

A MULTIFACETED INVESTIGATION OF METEOROLOGICAL DROUGHT DYNAMICS

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**A MULTIFACETED INVESTIGATION OF METEOROLOGICAL
DROUGHT DYNAMICS**

by

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Submitted

*in fulfillment of the requirements of degree of Doctor of Philosophy
to the*



**INDIAN INSTITUTE OF TECHNOLOGY DELHI
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Dedicated to

My

Husband

&

Parents

CERTIFICATE

This is to certify that the dissertation entitled “**A Multifaceted Investigation of Meteorological Drought Dynamics**” which is being submitted by **Mrs. Gauranshi Raj Singh**, for the award of the degree of **Doctor of Philosophy** in Civil Engineering, to the Indian Institute of Technology Delhi is a record of bona fide work carried out by her under my sustained guidance and supervision. The dissertation has reached the standard fulfilling the requirements of the regulations relating to the degree. The results embodied in the dissertation have not been submitted to any other university or institute for the award of any degree or diploma.

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ABSTRACT

Drought is a complex natural hazard, occurring across various climate zones over extended periods of space and time. The onset of drought is marked by the occurrence of a long-term deficiency in precipitation, also called meteorological drought. The spatio-temporal intensification of this atmospheric deficiency effects other components of the hydrological cycle which leads to the propagation of drought impacts on the Anthropocene. Hence, a realistic evaluation of drought onset is paramount for the effective implementation of mitigation strategies. Thus, the focus of my research is primarily on the dynamics of meteorological droughts, usually quantified through unbiased indices that consider the month-wise magnitude variations in historical climatic variables, while completely ignoring their intramonthly distributions. However, the applicability of such indices under the present scenario of changing climate, where intense short wet spells are reportedly increasing, is questionable. Such changes in the wet spells could eventually lead to prolonged intramonthly dry spells, which in turn will pose many agricultural and socioeconomic risks. To monitor the changed scenario realistically, I propose a new drought index—the Standardized Net-Precipitation Distribution Index (SNEPI), which incorporates the distribution characteristics of the daily net-precipitation variable. The applicability of SNEPI is critically evaluated using synthetically generated and observed precipitation series over six diverse climatic locations of India, at 1-, 3-, 6-, and 12-month time scales. The utility of SNEPI is more profound for longer time scales, understandably due to the enhanced emphasis imparted on the distribution of rainfall spells by the longer periods. SNEPI proves to be efficient in capturing the present scenario of increasing dryness (wetness) in wet (dry) regions when compared with the traditional Standardized Precipitation Evapotranspiration Index. Hence, the proposed index, which incorporates the changing precipitation characteristics, may aid in better quantification and monitoring of meteorological drought under the scenario of changing climate.

The increasing divergence/disagreement between the meteorological drought indicators, majorly due to the changing climate conditions, has disputed their pertinency in monitoring and modelling of drought events. In the present research, I attempted to quantify the divergence between widely used drought indices such as the standardized precipitation index (SPI), standardized precipitation evapotranspiration index (SPEI), and the newly developed standardized net precipitation index (SNEPI) and traced the evolution of this divergence/disagreement. A persistent presence of enhanced dry extremes in the annual divergence of SPEI with SPI and SNEPI was observed, which raises doubts about the utility of

traditional drought indices in capturing the changing climatic characteristics. The seasonal dispersion of this annual divergence revealed a strong, spatiotemporally dominant, signal of dryness in the monsoon season by SNEPI, which SPEI failed to unravel. Furthermore, the attribution analysis revealed that the SPI-SPEI disagreements evolved under the influence of the shortwave radiative fluxes. In addition to that, the divergence between SPEI and SNEPI, is driven by the characteristics of wet spells, with the relationship strengthening in the monsoon season and tropical climate zones. All these findings caution us to evaluate the need to incorporate the changing precipitation characteristics before deploying drought indices in operational uses, especially in tropical climate zones.

While the criticality of rainfall variability in driving the meteorological drought occurrences has been unravelled, a quantification of its contribution to the global drought dynamics is still unknown. The evolutionary characteristics of global meteorological droughts suggest that between 1951 and 2016, global drought frequency quadrupled due to shifts in climatic variables like rainfall deficit, evaporative losses, and rainfall variability. My research, extensively assessing these drivers, unveiled a 60% increase in the probability of drought occurrence, even in surplus rainfall years. This rise is attributed to precipitation variability, notably evident in Tropical/Subtropical regions. A 40% increase in precipitation-variability-led tropical droughts was also identified, marked by intense drought index values plummeting below -1. Interestingly, these events show increased skewness in rainfall spell distribution, explaining the dominance of precipitation-variability-induced droughts. This climatic behaviour significantly impacts diverse climate zones in the Tropics, from the monsoon region to arid deserts. The imprint of rainfall variability emerges as a defining factor in the dynamics of tropical droughts.

While I have unravelled the new-found contribution of changing precipitation characteristics in meteorological drought dynamics, the question of how meteorological drought develops is still unanswered from the perspective of lower atmospheric dynamics. Since the relationship between lower atmospheric dynamics and its inherent impact on the weather patterns share sensitivity to the geographical co-ordinates of a region, I conduct our investigation over an Indian subregion, owing to ease of data availability and familiarity with the region's climatology. Agricultural sector forms the backbone of India's socio-economy owing to the strong livelihood dependence of more than half the country's population. Despite consistent efforts to develop the irrigation network for increased agricultural production, approximately 60% of India's cropped area still remains rain fed, thereby functional to the strength of the Indian summer monsoon (ISM). The probability of a weak monsoon is strongly

correlated with the occurrence of droughts during the ISM season. The possible influence of atmospheric drivers in initiating these droughts is observed through the dynamics of low-level jets (LLJ) over the Northern Arabian Sea, forming the core of LLJ during the ISM. Interestingly, since the past 72 years, from 1951 to 2022, the core of LLJ has become dry (increased saturation deficit by 17%) and weak (reduced wind speed by 5%). Further, the wind speed (saturation deficit) at the core shares close dependence (75 % to 80 %) with the initiation of dry (wet) extremes, exhibiting maximum correlation at a 2-day lag. Furthermore, I observed a 50 % (40 %) increase in the dry (wet) extremes driven by the lower-atmospheric dynamics of the LLJ core. Consequently, these dry (wet) extremes are characterized by a 6% (12 %) enhancement in duration (intensity). Such conditions act as strong precursors for monsoon drought.

सार

सूखा एक जटिल प्राकृतिक संकट है, जो विभिन्न जलवायु क्षेत्रों में लंबे समय तक होता रहता है। सूखे की शुरुआत वर्षा में दीर्घकालिक कमी की घटना से होती है, जिसे मौसम संबंधी सूखा भी कहा जाता है। इस वायुमंडलीय कमी के स्थानिक-कालिक तीव्रता से हाइड्रोलॉजिकल चक्र के अन्य घटकों में वृद्धि होती है, जिससे मानव युग पर खतरे के प्रभाव का प्रसार होता है। इस प्रकार, शमन रणनीतियों के प्रभावी कार्यान्वयन के लिए सूखे की शुरुआत का यथार्थवादी मूल्यांकन अपरिहार्य है। इस प्रकार, हमारे शोध का ध्यान मुख्य रूप से मौसम संबंधी सूखे की गतिशीलता पर है, जिसे आमतौर पर निष्पक्ष सूचकांकों के माध्यम से मापा जाता है, जो ऐतिहासिक जलवायु चर में महीने-वार परिमाण भिन्नताओं पर विचार करते हैं, जबकि उनके अंतर-मासिक वितरण को पूरी तरह से अनदेखा करते हैं। हालांकि, बदलती जलवायु के वर्तमान परिदृश्य के तहत ऐसे सूचकांकों की प्रयोज्यता, जहां तीव्र लघु वर्षा कथित तौर पर बढ़ रही है, संदिग्ध है। वर्षा अवधि में इस तरह के बदलाव अंततः लंबे समय तक अंतर-मासिक शुष्क अवधि की ओर ले जा सकते हैं, जो बदले में कई कृषि और सामाजिक-आर्थिक जोखिम पैदा करेंगे। बदले हुए परिदृश्य पर वास्तविक रूप से नजर रखने के लिए, हम एक नया सूखा सूचकांक - स्टैंडर्डाइज़्ड नेट प्रेसिपिटेशन डिस्ट्रीब्यूशन इंडेक्स (SNEPI) प्रस्तावित करते हैं, जिसमें दैनिक शुद्ध-वर्षा चर की वितरण विशेषताओं को शामिल किया जाता है। भारत के छह अलग-अलग जलवायु वाले स्थानों पर 1-, 3-, 6- और 12 महीने के समय के पैमाने पर कृत्रिम रूप से उत्पन्न और देखी गई वर्षा श्रृंखला का उपयोग करके SNEPI की प्रयोज्यता का गंभीर रूप से मूल्यांकन किया गया है। SNEPI की उपयोगिता लंबे समय के पैमाने के लिए अधिक गहन है, जो कि लंबी अवधि में वर्षा के वितरण पर दिए गए बढ़े हुए जोर के कारण समझ में आता है। स्टैंडर्डाइज़्ड नेट

प्रेसिपिटेशन डिस्ट्रीब्यूशन इंडेक्स पारंपरिक स्टैंडर्डाइज़्ड प्रेसिपिटेशन इवॉपोटरांसपिरेशन इंडेक्स (SPEI) की तुलना में गीले (शुष्क) क्षेत्रों में बढ़ती सूखापन (नमी) के वर्तमान परिदृश्य को पकड़ने में कुशल साबित होता है। इसलिए, प्रस्तावित सूचकांक, जो बदलती वर्षा विशेषताओं को शामिल करता है, बदलती जलवायु के परिदृश्य के तहत मौसम संबंधी सूखे की बेहतर मात्रा निर्धारण और निगरानी में सहायता कर सकता है।

मौसम संबंधी सूखा संकेतकों के बीच बढ़ती हुई भिन्नता/असहमति, मुख्य रूप से बदलती जलवायु परिस्थितियों के कारण, सूखे की घटनाओं की निगरानी और मॉडलिंग में उनकी प्रासंगिकता पर सवाल उठाती है। वर्तमान शोध में, हमने स्टैंडर्डाइज़्ड प्रेसिपिटेशन इंडेक्स (SPI), SPEI और नव विकसित SNEPI जैसे व्यापक रूप से उपयोग किए जाने वाले सूखा सूचकांकों के बीच भिन्नता को मापने का प्रयास किया और इस भिन्नता/असहमति के विकास का पता लगाया। एसपीईआई और एसएनईपीआई के साथ एसपीईआई के वार्षिक विचलन में बढ़ी हुई शुष्क चरम सीमाओं की लगातार उपस्थिति देखी गई, जो बदलती जलवायु विशेषताओं को पकड़ने में पारंपरिक सूखा सूचकांक की उपयोगिता के बारे में संदेह पैदा करती है। इस वार्षिक विचलन के मौसमी फैलाव ने एसएनईपीआई द्वारा मानसून के मौसम में सूखे का एक मजबूत, स्थानिक रूप से प्रमुख संकेत प्रकट किया, जिसे एसपीईआई उजागर करने में विफल रहा। इसके अलावा, आरोपण विश्लेषण से पता चला कि एसपीआई-एसपीईआई असहमति शॉर्टवेव रेडिएटिव फ्लक्स के प्रभाव में विकसित हुई। इसके अलावा, एसपीईआई और एसएनईपीआई के बीच विचलन, गीले दौर की विशेषताओं से प्रेरित है, जिसमें मानसून के मौसम और उष्णकटिबंधीय जलवायु क्षेत्रों में संबंध मजबूत होते हैं।

जबकि मौसम संबंधी सूखे की घटनाओं को बढ़ाने में वर्षा परिवर्तनशीलता की महत्वपूर्ण भूमिका का पता लगाया जा चुका है, वैश्विक सूखे की गतिशीलता में इसके योगदान का परिमाणीकरण अभी भी अज्ञात है। वैश्विक मौसम संबंधी सूखे की विकासात्मक विशेषताओं से पता चलता है कि 1951 और 2016 के बीच, वर्षा की कमी, वाष्पीकरण से होने वाले नुकसान और वर्षा परिवर्तनशीलता जैसे जलवायु चर में बदलाव के कारण वैश्विक सूखे की आवृत्ति चौगुनी हो गई। हमारे शोध ने इन कारकों का व्यापक रूप से आकलन करते हुए, अधिशेष वर्षा वाले वर्षों में भी सूखे की संभावना में 60% की वृद्धि का खुलासा किया। यह वृद्धि वर्षा परिवर्तनशीलता के कारण है, जो विशेष रूप से उष्णकटिबंधीय/उपोष्णकटिबंधीय क्षेत्रों में स्पष्ट है। वर्षा-परिवर्तनशीलता-आधारित उष्णकटिबंधीय सूखे में 40% की वृद्धि की भी पहचान की गई, जो कि तीव्र सूखा सूचकांक मूल्यों में -1 से नीचे गिरने से चिह्नित है। दिलचस्प बात यह है कि ये घटनाएँ वर्षा अवधि वितरण में वृद्धि हुई विषमता को दर्शाती हैं, जो वर्षा-परिवर्तनशीलता-प्रेरित सूखे के प्रभुत्व की व्याख्या करती है। यह जलवायु व्यवहार उष्णकटिबंधीय क्षेत्र में मानसून क्षेत्रों से लेकर शुष्क रेगिस्तानों तक विविध जलवायु वर्गीकरणों को महत्वपूर्ण रूप से प्रभावित करता है। वर्षा की परिवर्तनशीलता की छाप उष्णकटिबंधीय सूखे की गतिशीलता में एक निर्णायक कारक के रूप में उभरती है।

जबकि हमने मौसम संबंधी सूखे की गतिशीलता में वर्षा की बदलती विशेषताओं के नए-नए योगदान को उजागर किया है, निचले वायुमंडलीय गतिशीलता के परिप्रेक्ष्य से मौसम संबंधी सूखा कैसे विकसित होता है, यह प्रश्न अभी भी अनुत्तरित है। चूंकि निचले वायुमंडलीय गतिशीलता और मौसम के पैटर्न पर इसके अंतर्निहित प्रभाव के बीच संबंध एक क्षेत्र के भौगोलिक निर्देशांक के प्रति संवेदनशीलता साझा करते हैं, इसलिए डेटा की उपलब्धता में आसानी और क्षेत्र के जलवायु विज्ञान से परिचित होने के कारण, हम एक भारतीय उप-क्षेत्र पर अपनी जांच करते हैं। देश की आधी से अधिक आबादी की आजीविका पर मजबूत निर्भरता के कारण कृषि क्षेत्र भारत की सामाजिक-अर्थव्यवस्था की रीढ़ है। कृषि उत्पादन में वृद्धि के लिए सिंचाई नेटवर्क विकसित करने के लगातार प्रयासों के बावजूद, भारत का लगभग 60% फसल क्षेत्र अभी भी वर्षा पर निर्भर है इन सूखे की शुरुआत में वायुमंडलीय चालकों के संभावित

प्रभाव को उत्तरी अरब सागर के ऊपर निम्न-स्तरीय जेट (एलएलजे) की गतिशीलता के माध्यम से देखा जाता है, जो आईएसएम के दौरान एलएलजे का कोर बनाता है। दिलचस्प बात यह है कि पिछले 72 वर्षों से, 1951 से 2022 तक, एलएलजे का कोर शुष्क (17%) की संतृप्ति कमी में वृद्धि और कमजोर (5%) की हवा की गति में कमी) हो गया है। इसके अलावा, कोर पर हवा की गति (संतृप्ति कमी) शुष्क (गीले) चरम सीमाओं की शुरुआत के साथ निकट निर्भरता (75% से 80%) साझा करती है, जो 2-दिवसीय अंतराल पर अधिकतम सहसंबंध प्रदर्शित करती है। इसके अलावा, हमने एलएलजे कोर की निम्न-वायुमंडलीय गतिशीलता द्वारा संचालित शुष्क (गीले) चरम सीमाओं में 50% (40%) की वृद्धि देखी। ऐसी स्थितियाँ मानसूनी सूखे के लिए प्रबल पूर्वसूचक के रूप में कार्य करती हैं।

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ABBREVIATIONS

PDSI	Palmer Drought Severity Index
SPI	Standardized Precipitation Index
SPEI	Standardized Precipitation Evapotranspiration Index
RDI	Reconnaissance Drought Index
PET	Potential evapotranspiration
CMI	Crop Moisture Index
PMAI	Palmer Moisture Anomaly Index
SMAI	Soil Moisture Anomaly Index
TWDI	Total Water Deficit Index
PHDI	Palmer Hydrological Drought Severity Index
SWSI	Surface Water Supply Index
SRI	Standardized Runoff Index
IPCC	Intergovernmental Panel on Climate Change
ISM	Indian summer monsoon
LLJ	Low level jets
CMIP6	Coupled Model Intercomparison Project 6
SSP	Shared Socioeconomic Pathways
IMD	India Meteorological Department
GLEAM	Global Land Evaporation Amsterdam Model
PDF	Probability Distribution Function
CDF	Cumulative Distribution Function
SNEPI	Standardized Net-Precipitation Distribution Index
PM	Penman-Monteith
LL	Log Logistic
GEV	Generalized Extreme Value
LN	Lognormal
P3	Pearson Type III
AET	Actual Evapotranspiration
RMSE	Root Mean Square Error
SPDI	Standardized Precipitation Distribution Index
PCA	Principal Component Analysis

DI	Divergence Index
MEEMD	Multidimensional Ensemble Empirical Mode Decomposition
IMF	Intrinsic Mode Function
DDI	Differential Divergence Index
SAAM	Spatially Averaged Annual Maximum
TID	Traditionally identified driver
RID	Recently identified drivers
BS	Binary Segmentation
CUSUM	Cumulative Sum
DR	Dominance Ratio
FR	Frequency Ratio
GDP	Gross Domestic Product
SST	Sea Surface Temperature
SD	Saturation Deficit

LIST OF SYMBOLS AND UNITS

P	precipitation	mm
PET	potential evapotranspiration	mm
D	net precipitation	mm
Δ	slope of saturated vapour pressure and air temperature	PaK^{-1}
γ	psychometric constant	PaK^{-1}
R_{net}	net radiation	Wm^{-2}
W_s	wind speed at 2 m height	ms^{-1}
VPD	vapour pressure deficit	Pa
Li	excess/deficit period duration	days
R_{LW}	downward longwave radiation	Wm^{-2}
R_{SW}	downward shortwave radiation	Wm^{-2}
T_{air}	air temperature	$^{\circ}\text{C}$
RH	relative humidity	%
q^*	saturated specific humidity	g/kg
q	specific humidity	g/kg
W_H	horizontal wind speed	ms^{-1}
W_V	vertical wind speed	ms^{-1}
SD	saturation deficit	g/kg