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Recent Multidecadal Strengthening of the Wet Season Drought in Low-Latitude Highlands of China

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Abstract

The low-latitude highlands (LLH) of China are subject to highly variable and complex climatic conditions, shaped by the combined influences of monsoonal systems and mid- to high-latitude forcing. These climatic complexities pose persistent challenges to local agricultural sustainability and ecological security, underscoring the need for in-depth investigations into drought dynamics in this region. To address this gap, a sliding-window trend analysis was employed to examine long-term drought trends, using the Standardised Precipitation Evapotranspiration Index (SPEI) derived from temperature and precipitation datasets spanning 1901-2020. Results demonstrate a consistent escalation in drought severity across all four seasons in China's LLH, with summer and autumn exhibiting more pronounced drying tendencies—autumn shows the strongest up-ward trend in drought intensity. Running trend analysis further confirms a marked intensification of drought conditions in the region since the 1990s. Spatially, drought has intensified in most parts of the LLH during summer and autumn, driven by the combined effects of reduced precipitation and simultaneous warming; conversely, the northeastern LLH has seen a mitigation in drying, mainly attributed to increased precipitation. A statistically significant warming trend in summer and autumn since the 1990s has also been observed in the LLH.

Keywords

Low-Latitude Highlands, Drought, Trend, Running Trend, Precipitation, Temperature

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report on Climate Change noted that surface temperatures in China have risen by 0.8˚C over the past century [1]. There were two main warming periods in the 20th century, with the most recent one occurring after the 1980s [2]. The continuous warming of the climate system will lead to more frequent and severe meteorological disasters in China in the future [3] [4]. Global climate change will increase the frequency and intensity of extreme meteorological disasters in China, among which drought-related losses account for more than half of total losses from meteorological disasters [5]. As a natural disaster with the longest time span and the widest distribution in China, drought is extremely harmful [6] [7]. It not only causes huge economic losses to people's daily lives but also leads to problems such as reduced or complete failure of grain crop yields, production shutdowns due to reduced industrial water use, and land desertification [8].

The drought index is usually constructed from meteorological, hydrological, soil, and satellite remote sensing data [9]. It is designed to monitor drought by integrating climatic variables, such as precipitation, evapotranspiration, and temperature [10]-[12]. It can represent the beginning and end of drought, as well as its duration, intensity, and spatial coverage [13]. Drought indices are usually classified into two categories based on the factors causing drought [14]. The first type of Index considers only a single influencing factor to characterize drought intensity, such as the Standardized Precipitation Index (SPI) [15] [16]. In 1993, McKee proposed the SPI index while studying the drought in Colorado, USA. This index assumes that precipitation follows a statistical distribution, thereby overcoming the theoretical defect that precipitation must follow a normal distribution in the calculation of precipitation anomaly percentage [15]. As the SPI index focuses solely on precipitation and neglects the influence of other factors, especially evapotranspiration driven by rising temperatures, the SPI drought index can only explain the mechanism of partial drought [17]. Therefore, a multi-factor drought index was proposed that accounts for two or more factors that cause droughts. For example, the Standardized Precipitation Evapotranspiration Index (SPEI) proposed by Vicente Serrano is now widely used internationally for monitoring and studying changes in drought [18]-[20]. The SPEI was constructed from the SPI index using the Thornthwaite method and accounting for potential evapotranspiration based on temperature [21] [22]. This index has a significantly better effect on drought monitoring than the SPI index [23]. Given the potential increase in evapotranspiration due to global warming, SPEI is more suitable than SPI for monitoring drought [24].

As an important base for agricultural and sideline products and grain production in our country, the low-latitude highlands (LLH) of China have a complex terrain, including the Qinghai-Xizang Plateau, the Yunnan-Guizhou Plateau, and the Hengduan Mountains [25] [26]. The low-latitude highlands of our country are influenced by the strong East Asian monsoon and by weather systems in the middle and high latitudes, and climate change is complex [27]-[29]. Winter and spring are the dry seasons on low-latitude highlands, while summer and autumn are the wet seasons, with wet season precipitation accounting for 80% - 90% of the annual precipitation [30]. Studies show that the reduction in water vapor supply and the rise in temperature are the key factors leading to drought [31]-[34]. The insufficient supply of water vapor leads to less precipitation, causing drought in the low-latitude highlands of our country [35]. In addition to the contribution of water vapor supply, the more intense and longer-lasting droughts observed in many regions are closely related to the increase in ground temperature. At above-average temperatures, air humidity is less likely to reach saturation, resulting in reduced precipitation. At the same time, higher temperatures increase surface evaporation, leading to drought [36]-[38]. Evidence suggests that extreme drought events in low-latitude plateau regions are closely linked to high temperatures, as seen in the 2009 autumn drought [39]. Against the backdrop of global warming, previous studies have found that drought on low-latitude highlands of China has intensified since 1982 [40]-[45]. The intensification of this drought trend may be due to rising temperatures. The calculation of trends depends on the selected time. Previous studies have mostly analyzed trends using data from after 1980. On the one hand, if the selected period is short, it may not reflect the changes in the drought trend [46]. On the other hand, if the sliding trend method is chosen to obtain a stable positive (negative) trend over a given period, the trend minimization calculation will be affected by the selected period [47]. Based on this, the paper will use drought data on a longer timescale to analyze the drought trend on low-latitude plateaus in China. Using the sliding trend analysis method, the stability of drought trends on low-latitude highlands and the effects of temperature and precipitation on drought were examined.

2. Materials and Methods

2.1. Materials

This paper uses the Standardized Precipitation Evapotranspiration Index (SPEI) developed by Vicente-Serrano *et al.* [18] [19]. to examine drought trends on LLH. This index can be used to monitor and evaluate drought characteristics lasting for 1 month or longer [48]. The data is sourced from the Spanish Drought Data Center, with a spatial resolution of $0.5^{\circ} \times 0.5^{\circ}$, and the selected data length is monthly from January 1901 to December 2020. The rainfall and surface temperature data are from the CRU dataset at the University of East Anglia, with a spatial resolution of $0.5^{\circ} \times 0.5^{\circ}$, and the selected data length is monthly from January 1901 to December 2020. Previous studies have evaluated the SPEI [49] and the CRU dataset [50] using observational data from meteorological stations in China. The results show that both datasets accurately reflect drought conditions, temperature changes, and precipitation trends in China [51]. After verification, these data are highly credible in China due to their high spatiotemporal resolution and reliability, providing a solid foundation for further climate research. The Digital Elevation Model (DEM) data are derived from 1:250,000 contour lines and 1 km high-precision elevation point data from the National Tibetan Plateau Data Center, including altitude, hill shade, slope, and aspect [52].

2.2. Methods

LLH in China refers to the area south of 30˚N in East Asia with an average altitude of over 1000 meters per 0.5˚ grid cell. According to the research by Wang Lin *et al.*, the study area is defined as 22˚N-28˚N and 97˚E-106˚E, covering the northwest of Guangxi, Yunnan, the south of Sichuan, and the west of Guizhou [53]. To construct the regional mask at 0.5˚ resolution, the original DEM was resampled to 0.5˚ grids using bilinear interpolation. Grid cells with an elevation of 1000 m or lower were excluded. Regional mean SPEI series were then calculated using area-weighted averaging, where the weight for each grid cell is the cosine of its latitude. **Figure 1** shows the regional scope of LLH. This article will focus on the trends in drought during the wet season (summer and autumn) in this region.

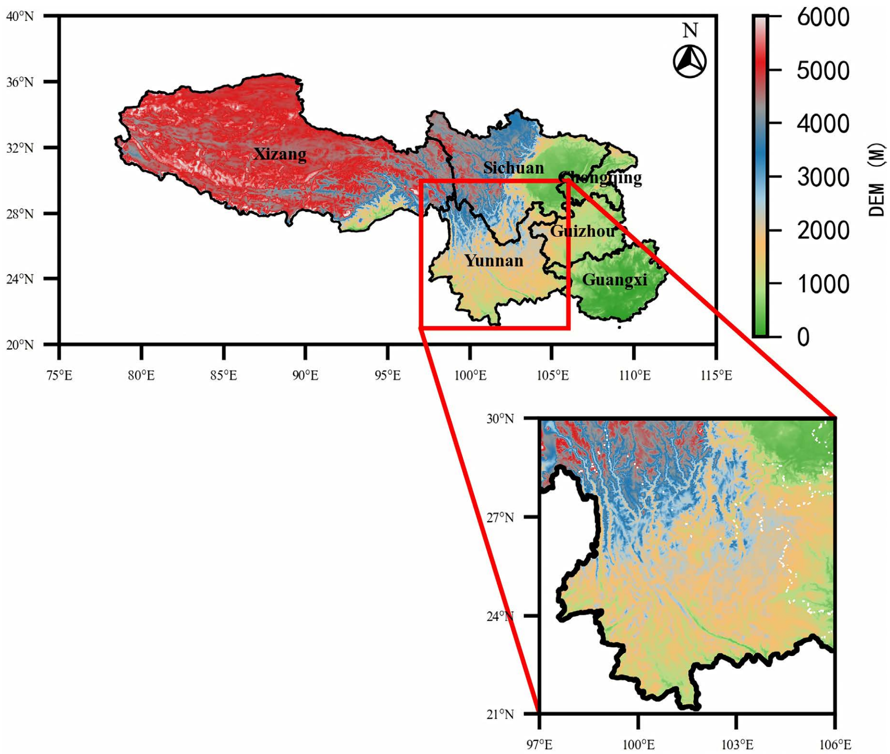

Figure 1. Topographic map of low-latitude highlands in China (unit: m).

To smooth interannual variability while preserving decadal signals, a 20-year moving window was used to calculate sliding trends. For each starting year i, data from year i to i + 19 were selected, and the linear trend was estimated using the least squares method. The window was shifted forward year by year, covering the period 1901-2020. Trend significance was assessed using the Mann-Kendall test [54]-[56], with Sen's slope estimator applied to determine trend magnitudes. Serial autocorrelation was examined using the autocorrelation function (ACF) prior to trend testing. Significance levels were evaluated at 90% ($p < 0.10$), 95% ($p < 0.05$), and 99% ($p < 0.01$). The reference period for SPEI calculation was the 1901-2020 climatological average.

3. Results

3.1. Changes in the SPEI of LLH

Figure 2 presents the SPEI time series for spring, summer, autumn, and winter in the LLH over the period 1901-2020. The results reveal considerable interannual variability across all four seasons, reflecting the complex fluctuations in dry-wet conditions in this region. To extract low-frequency variations within the SPEI time series, a nine-year low-pass filter was applied to each seasonal series. The filtered results show that summer SPEI exhibited a declining trend after 2000, while autumn SPEI began to decrease noticeably after the 1990s, indicating an accelerated drying process in these two seasons in recent decades.

A long-term trend analysis of SPEI for the four seasons reveals a consistent downward trend across all seasons, suggesting a sustained strengthening of drought conditions throughout the year in the LLH region. The drying trend is particularly pronounced in summer and autumn, with SPEI decreasing by 0.183 and 0.452 per 120 years, respectively, both of which are statistically significant at the 99% confidence level ($p < 0.01$). In contrast, spring and winter exhibit relatively smaller decreasing magnitudes and weaker trend significance. These findings indicate that the long-term drying trend is stronger in summer and autumn than in spring and winter. Comparing the long-term trends between summer and

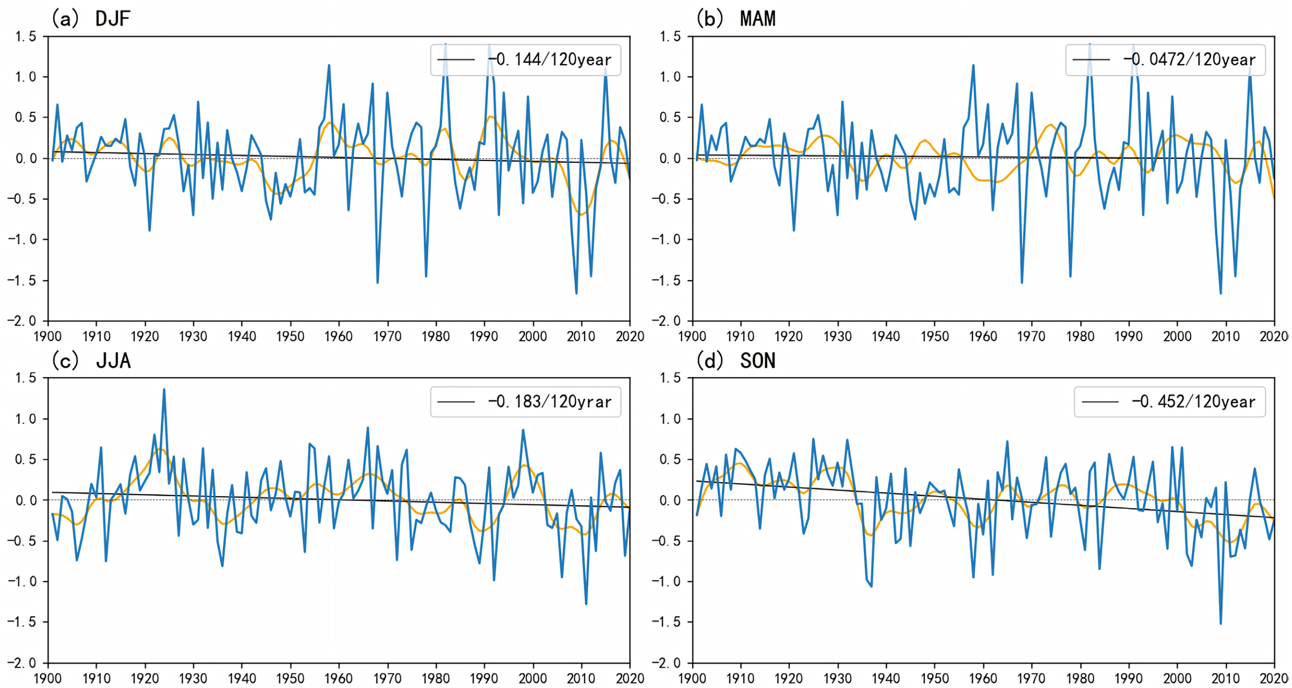

Figure 2. SPEI time series from 1901 to 2020: the blue line is the SPEI, the black line is the trend of SPEI, the orange line is the 9-year low-pass-filtered time series. DJF is winter, MAM is spring, JJA is summer, and SON is autumn.

autumn further shows that autumn SPEI exhibits a faster decline rate and greater magnitude, reflecting a more pronounced drought intensification. Overall, the drying trend in the LLH region is not only prominent in summer but is especially severe in autumn.

3.2. The Long-Term Trend of Drought in LLH

To examine the spatial variability of climatic trends over the past century, Figure 3 presents the spatial trend distribution of SPEI, precipitation, and near-surface temperature from 1901 to 2020. In summer, SPEI shows a weak upward trend only in the northeastern part of the LLH, while the central and northern parts show a weak downward trend, and the SPEI in the southern part shows a significant downward trend (Figure 3(a)). The overall spatial distribution in summer is characterized by localized wetting in the northeast and widespread drying in other regions, especially the south. An analysis of the summer precipitation trend reveals a spatial pattern similar to that of SPEI (Figure 3(d)). The overall temperature shows an upward trend, with a significant increase in temperature in the western part of the region (Figure 3(g)). Figure 3(b) shows that the LLH exhibits a significant drought trend in autumn, concentrated in the western part; overall precipitation shows a downward trend, and compared with the west, the east shows a more significant downward trend (Figure 3(e)). On the contrary, the

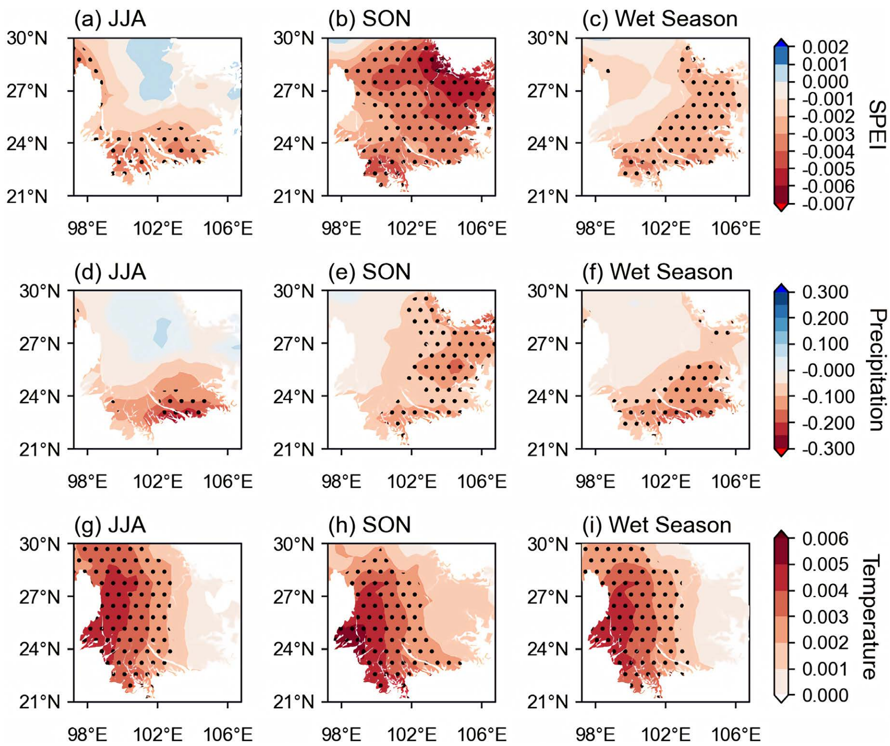

Figure 3. Long-term trends of SPEI over China low-latitude highlands from 1901 to 2020 summer, autumn, wet season ((a)-(c), unit: year^{-1}), Precipitation ((d)-(f), unit: mm/year^{-1}), Ground air temperature ((g)-(i), unit: ˚C/year^{-1}), black dots indicate that the linear trend passes the 90% significance MK test.

overall temperature shows an upward trend, and the westward trend is more significant than that in the east. Analysis of the distribution of autumn drought shows that decreases in precipitation and increases in temperature are conducive to drought formation (Figure 3(h)). The overall spatial distribution of drought in the LLH during the wet season is the same as in autumn, but the downward trend is weaker. Precipitation generally shows a downward trend, with a significant decline in the south. The spatial characteristics of temperature distribution are the same as those in summer and autumn. By comparing the distributions of drought trends in summer, autumn, and the wet season, precipitation in the northeastern LLH shows significant differences across seasons: an increasing trend in summer and decreasing trends in autumn and the wet season. Correspondingly, SPEI shows a humid trend in the northeast in summer, and a widespread dry trend in autumn and the wet season. This highlights that reduced precipitation has consistently contributed to drought in this region.

3.3. The Trend of Sliding Drought in LLH

To reduce dependence on the choice of time intervals, a 20-year sliding-window linear trend analysis was applied to the SPEI series for summer, autumn, and the wet season in the low-latitude highlands (LLH) over the period 1901-2020 (Figure 4). The results show that since 1990, summer SPEI exhibited a persistent downward trend, with particularly significant declines during 1994-1997. In contrast, autumn experienced an earlier onset of drying, entering an intensified drought phase as early as 1980, followed by a sustained significant negative trend from

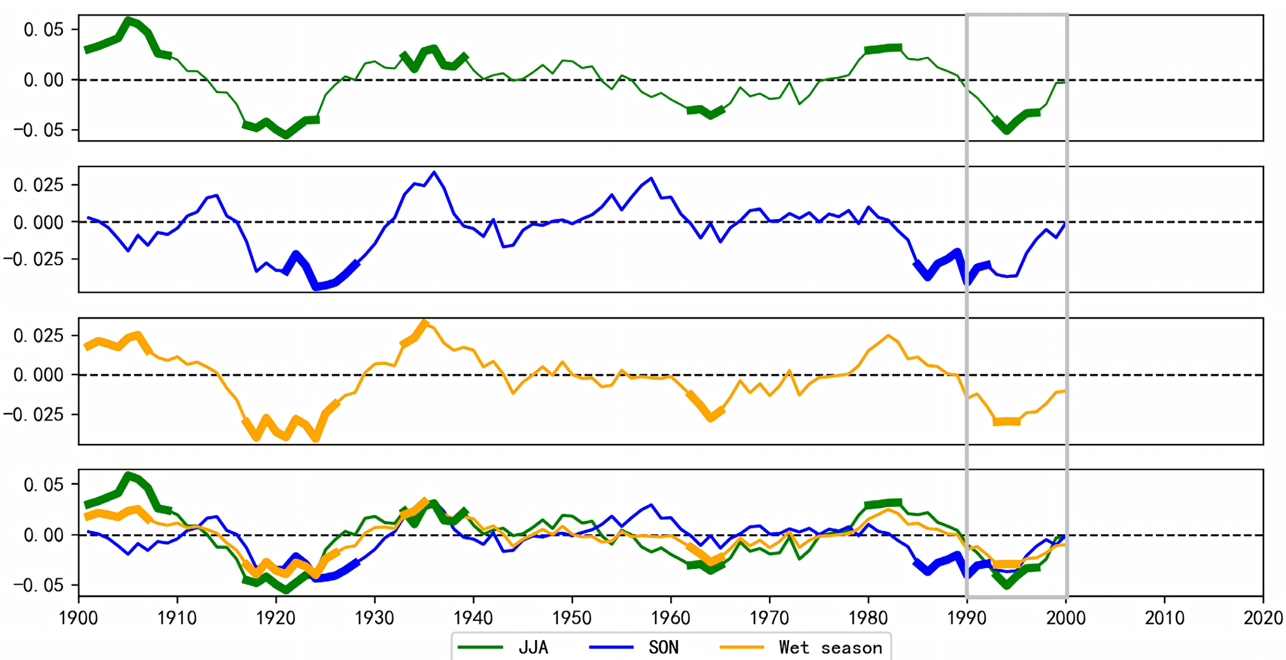

Figure 4. Based on the linear trend of the 20-year sliding window, the color deepening curve indicates that the linear trend passes the 90% significance MK test. The 1950 point on the graph indicates the slope of the linear trend in the SPEI data for the 1950-1970 window.

1986 to 1994. The wet season exhibited a pattern similar to that of summer, with a stable downward trend beginning in 1990 and a marked significant decline during 1994-1996.

Taken together, these findings indicate that the LLH region entered a consistent drought-formation phase around 1990, with downward trends in SPEI persisting through 2020. This suggests that drought conditions in the region remained steadily intensifying over the period 1990-2020, reflecting a sustained and phase-characteristic drying process.

3.4. Drought Trend in LLH since 1990

For examining the spatial patterns of drought trends in the LLH region since 1990, **Figure 5** displays the spatial distributions of trends in SPEI, precipitation, and 2-meter surface air temperature from 1990 to 2020. In summer, the SPEI in the northeastern part of the LLH shows a weak upward trend, while other regions show a downward trend, with a significant decrease in the northwest (**Figure 5(a)**). This indicates that in summer, the LLH presents a spatial distribution of wetness in the northeast and aridity in other regions. The trend of precipitation is broadly consistent in direction with that of SPEI but differs in magnitude and significance. Unlike SPEI, precipitation in the northeastern part of this region shows a significant increasing trend, while precipitation in the northwestern and

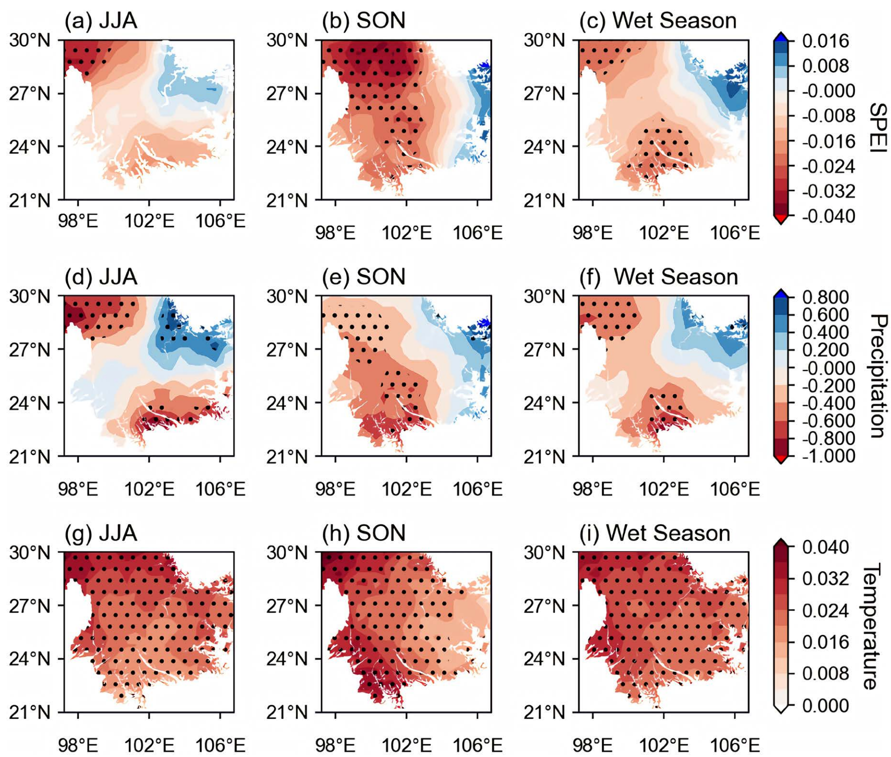

Figure 5. Long-term trends of SPEI over China low-latitude highlands from 1990 to 2020 summer, autumn, wet season ((a)-(c), unit: year^{-1}), Precipitation ((d)-(f), unit: mm/year^{-1}), Ground air temperature ((g)-(i), unit: ˚C/year^{-1}), black dots indicate that the linear trend passes the 90% significance MK test.

southern parts shows a significant decreasing trend (**Figure 5(d)**). The overall temperature shows a significant upward trend (**Figure 5(g)**). In autumn, the SPEI in LLH shows an upward trend in the east and a significant downward trend in the west, presenting a spatial distribution of wet in the east and dry in the west; the spatial distribution of precipitation trends is the same as that of SPEI (**Figure 5(e)**); the spatial distribution of temperature trends is the same as that in summer (**Figure 5(h)**). The overall spatial distribution of drought in LLH during the wet season is like that in autumn (**Figure 5(c)**), but the upward trend in precipitation in the northeast is stronger than in autumn (**Figure 5(f)**). The spatial distribution of temperature is like that in summer, both showing a significant warming trend (**Figure 5(i)**). By analysing the spatial distribution of droughts since 1990, precipitation in the northwestern and southern parts of the LLH has decreased significantly, while temperature has risen significantly across the entire region. The SPEI in these areas shows a pronounced downward trend, indicating intensified drought, suggesting that both reduced precipitation and increased temperature have exacerbated drought formation. An analysis of drought trends in summer, autumn, and the wet season reveals that precipitation in the northwestern LLH decreases significantly in both summer and autumn, with a more pronounced reduction in summer. Correspondingly, SPEI shows a stronger downward trend in summer than in autumn, indicating that drought severity in the northwestern LLH is greater in summer. This confirms that reduced precipitation is a key driver of drought intensification.

3.5. The Potential Processes of Drought in LLH

Analysis of the 120-year spatial pattern of drought trends (**Figure 3**) reveals that summer precipitation shows a weak increasing trend only in the northeastern LLH, while the northcentral part shows a weak decreasing trend, consistent with the SPEI pattern (**Figure 3(a)**, **Figure 3(d)**). Precipitation in the northcentral LLH shows a weak decreasing trend in autumn and the wet season, consistent with the widespread drought trend across most of the region (**Figure 3(b)**, **Figure 3(c)**). This indicates that reduced precipitation is a key driver of drought and is of great significance to its development. Reduced precipitation leads to soil moisture deficit, which weakens soil evaporation and plant transpiration, lowering atmospheric moisture and further suppressing rainfall. This feedback loop creates increasingly dry conditions and promotes drought development, with reduced rainfall as the dominant driver.

Based on the 30-year spatial distribution of drought trends (**Figure 5**), precipitation in the northeastern LLH increases significantly in summer, autumn, and the wet season. The temperature in this region rises significantly in summer, autumn, and the wet season, and the region shows a wetting trend, indicating that increased rainfall has helped alleviate drought. On the contrary, precipitation in the northwestern and southern parts of the LLH shows a significant decreasing trend in summer (**Figure 5(d)**), while temperature rises significantly across the entire region (**Figure 5(g)**). Correspondingly, SPEI in these areas shows a pronounced decreasing trend (**Figure 5(a)**), with intensifying drought. This indicates that the increase in near-surface air temperature has intensified drought in this region. It indicates that near-surface air temperature plays a positive role in drought formation and that higher near-surface air temperature can further increase drought frequency and severity. Against the backdrop of global warming, rising near-surface air temperatures will intensify evaporation of soil moisture and plant transpiration, leading to lower soil moisture content and triggering droughts. At the same time, high temperatures will reduce atmospheric humidity, making air moisture even scarcer. Taken together, these factors will exacerbate the intensity and frequency of drought. Temperature has consistently played a key driving role in intensifying short-term drought.

4. Discussion

The findings of this study provide a long-term observational basis for understanding drought trends in the LLH region over the past 120 years, which helps advance research on regional climate change and drought evolution. Although the study focuses on the spatiotemporal patterns of drought trends, the identified characteristics establish a foundation for further investigation of drought formation mechanisms. From a climate perspective, this work fills a research gap regarding long-term drought variability in the LLH and supports comparative analyses of drought patterns across Southwest China. The results also improve understanding of long-term drought behavior and provide a scientific reference for regional drought adaptation planning.

Compared with previous drought studies in the LLH and Southwest China, which have mostly relied on relatively short observational periods and conventional static trend analysis, this study benefits from a continuous 120-year dataset and a sliding-trend method. The extended long-term series enables the detection of centennial-scale shifts and multidecadal drought variability that cannot be fully captured by shorter records. Meanwhile, the sliding-trend approach reveals temporal changes in the direction and magnitude of drying and wetting tendencies, rather than only providing static trend results. These advantages allow a more comprehensive and dynamic understanding of drought evolution, thereby complementing existing literature and enhancing the novelty of regional drought research.

5. Conclusions

This study systematically analyzed the seasonal SPEI across LLH during the 120-year period (1901-2020) to characterize long-term drought dynamics. The results demonstrate a consistent downward trend in SPEI values for all four seasons, indicating a widespread intensification of drought conditions across the entire LLH region over the study period. Notably, the drying trends in summer and autumn are more pronounced than those in spring and winter, with the strongest upward trend in drought severity observed in autumn—highlighting seasonal heterogeneities in regional drought evolution.

To further capture the temporal variability of drought, a sliding trend analysis was applied to the summer, autumn, and wet-season SPEI series from 1901 to 2020. This analysis revealed phased changes in drought patterns, with a particularly robust and sustained intensification of drought in the LLH since the 1990s. This post-1990 drying acceleration underscores a recent shift in regional hydroclimatic conditions, which may be linked to global climate change.

Spatial patterns of drought trends over the 120-year study period further clarify the drivers of regional drought formation. In the northeastern LLH, precipitation shows a weak increasing trend in summer but decreases in autumn and the wet season. Correspondingly, drought severity in autumn and the wet season is substantially higher than in summer, indicating that reduced precipitation is closely associated with drought formation in these seasons and regions. This finding emphasizes the critical role of seasonal precipitation variability in regulating drought dynamics across the LLH.

Focusing on the recent 30-year period (1990-2020), spatial analysis of drought trends reveals additional insights into the combined effects of temperature and precipitation. In the northwestern and southern LLH, summer precipitation has shown a significant decreasing trend, while regional temperatures have risen significantly; even with decreasing rainfall, drought conditions in these sub-regions have intensified. This pattern suggests that rising temperatures appear to be linked to more severe drought by enhancing evapotranspiration, amplifying the drying tendency associated with reduced precipitation and highlighting the growing importance of thermal conditions in shaping recent drought patterns in the LLH.

Collectively, these findings improve our understanding of long-term and recent drought trends and their driving mechanisms across LLH. They provide a scientific basis for projecting future hydroclimatic changes in this ecologically and agriculturally vulnerable region and inform the development of targeted drought adaptation and mitigation strategies under ongoing global warming.

6. Study Limitations

This study has certain limitations that need to be acknowledged. First, the research is mainly based on phenomenological description and data analysis and does not conduct in-depth exploration and analysis on the underlying thermodynamic and dynamic mechanisms of drought formation in the LLH region. The lack of in-depth discussion of physical processes, such as atmospheric circulation anomalies and land-atmosphere interactions, limits a comprehensive understanding of the intrinsic drivers of regional drought evolution. Second, the study focuses only on the retrospective analysis of historical drought trends over the past 120 years and does not project future drought changes, making it difficult to provide direct long-term and forward-looking decision-making support for regional drought prevention and control. Third, the study only presents preliminary ideas on drought prevention and response measures and does not conduct quantitative evaluation or empirical verification of the effectiveness of specific measures, which limits the practical operability of the research results. Future research will focus on addressing these limitations, strengthening the exploration of drought formation mechanisms, carrying out scenario-based drought projection research, and verifying the effectiveness of drought prevention measures through empirical research to improve the depth and practical value of the research.

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Data Availability

The SPEI data were obtained from the Spanish National Research Council (CSIC) Drought Research Center, available at https://www.gob.pe/senamhi. Precipitation and surface air temperature data were obtained from the CRU dataset, available at https://www.uea.ac.uk/groups-and-centres/climatic-research-unit/data.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Ding, Y.H., Ren, G.Y. and Shi, G.Y. (2006) National Assessment Report of Climate Change (I): Climate Change in China and Its Future Trend. *Advances in Climate Change Research*, **2**, 3.

[2] Hu, Z., Yang, S. and Wu, R. (2003) Long-Term Climate Variations in China and Global Warming Signals. *Journal of Geophysical Research*: *Atmospheres*, **108**, Article No. 4614. https://doi.org/10.1029/2003jd003651

[3] Xu, Y., Zhang, X., Hao, Z., Hao, F. and Li, C. (2021) Projections of Future Meteorological Droughts in China under CMIP6 from a Three-Dimensional Perspective. *Agricultural Water Management*, **252**, Article 106849. https://doi.org/10.1016/j.agwat.2021.106849

[4] Zhang, Y., Sun, Y. and Hu, T. (2024) Changes in Extreme High Temperature Warning Indicators over China under Different Global Warming Levels. *Science China Earth Sciences*, **67**, 1895-1909. https://doi.org/10.1007/s11430-023-1299-1

[5] Xiao, C., Wu, P., Zhang, L. and Clark, R.T. (2018) Increasing Flash Floods in a Drying Climate over Southwest China. *Advances in Atmospheric Sciences*, **35**, 1094-1099. https://doi.org/10.1007/s00376-018-7275-7

[6] Liu, Y., Yang, Y. and Li, L. (2012) Major Natural Disasters and Their Spatio-Temporal Variation in the History of China. *Journal of Geographical Sciences*, **22**, 963-976. https://doi.org/10.1007/s11442-012-0976-4

[7] Li, H., Gupta, J. and Van Dijk, M.P. (2012) China's Governance Structure on Drought

Disaster in Rural Areas. *Disaster Advances*, **5**, 733-737.

[8] Wang, L., Huang, G., Chen, W., Zhou, W. and Wang, W. (2018) Wet-to-Dry Shift over Southwest China in 1994 Tied to the Warming of Tropical Warm Pool. *Climate Dynamics*, **51**, 3111-3123. https://doi.org/10.1007/s00382-018-4068-8

[9] Afshar, M.H., Bulut, B., Duzenli, E., Amjad, M. and Yilmaz, M.T. (2022) Global Spatiotemporal Consistency between Meteorological and Soil Moisture Drought Indices. *Agricultural and Forest Meteorology*, **316**, Article 108848. https://doi.org/10.1016/j.agrformet.2022.108848

[10] Hao, Z. and Singh, V.P. (2015) Drought Characterization from a Multivariate Perspective: A Review. *Journal of Hydrology*, **527**, 668-678. https://doi.org/10.1016/j.jhydrol.2015.05.031

[11] Jiao, W., Tian, C., Chang, Q., Novick, K.A. and Wang, L. (2019) A New Multi-Sensor Integrated Index for Drought Monitoring. *Agricultural and Forest Meteorology*, **268**, 74-85. https://doi.org/10.1016/j.agrformet.2019.01.008

[12] Wang, L., D'Odorico, P., Evans, J.P., Eldridge, D.J., McCabe, M.F., Caylor, K.K., *et al.* (2012) Dryland Ecohydrology and Climate Change: Critical Issues and Technical Advances. *Hydrology and Earth System Sciences*, **16**, 2585-2603. https://doi.org/10.5194/hess-16-2585-2012

[13] Ho, S., Tian, L., Disse, M. and Tuo, Y. (2021) A New Approach to Quantify Propagation Time from Meteorological to Hydrological Drought. *Journal of Hydrology*, **603**, Article 127056. https://doi.org/10.1016/j.jhydrol.2021.127056

[14] Tirivarombo, S., Osupile, D. and Eliasson, P. (2018) Drought Monitoring and Analysis: Standardised Precipitation Evapotranspiration Index (SPEI) and Standardised Precipitation Index (SPI). *Physics and Chemistry of the Earth*, *Parts A*/*B*/*C*, **106**, 1-10. https://doi.org/10.1016/j.pce.2018.07.001

[15] McKee, T.B., Doesken, N.J. and Kleist, J. (1993) The Relationship of Drought Frequency and Duration to Time Scales. *Proceedings of the* 8*th Conference on Applied Climatology*, *American Meteorological Society*, Anaheim, 17-22 January 1993, 179-183.

[16] Guttman, N.B. (1999) Accepting the Standardized Precipitation Index: A Calculation Algorithm. *JAWRA Journal of the American Water Resources Association*, **35**, 311-322. https://doi.org/10.1111/j.1752-1688.1999.tb03592.x

[17] Wu, H., Svoboda, M.D., Hayes, M.J., Wilhite, D.A. and Wen, F. (2007) Appropriate Application of the Standardized Precipitation Index in Arid Locations and Dry Seasons. *International Journal of Climatology*, **27**, 65-79. https://doi.org/10.1002/joc.1371

[18] Vicente-Serrano, S.M., Beguería, S. and López-Moreno, J.I. (2010) A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index. *Journal of Climate*, **23**, 1696-1718. https://doi.org/10.1175/2009jcli2909.1

[19] Vicente-Serrano, S.M. and López-Moreno, J.I. (2006) The Influence of Atmospheric Circulation at Different Spatial Scales on Winter Drought Variability through a Semi-arid Climatic Gradient in Northeast Spain. *International Journal of Climatology*, **26**, 1427-1453. https://doi.org/10.1002/joc.1387

[20] Beguería, S., Vicente-Serrano, S.M., Reig, F. and Latorre, B. (2014) Standardized Precipitation Evapotranspiration Index (SPEI) Revisited: Parameter Fitting, Evapotranspiration Models, Tools, Datasets and Drought Monitoring. *International Journal of Climatology*, **34**, 3001-3023. https://doi.org/10.1002/joc.3887

[21] Mokhtar, A., Jalali, M., He, H., Al-Ansari, N., Elbeltagi, A., Alsafadi, K., *et al.* (2021)

Estimation of SPEI Meteorological Drought Using Machine Learning Algorithms. *IEEE Access*, **9**, 65503-65523. https://doi.org/10.1109/access.2021.3074305

[22] Fischer, R., Anders, T., Bugmann, H., Djahangard, M., Dreßler, G., Hetzer, J., Hickler, T., Hiltner, U., Marano, G., Sperlich, D. and Yousefpour, R. (2025) Perspectives for Forest Modeling to Improve the Representation of Drought-Related Tree Mortality. *Journal of Cultivated Plants*/*Journal für Kulturpflanzen*, **77**, 50-69.

[23] Li, L., She, D., Zheng, H., Lin, P. and Yang, Z. (2020) Elucidating Diverse Drought Characteristics from Two Meteorological Drought Indices (SPI and SPEI) in China. *Journal of Hydrometeorology*, **21**, 1513-1530. https://doi.org/10.1175/jhm-d-19-0290.1

[24] Lu, E., Luo, Y., Zhang, R., Wu, Q. and Liu, L. (2011) Regional Atmospheric Anomalies Responsible for the 2009-2010 Severe Drought in China. *Journal of Geophysical Research*: *Atmospheres*, **116**, D21114. https://doi.org/10.1029/2011jd015706

[25] Wen, D., Gui, S. and Cao, J. (2024) Impact of May Atmospheric Latent Heating over the Southeast Asian Low-Latitude Highlands on Interannual Variability in the Meiyu Onset Date. *Atmospheric Research*, **298**, Article 107158. https://doi.org/10.1016/j.atmosres.2023.107158

[26] Zhou, H., Yan, Y., Dai, Q., He, Z. and Yi, X. (2023) Latitudinal and Altitudinal Patterns and Influencing Factors of Soil Humus Carbon in the Low-Latitude Plateau Regions. *Forests*, **14**, Article 344. https://doi.org/10.3390/f14020344

[27] Cao, J., Wen, D., Yang, R. and Zhu, Y. (2022) Impact of Indian and East Asian Summer Monsoons on the Diurnal Temperature Range of the Low-Latitude Highlands of China in the Rainy Season. *Journal of Climate*, **35**, 2161-2172. https://doi.org/10.1175/jcli-d-21-0189.1

[28] Pan, W., Zhao, J., Chen, B., Wu, J., Yang, Y., Li, H., *et al.* (2024) Impact of Late Winter Sea Surface Temperature Seesaw between Equatorial Central Pacific and Philippine Sea on Early Spring Vegetation over the Low-Latitude Highlands of China. *Climate Dynamics*, **62**, 8497-8526. https://doi.org/10.1007/s00382-024-07344-6

[29] Yu, G., Chen, Z., Piao, S., Peng, C., Ciais, P., Wang, Q., *et al.* (2014) High Carbon Dioxide Uptake by Subtropical Forest Ecosystems in the East Asian Monsoon Region. *Proceedings of the National Academy of Sciences*, **111**, 4910-4915. https://doi.org/10.1073/pnas.1317065111

[30] Dai, A. (2011) Drought under Global Warming: A Review. *WIREs Climate Change*, **2**, 45-65. https://doi.org/10.1002/wcc.81

[31] Dai, A., Trenberth, K.E. and Qian, T. (2004) A Global Dataset of Palmer Drought Severity Index for 1870-2002: Relationship with Soil Moisture and Effects of Surface Warming. *Journal of Hydrometeorology*, **5**, 1117-1130. https://doi.org/10.1175/jhm-386.1

[32] Nielsen-Gammon, J.W., Banner, J.L., Cook, B.I., Tremaine, D.M., Wong, C.I., Mace, R.E., *et al.* (2020) Unprecedented Drought Challenges for Texas Water Resources in a Changing Climate: What Do Researchers and Stakeholders Need to Know? *Earth's Future*, **8**, e2020EF001552. https://doi.org/10.1029/2020ef001552

[33] Orimoloye, I.R., Belle, J.A., Orimoloye, Y.M., Olusola, A.O. and Ololade, O.O. (2022) Drought: A Common Environmental Disaster. *Atmosphere*, **13**, Article 111. https://doi.org/10.3390/atmos13010111

[34] Lesk, C., Anderson, W., Rigden, A., Coast, O., Jägermeyr, J., McDermid, S., *et al.* (2022) Compound Heat and Moisture Extreme Impacts on Global Crop Yields under Climate Change. *Nature Reviews Earth & Environment*, **3**, 872-889. https://doi.org/10.1038/s43017-022-00368-8

[35] Dong, H., Zhao, S. and Zeng, Q. (2007) A Study of Influencing Systems and Moisture Budget in a Heavy Rainfall in Low Latitude Plateau in China during Early Summer. *Advances in Atmospheric Sciences*, **24**, 485-502. https://doi.org/10.1007/s00376-007-0485-z

[36] Dai, A., Zhao, T. and Chen, J. (2018) Climate Change and Drought: A Precipitation and Evaporation Perspective. *Current Climate Change Reports*, **4**, 301-312. https://doi.org/10.1007/s40641-018-0101-6

[37] Zhao, M., A, G., Liu, Y. and Konings, A.G. (2022) Evapotranspiration Frequently Increases during Droughts. *Nature Climate Change*, **12**, 1024-1030. https://doi.org/10.1038/s41558-022-01505-3

[38] Wang, C., Chen, C., Zhang, S., Ma, Z. and Pang, Y. (2023) Variation Characteristics of Extreme Climate Events in Southwest China from 1961 to 2017. *Heliyon*, **9**, e19648. https://doi.org/10.1016/j.heliyon.2023.e19648

[39] Tao, Y., Zhang, W., Duan, C., Chen, Y., Ren, J., Xing, D. and He, Q. (2014) Climatic Causes of Continuous Drought over Yunnan Province from 2009 to 2012. *Journal of Yunnan University: Natural Sciences Edition*, **36**, 866-874.

[40] Li, Y., Wang, Z., Zhang, Y., Li, X. and Huang, W. (2019) Drought Variability at Various Timescales over Yunnan Province, China: 1961-2015. *Theoretical and Applied Climatology*, **138**, 743-757. https://doi.org/10.1007/s00704-019-02859-z

[41] Gao, L., Han, X., Chen, X., Liu, B. and Li, Y. (2023) The Spring Drought in Yunnan Province of China: Variation Characteristics, Leading Impact Factors, and Physical Mechanisms. *Atmosphere*, **14**, Article 294. https://doi.org/10.3390/atmos14020294

[42] Lan, T. and Yan, X. (2024) Analysis of Drought Characteristics and Causes in Yunnan Province in the Last 60 Years (1961-2020). *Journal of Hydrometeorology*, **25**, 177-190. https://doi.org/10.1175/jhm-d-23-0092.1

[43] Cao, J., Yao, P., Wang, L. and Liu, K. (2014) Summer Rainfall Variability in Low-Latitude Highlands of China and Subtropical Indian Ocean Dipole. *Journal of Climate*, **27**, 880-892. https://doi.org/10.1175/jcli-d-13-00121.1

[44] Cao, J., Zhang, W. and Tao, Y. (2017) Thermal Configuration of the Bay of Bengal-Tibetan Plateau Region and the May Precipitation Anomaly in Yunnan. *Journal of Climate*, **30**, 9303-9319. https://doi.org/10.1175/jcli-d-16-0802.1

[45] Cao, J., Ding, Y., Wang, J. and Tao, Y. (2018) The Sea Surface Temperature Configuration of Greenland Sea-Subpolar Region of North Atlantic and the Summer Rainfall Anomaly in Low-Latitude Highlands of China. *International Journal of Climatology*, **38**, 3082-3089. https://doi.org/10.1002/joc.5484

[46] Zou, X.K., Ren, G.Y. and Zhang, Q. (2010) Study on the Variation Trend of Drought in China Based on the Comprehensive Meteorological Drought Index. *Climatic and Environmental Research*, **15**, 371-378.

[47] L'Heureux, M.L., Lee, S. and Lyon, B. (2013) Recent Multidecadal Strengthening of the Walker Circulation across the Tropical Pacific. *Nature Climate Change*, **3**, 571-576. https://doi.org/10.1038/nclimate1840

[48] Hu, X.P., Wang, S.G. and Xu, P.P. (2014) Cause Analysis of Consecutive Droughts in Southwest China from 2009 to 2013. *Meteorology Journal*, **40**, 1216-1229.

[49] Wang, Y., Wang, Y., Chen, Y., Chen, H., Li, X., Ding, Z., *et al.* (2023) Spatial and Temporal Characteristics of Drought Events in Southwest China over the Past 120 Years. *Remote Sensing*, **15**, Article 3008. https://doi.org/10.3390/rs15123008

[50] Ge, S., Jiang, C., Wang, J., *et al.* (2023) Analyzing Temperature and Precipitation Extremes in China Using Multiple Gridded Datasets: A Comparative Evaluation. *Weather*

and Climate Extremes, **42**, Article 100614.

[51] Zhao, T. and Fu, C. (2006) Comparison of Products from ERA-40, NCEP-2, and CRU with Station Data for Summer Precipitation over China. *Advances in Atmospheric Sciences*, **23**, 593-604. https://doi.org/10.1007/s00376-006-0593-1

[52] Philipp, M., Dietz, A., Buchelt, S. and Kuenzer, C. (2021) Trends in Satellite Earth Observation for Permafrost Related Analyses—A Review. *Remote Sensing*, **13**, Article 1217. https://doi.org/10.3390/rs13061217

[53] Wang, L., Liu, Y. and Wang, J. (2015) Simulations and Estimates of Low Latitude Highland Temperature by 5 CMIP5 Models. *Journal of Yunnan University: Natural Sciences Edition*, **37**, 851-860.

[54] Mallick, J., Talukdar, S., Alsubih, M., Salam, R., Ahmed, M., Kahla, N.B., *et al.* (2020) Analysing the Trend of Rainfall in Asir Region of Saudi Arabia Using the Family of Mann-Kendall Tests, Innovative Trend Analysis, and Detrended Fluctuation Analysis. *Theoretical and Applied Climatology*, **143**, 823-841. https://doi.org/10.1007/s00704-020-03448-1

[55] Gaddikeri, V., Sarangi, A., Singh, D.K., Jatav, M.S., Rajput, J. and Kushwaha, N.L. (2024) Trend and Change-Point Analyses of Meteorological Variables Using Mann–kendall Family Tests and Innovative Trend Assessment Techniques in *new Bhupania* Command (India). *Journal of Water and Climate Change*, **15**, 2033-2058. https://doi.org/10.2166/wcc.2024.462

[56] Rajput, P., Verma, M.K., Ghodichore, N. and Sinha, M.K. (2025) Investigation of Spatiotemporal Changes of Drought Trend in Indian River Basin System over the Century. *Theoretical and Applied Climatology*, **156**, Article No. 100. https://doi.org/10.1007/s00704-024-05328-4