing changes in precipitation characteristics through Intensity-Duration-Frequency (IDF) relationships, and evaluating changes in flash drought characteristics through a newly proposed flash drought index. Future changes are assessed under three Shared Socioeconomic Pathways (SSPs), namely SSP126, SSP245, and SSP585, considering two future periods (epoch-1: 2022-2060 and epoch-2: 2061-2100).

The first objective (Chapter 2) focuses on analysing the historical evolution of aridity regimes using 120 years of climate data, together with an assessment of desertification vulnerability across the Indian mainland. The findings reveal substantial spatio-temporal variations. Significantly increasing dryness is observed across the humid regions of northeastern and northern India, including the Indo-Gangetic Plains (IGP), while decreasing dryness is most prominent in the semi-arid zones of southern peninsular India. Change point analysis revealed significant shifts in aridity between the 1950s and 1980s, based on which the observed period is divided into two distinct epochs: pre-change point period (1902-1951) and post-change point period (1982-2021). A comparison of the aridity index between these two epochs, together with the desertification vulnerability analysis, highlights an increasing desertification vulnerability in northern India, particularly across the IGP, associated with a regime shift from humid to sub-humid conditions. In contrast, parts of southern India and northern Jammu and Kashmir show a decreasing desertification vulnerability, with evidence of oasification from semi-arid to sub-humid conditions.

Building on these findings, the second objective (Chapter 3) extends the analysis into future periods to investigate patterns of desertification and oasification under different climate change scenarios. Future projections indicate an expansion of drylands under SSP126 and SSP245, while a gradual expansion of humid regions is projected under SSP585. A comparison with the post-change point historical period shows that desertification is projected to expand across western and northern India, including the IGP, while oasification is projected to increase across southern India. Although all SSPs project expansions of both patterns, shifts toward drier regimes are more extensive under SSP126 and SSP245, while oasification is more widespread under SSP585. Notably, the historically drier regimes are projected to become less arid, whereas historically humid areas are projected to become more arid, which is in contrast to the dry gets dries and wet gets wetter paradigm.

The third objective (Chapter 4) evaluates the changes in precipitation regimes in the future through the precipitation Intensity-Duration-Frequency (IDF) relationships, with a focus on hourly precipitation extremes under a changing climate. IDF relationships, traditionally derived from historical records, are essential tools for quantifying the characteristics of precipitation extremes for the design of water infrastructure. However, they are likely to change in the future due to the influence of climate change. Analysis using a bias-corrected multi-model ensemble approach for the future period projects significant intensification of hourly precipitation extremes across most parts of India compared to the historical period, with average increases ranging from 10% to 26% for 2-year events and 20% to 56% for 100-year events, depending on the scenario and epoch. The generated future IDF dataset are made available on an open repository (https://data.mendeley.com/datasets/gg3vy49jzg/1). This intensification is particularly pronounced in arid/semi-arid Gujarat and Rajasthan, humid northern and northeastern regions including IGP, and the Himalayan Terai region. Moreover, an analysis considering major metropolitan cities namely, Kolkata, New Delhi, Mumbai, and Chennai, indicates that these cities are projected to experience substantial increases in short-duration precipitation extremes, with the intensification being more pronounced in Kolkata and New Delhi. Notably, the regions showing increasing aridity are likely to experience greater increase in precipitation intensity.

The fourth and final objective (Chapter 5) aims to evaluate the past and future alterations in the flash drought (FD) characteristics. FDs can be driven by different factors, including heatwave-induced (H-FD), precipitation-deficit-induced (P-FD), and compound (HP-FD) types, which can adversely affect agricultural productivity and vegetation health. However, reliably identifying the different FD types with a single index remains challenging, as existing indices often exhibit bias toward specific drivers. To overcome this limitation, a new Combined Flash Drought Index (CFDI) is developed using copula-based integration of the Evaporative Stress Index (ESI) and the Soil Moisture Anomaly Index (SMAI) and validated against observed vegetation stress using the Vegetation Health Index (VHI). The CFDI demonstrates superior performance compared to both individual indices, ESI and SMAI. It successfully captures different types of FDs within a unified framework, achieving the highest overall precision of 81%. The analysis further suggests that regions exhibiting desertification tendencies, such as the Indo-Gangetic Plains and western India, are more exposed to flash droughts than areas showing oasification. Seasonal analysis shows that most FDs occur during monsoon and post-monsoon seasons, posing a severe threat to agricultural production. Although the frequency of flash droughts and their areal extent are projected to decline in the future, their average severity and duration are expected to increase across parts of western and northern India where desertification is projected to expand.

This thesis provides a comprehensive, multi-faceted assessment of hydroclimatic regime shifts across India, demonstrating a significant departure from the established dry gets drier and wet gets wetter paradigm. The findings reveal a contrasting trajectory where historically humid regions are becoming drier and more vulnerable to desertification and flash droughts, while semi-arid regions are undergoing oasification. Concurrently, short-duration precipitation extremes are projected to intensify, particularly in arid regions and in areas transitioning toward drier regimes, elevating flash-flood risk. The future IDF dataset generated in this study are made freely available on an open repository that will support future climate resilience and adaptation planning. Overall, these findings provide a detailed understanding of regime shifts across Indian mainland under a changing climate and highlight regions with critical need for tailored regional strategies to mitigate the compounded risks of increasing aridity, intense precipitation, and severe flash droughts in a warming climate.

Keywords: Climate Change; Hydroclimatology; Regime Shift; Aridity; Desertification; Oasification; Flash Drought; Intensity-Duration-Frequency (IDF) curve; Water Management.