Regional Meteorological Drought Characterization using Standard Drought Indices under Observed and Changing Climate Scenarios over Uttar Pradesh, India

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By

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CHAPTER 9

Conclusion

9.1 Overview

Climate change causes a detrimental impact on the hydrological cycle resulting in frequent occurrences of flood and drought events which pose a severe threat to the availability of water resources. Changes in the pattern and magnitude of climatic extremes are indicators of climate change. Changes in magnitude and pattern of temperature and rainfall are responsible for changes in extreme hydrologic events like droughts due to climate change. This study provides a framework for assessing meteorological drought under observed and changing climate scenarios. The present study evaluated the applicability of globally used drought indices SPI and SPEI at different timescales across the study region for the historical period (1971 to 2018). The drought characteristics are estimated and evaluated based on the severity, duration, and frequency of occurrences at different severity (moderate, severe, and extreme). Drought characteristics are calculated by applying the run theory approach at the threshold of SPI/SPEI≤-1. The patterns of drought intensity, duration, frequency of occurrence, and trend are assessed through various statistical assessments and portrayed through various spatial maps. Station proportion has been used to evaluate the temporal variability of the spatial extent of drought occurrence of different severity (moderate, severe, and extreme).

The drought characteristics estimated using SPI and SPEI were evaluated and compared at different timescales over the observed period. The present evaluation used widely acknowledged scientific methodology to assess the situation and intended to

advance our knowledge of meteorological drought jeopardy over Uttar Pradesh, India. The jeopardy increased when climate extremes (dry and wet events) occurred in rapid succession over the study region, as compared to individual climatic extremes. The characteristics of climatic extremes (dry and wet events) are estimated and evaluated based on severity, duration, and intensity, calculated using SPEI at a 1-month timescale. The successive occurrence of climate extremes (dry and wet events) and their rapid transition over the study region amplify the jeopardy with respect to the occurrence caused by single climatic extremes over the study region. The characteristics of climatic extremes (dry and wet events) are estimated and evaluated based on severity, duration, and intensity, calculated using SPEI at a 1-month timescale. The dry and wet event characteristics and the transition time between the climatic extremes were estimated through various statistical methodologies and portrayed temporally and spatially over Uttar Pradesh (India) for the observed period from 1971 to 2018. The statistical downscaling model (SDSM) tool used to downscale the temperature and precipitation to estimate meteorological drought for the future period under changing climate scenarios RCP 4.5 and RCP 8.5. Observed daily maximum temperature (Tmax), lowest temperature (Tmin), and rainfall data for 18 synoptic stations in Uttar Pradesh, India, from 1971 to 2005 were used in the statistical downscaling method. The NCEP reanalysis data considers 26 atmospheric variables on a daily timescale for the same period. CanESM2 data from RCP 4.5 and RCP 8.5 scenarios are used to create future scenario climate variables. The projected rainfall and temperature under RCP 4.5 and RCP 8.5 are used as input variables for estimating the SPEI at various timescales from 2019 to 2050. Climate change impacts on the severity, duration, and frequency of

drought events were evaluated and compared in the study region using RCP 4.5 and RCP 8.5.

9.1.1 Changes in precipitation and temperature

Climate change is affecting the pattern of precipitation and temperature across Uttar Pradesh, India. Therefore, to assess the variability in the meteorological variable at temporal scale, nonparametric trend assessment methods are employed over the meteorological variable that controls drought occurrence over the study region. The nonparametric Mann-Kendall test was applied over the rainfall time series for (i) pre-monsoon (ii) monsoon (iii) post-monsoon (iv) winter, (v) annual rainfall, and (v) mean temperature time series of 48 years from 1971 to 2018 to determine the monotonic trend over the 18 synoptic stations of Uttar Pradesh, India. Sen's slope test was applied to detect the magnitude of the trend in meteorological time series data.

The following specific conclusions were drawn from this study:

- The annual precipitation time series trend assessment indicated a significant negative trend at a significance level of 0.05. Z_{MK} values over the annual precipitation time series range from -3.24 to 2.66 and a significant declining trend was observed over the 14 stations, whereas Bareilly, Basti, and Lucknow stations exhibit a non-significant decreasing trend.
- The magnitude of the annual precipitation trend was estimated using Sen's slope result varies from -8.24 $mmyr^{-1}$ to 7.11 $mmyr^{-1}$. The study area experienced decreasing magnitude of annual rainfall trend over all the stations except for station Saharanpur. The synoptic location Jhansi, Kanpur, Chitrakoot, and Allahabad (Prayagraj) recorded a higher negative slope of the annual precipitation trend.

- During the monsoon season, the study area recorded a significant decreasing trend in monsoon rainfall except at station Saharanpur. The study region recorded a higher negative slope of monsoon rainfall trend over the southern and western parts of the study regions.
- The trend assessment of precipitation depicts the decreasing rainfall trend in all seasons except during the pre-monsoon season.
- The trend assessment of monthly temperature indicates a significant rising trend for 61% of the stations in the studied regions. Gonda, Faizabad, Gorakhpur, and Lucknow exhibit significantly declining monthly temperatures.

Reduced precipitation coupled with an increase in temperature results in less water storage and greater water stress, escalating the severity of extreme climatic situations like drought and making life in the state challenging.

9.1.2 Spatiotemporal meteorological drought characteristics assessment

The present research work provides a detailed assessment of drought characteristics estimated based on the standard drought indices SPI and SPEI at the scale of 3-month, 6-month, 9-month, and 12-months from 1971 to 2018 across Uttar Pradesh (India). The SPI has the drawback of including only the average precipitation and neglecting the effect of temperature over drought characteristics. Moreover, the SPEI has several disadvantages, such as the Thornthwaite equation used in calculating PET, which only considers average temperature, and heat waves might be misinterpreted for meteorological dryness. In this study, drought characteristics (Intensity, duration, and frequency) were calculated through various statistical methodologies and portrayed through a spatial distribution map to understand the drought vulnerability over Uttar Pradesh. In this study, drought characteristics

(Intensity, duration, and frequency) were calculated through various statistical methodologies and portrayed through a spatial distribution map to understand the drought vulnerability over Uttar Pradesh.

The following specific conclusions were drawn from this study:

- The SPEI and SPI time series depicts a similar pattern temporal evaluation of drought characteristics with multiple timescales but with different magnitudes of drought characteristics. In addition, SPEI-based drought characteristics occur with higher magnitude.
- Decadal variability of meteorological drought events assessed using SPEI and SPI at various accumulation periods of the climate variable for five decades. The decadal shift in the occurrences of drought events of different categories highlights the largest number of drought occurrences reported during the 1970s, followed by the 2000s. The decadal review of drought occurrence shows that SPEI indices account for a higher number of moderate and severe droughts throughout the 1970s, and both indices show a considerable increase in drought events after the 2000s.
- Spatiotemporal trend assessment of drought severity time series for both indices indicate that nearly 85% percent of the synoptic locations of the state experienced a negative trend at a significance level of ($p>0.05$), which implies an increase in the severity of drought events. In addition, a higher magnitude of negative trend is associated with the SPEI time series. Decreasing trends occupied the central and western parts of the state for SPEI, whereas for SPI time series, decreasing trend occupied the eastern part of the state. The difference in spatial pattern for both time series identified may occur due to the spatially heterogeneous climate across Uttar Pradesh. At a shorter timescale of SPI, all the stations tend towards the drying

conditions, whereas with the increase in timescale, Bareilly and Moradabad experience an increase in wetness conditions over the year. Interestingly, the drying condition spread over the region with the SPI time series compared to the SPEI time series, with stations Aligarh, Saharanpur, and Meerut showing drying conditions with SPI but not with SPEI.

- The study area records average drought duration of 3, 6, 9, and 12-month for SPEI is 2.30, 3.50, 4.60, and 7.90 months & SPI is 2.20, 3.07, 4.09, and 7.02 months. The spatial distribution drought duration indicates that the eastern and northernmost part of the study area record drought event of relatively shorter duration for the SPEI time series, whereas SPI time series records the higher duration of drought over Prayagraj, Gorakhpur, Basti, and Azamgarh in the eastern region of Uttar Pradesh.
- The spatial map indicate that all studied stations experience nearly the same intensity of drought events over the study area at a shorter scale. It's worth noting that the area with high drought intensity hasn't extended with the increase in timescale, implying that this region was primarily affected by short-term drought.
- A comparison of the spatial distribution of drought frequency based on three severity classes (moderate, severe, and extreme) shows that the moderate class has a much greater prevalence over the region. SPEI time series records the higher frequency of drought of ‘moderate’ and ‘severe’ severity, whereas SPI accounts for the greater frequency of extreme severity of drought events. The station proportion investigates the year-wise spatial extent of the drought of different severity class. It provides insight into the percentage of the area hit by the drought of a particular severity. For SPI and SPEI, a greater areal extent is affected by the moderate severity of drought over the state. Due to the difference in the magnitude of SPI and

SPEI time variability in the spatial extent of drought event of particular severity observed across the region. In conclusion, the study area's susceptibility is anticipated to rise in the near future as it encounters drought events of more frequently of short duration and moderate severity.

- Due to differences in the climatic condition across the study area, differences in the drought characteristics were estimated from SPI and SPEI, where SPI only considers the precipitation deficit as an input variable for the drought estimation, which can lead to the inaccurate estimation of drought characteristics for arid and semi-arid regions. This evaluation's result depicts that the SPEI index records the effect of temperature on the severity of the drought characteristics. This observation inferences that the study area is at risk of erratic meteorological drought conditions, where the Bundelkhand region and Vindhyan region of the study area are worse affected in comparison with the eastern part and northernmost part of Uttar Pradesh (India).

9.1.3 Spatiotemporal assessment of concurrent occurrence of dry-wet event

The present work provides a detailed evaluation of the concurrent occurrence of dry-wet event characteristics and their transition time estimated based on SPEI at a monthly scale from 1971 to 2018 across 18 synoptic locations over Uttar Pradesh (India). The dry and wet event characteristics are calculated using the SPEI which assess the influence of temperature on the estimation of dry and wet characteristics. This study uses SPEI at longer timescales to measure meteorological drought, but its averaging effect makes it inefficient for estimating flood conditions. SPEI at a 1-month timescale is used to detect and classify wet and dry occurrences with varying degrees of severity (moderate, severe, and extreme). Dry and wet event characteristics such as

the number of dry and wet events, severity, duration, and intensity are estimated using run theory over SPEI output. This study evaluated wet and dry transition characteristics using the wet-dry ratio (WD), average transition time (T_t), and rapid transition time assessment methodologies to understand the interplay of wet and dry extremes at the location. Repeated concurrent dry and wet events have served as indicators of growing vulnerability and the insufficiency of occasional mitigation attempts.

The following specific conclusions were drawn from this study:

- The result of temporal variation of dry and wet event outline that the research area is the hotspot of the frequent occurrence of dry and wet event of moderate category. Extreme dry and wet events infrequently occurred over the study period. The number of dry events in the research area was 4.5% higher than the number of wet events.
- The results of the evaluation of the characteristics of dry-wet events spatiotemporally indicate that the semi-arid climate-dominated region and the Central Plain of the study area had more severe, prolonged, and intense dry events. On average, dry episodes lasted slightly longer than a month which is indicative of flash drought conditions over the studied region.
- The eastern region of the study area, characterized by humid to sub-humid climates, experienced a substantially high number of dry events throughout the study period. The western and Bundelkhand regions experience more intense dry events, whereas the eastern region is characterized by intense wet events.
- The WD ratio outcome indicate the prevalence of a higher frequency of dry and wet events of moderate to severe category throughout the study region. Except for a few synoptic locations, the study area is subject to a higher frequency of extreme

wet events. Moderate to severe dry events were more prevalent than wet events across 77% of the research region. The northeastern and eastern plains of the study area had the highest positive WD ratio values for extreme wet events indicating a higher sensitivity to their occurrence.

- The average transition time from dry-to-wet or wet-to-dry type varied spatially for different severity "moderate," "severe," and "extreme." Overall, a greater percentage of synoptic locations require less time to transition from wet-to-dry events than from dry-to-wet events. The region under study experienced rapid transitions between wet and dry events.
- The rapid transition time over the study area ranges from the dry-to-wet event from 2.50 to 4.10 months, and the wet-to-dry event from 2.05 to 5.25 months. This rapid transition time result highlights that 11 synoptic locations have a lengthier dry-to-wet transition time compared to the wet-to-dry event across the study region.

9.1.4 Drought characteristics under changing climate scenarios

This study aims to assess drought characteristics in Uttar Pradesh over the historical and future periods according to RCP 4.5 and RCP 8.5 scenarios under the context of changing climate. Drought characteristics assessed by globally used drought index SPEI at the timescale of 3, 6, 9, and 12-month under projected climate scenario scenarios RCP 4.5 and RCP 8.5 for the future period 2019 to 2050. Drought characteristics, including severity, duration, and frequency, evaluated using statistical analysis illustrated by multiple spatial maps and tables.

The following specific conclusion is drawn from this study:

- The SDSM tool is used to estimate the projection of daily rainfall, maximum and minimum temperatures under RCP 4.5 and RCP 8.5 from 2019 to 2050 across 18

synoptic locations in Uttar Pradesh, India. It should also be noted that SDSM performs more accurately when modeling daily maximum and minimum temperatures than when modeling daily rainfall.

- The projected change in the climatic variable shows that temperature will rise with spatial variation. Precipitation will gradually increase in the near future, with significant variations in the magnitude of precipitation change. 66% of synoptic locations will experience less than a 10% precipitation increase over the study area. The study area will be vulnerable to dry and wet events as temperatures and precipitation will increase in the future. In the RCP 4.5 emission scenario, the increase in temperature and precipitation is more intense compared to the RCP 8.5 scenario for 2019 to 2050 over Uttar Pradesh, India.
- The spatial distribution map illustrates that the frequent occurrence of drought as short-term drought events majorly impacts the study region. The study region will likely experience more frequent drought occurrences from 2019 to 2050 under the RCP 4.5 scenario than under RCP 8.5 scenario.
- A drought event with maximum severity with a prolonged duration of drought events is associated with RCP 8.5. However, the drying tendency is more pronounced and has a broader spread region under the RCP 4.5 scenario than in the RCP 8.5 scenario.
- Drought severity shows a mixed pattern in both scenarios, with some areas experiencing more severe drought than others and others experiencing less severe drought events. There was a significant variation in drought severity spatially and temporally along with the SPEI timescale. The spatial distribution and magnitude of average duration changes were observed at the different timescales of SPEI under

the RCP 4.5 and RCP 8.5 scenarios. The study region will likely experience the most severe drought over a shorter timescale SPEI-3 and SPEI-6 under the RCP 4.5 scenario, while the most severe drought event will likely occur over a longer timescale SPEI-9 and SPEI-12 under the RCP 8.5 scenario.

- The spatial distribution map for the SPEI output under the RCP 4.5 and RCP 8.5 scenario shows that most of the study region is at high risk for experiencing a drought episode of relatively short duration. At the short timescale (SPEI-3, SPEI-6), the average duration ranges from 1.8 to 3 months, whereas at the longer timescale (SPEI-9, SPEI-12), the drought duration ranges from 3.5 to 7 months. Under the RCP 8.5 scenario, the research area will experience longer-duration meteorological drought events.

These findings suggested that climate change would significantly impact drought characteristics. Drought was an estimated widely accepted drought index SPEI, which reportedly accounts for the effect of global warming on the severity of drought. So, SPEI can be used to detect, monitor, and compare the drought to monitor at multiple timescales to update the understanding of drought jeopardy over Uttar Pradesh, India. The projected change in drought characteristics in the study area are expected to change in the near future, resulting in more frequent occurrences of moderate to severe droughts with shorter durations. Additionally, there will be a notable shift in the spatial pattern of drought occurrence. It is therefore crucial to handle future drought episodes caused by climate change with great care, based on this analysis

9.2 Major Contribution of the Thesis

- The primary goal of this study is to quantify drought characteristics by using two widely used indices and evaluating their applicability over the study area, as climatology significantly varies spatially over Uttar Pradesh, India. Due to the extensive process studies conducted at the district level, its primary scientific implication is increased process understanding.
- This study demonstrates how the incorporation of temperature in the calculation of drought indices impacts drought characteristics. This will encourage researchers to focus more on providing accurate drought depictions.
- This research demonstrated the methodology for evaluating the occurrence of successive climatic extremes (dry and wet events) in the same region. The concurrent occurrence of climate extremes and their interplay are evaluated spatially and temporally. This improves our understanding of the scarcity and excess of regional water resources. This research examines the transition times between climate extremes since such rapid succession challenges emergency planning, event management, and long-term risk reduction and is especially problematic for agriculture.
- This study provides a comprehensive analysis of the variability in trends of different meteorological variables over observed period. It also investigates the projected changes in precipitation and temperature due to climate change using SDSM, as these variables are crucial in determining the likelihood of drought. The study examines the spatial and temporal characteristics of drought under observed and changing climate scenarios (RCP 4.5 and RCP 8.5) across the Uttar Pradesh of India.

The study research findings are essential information for agriculture management, managers of water resources, and decision-makers as they update current policies and develop new plans for reducing the effects of extreme stream flow events brought on by climate change.

9.3 Recommendation of Future Work

The research findings and study conclusions provided an understanding of the characteristics of drought in the context of an observed and changing climate.

The following are a few scopes that have been identified for further study:

- SPI and SPEI were calculated in this study under the assumption of stationarity of the input meteorological variable. In the context of climate change, precipitation and temperature may vary in a nonstationary way. As a result, it was proposed in this work to establish non-stationary drought indices for estimating drought characteristics in a changing climate.
- This assessed the drought characteristics based using SPI and SPEI. Evaluation of temporal variability of SPI and SPEI over time indicate alternate dying and wet event over the considered period. Therefore, it is suggested to collectively evaluate the variation of dry-to-wet events and the transition of dry-to-wet events and wet-to-dry events during the study period.
- The examination of wet and dry features computed based on SPEI = ≤-1 shows that the research area is vulnerable to flash drought because of the frequent occurrence of dry events of a shorter duration. The changes in soil moisture must be taken into consideration to provide an accurate assessment of flash drought. Due to its abrupt

onset, soil moisture flash drought can inflict severe damage on agricultural production, ecological systems, and economic activity.

- The current analysis concludes that the studied area predominantly experienced a moderate drought of short duration. The next step in this effort is to analyze the influence of frequent short-term drought occurrences on specific crop yields.
- The current work SPEI used for assessing drought features, which uses the Thornthwaite equation used in computing PET, which only considers average temperature as input climatic variable. So, heat waves could be interpreted as meteorological drought.
- The fundamental assumption of the statistical downscaling model is stationary for future climates. A region's current land use is considered stationary under future conditions in a hydrological model. Various approaches can be used to solve these difficulties, including more GCM data, a different statistical downscaling strategy, an SDSM with more GCMs and better resolution gridded data, RCMs, and other regression techniques.