Relationship between meteorological and hydrological droughts in the upstream regions of the Lancang–Mekong River

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ABSTRACT

Information on the relationship between meteorological drought (MD) and hydrological drought (HD) can serve as the basis for early warning and mitigation of HD. In this study, the standardized precipitation index and standardized streamflow index were applied to characterize MD and HD, respectively, and the evolution characteristics of MD and HD were assessed in the upstream regions of the Lancang–Mekong River (ULMR) from 1961 to 2015. Furthermore, the relationship between MD and HD was investigated using the Pearson correlation and wavelet analysis. The results revealed that (1) there was no significant change in the annual precipitation and streamflow; however, the ULMR experienced successive alternations of wet and dry episodes; (2) the average duration and magnitude of MD and HD increased with an increase in the time scale, while the duration and magnitude of MD lengthened and amplified in HD; (3) MD more likely propagated to HD as the time scale increased, and the propagation time exhibited marked seasonality, which was shorter in the wet season and longer in the dry season; and (4) there was a positive correlation between MD and HD; these two types of drought exhibited similar resonance frequency and phase-shift characteristics, and HD lagged behind MD.

Key words: drought propagation, hydrological drought, meteorological drought, wavelet analysis

HIGHLIGHTS

- Duration and magnitude of meteorological drought lengthened and amplified in hydrological drought.
- Longer time scales of meteorological drought more likely propagated to hydrological drought.
- Propagation time from meteorological to hydrological drought exhibited marked seasonality.
- Hydrological and meteorological drought presented similar patterns in terms of resonance frequency and phase shift.

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INTRODUCTION

Drought is one of the most common natural disasters with characteristics such as slow development, large influence, and huge socio-economic loss (Mishra & Singh 2010; Van & Anne 2015; Su et al. 2021). Ongoing global warming leads to changes in the spatio-temporal patterns of precipitation and evapotranspiration (Dai 2012; Pascolini-Campbell et al. 2021). Consequently, the frequency and intensity of extreme hydrological events are likely to increase, further aggravating the risk of drought (Trenberth et al. 2013; Liu et al. 2018). This has led to extraordinary challenges to the increasingly serious contradiction between the water supply and demand (Liu et al. 2017).

Drought is associated with a deficit of water compared to the normal conditions, which is typically divided into meteorological, agricultural, hydrological, and socio-economic droughts (Wilhite & Glantz 1985). These subtypes of drought are closely related to water or energy connectivity (Guo et al. 2020; Li et al. 2020b; Wu et al. 2021). A prolonged lack of precipitation (meteorological drought, MD) can translate into soil moisture deficits (agricultural drought) and further propagate to streamflow deficits (hydrological drought, HD) through the water cycle, thereby resulting in a shortage of social water supply (socio-economic drought) (Wanders & Wada 2015; Yao et al. 2020; Zhou et al. 2021b). This transition between different types of droughts is referred to as drought propagation (Van Loon & Van Lanen 2012; Van & Anne 2015).

Several indices have been developed to quantify MD and HD (Mishra & Singh 2010). Representative indices include the standardized precipitation index (SPI) and the standardized streamflow index (SSI) (McKee et al. 1993; Van Loon & Van Lanen 2012). The SPI exhibits advantages, such as simple calculation, multiple time scales, and convenient data acquisition, and has been widely accepted as a robust drought monitoring tool (Belayneh et al. 2014). The SSI operates on the same principle as that of the SPI and uses streamflow data for the quantification of HD at various time scales. However, the calculation of SSI requires an appropriate probability distribution function to fit the input data (Wu et al. 2018a; Li et al. 2020a). The SSI has been used to assess HD in different regions (Huang et al. 2016; Bhardwaj et al. 2020; Guo et al. 2020).

Drought propagation from MD to HD is characterized by a number of features, including pooling, attenuation, lag, and lengthening (Van Loon & Van Lanen 2012). In previous studies, researchers have investigated the propagation time (PT) from MD to HD using the correlation and cross-wavelet analyses (Barker et al. 2016; Huang et al. 2017; Yang et al. 2017; Wang et al. 2020b). Generally, the PT from MD to HD exhibits obvious regional and seasonal characteristics (Li et al. 2020a; Zhou et al. 2021b). Additionally, some studies have revealed the propagation threshold from MD to HD through
establishing different statistical models, such as the non-linear function, copula, and Bayesian models (Sattar et al. 2019; Guo et al. 2020; Wu et al. 2021). Conclusively, HD is determined by the propagation of MD through the hydrological cycle and is therefore controlled by the climate, catchment characteristics, and anthropogenic disturbances (Zhou et al. 2019; Veettil & Mishra 2020; Yang et al. 2020; Ding et al. 2021).

The Lancang–Mekong River, which is shared between six countries and home to more than 60 million individuals, is the most important transboundary river in Southeast Asia (Ziv et al. 2012). The hydrological regime and water resources in the upstream regions of the Lancang–Mekong River (ULMR) are crucial for food security, hydropower, and ecosystem services (Sabo et al. 2017). Previous studies have made important progress in assessing temporal and spatial changes of drought in the ULMR (Li et al. 2011; Zeng et al. 2012; Yu et al. 2015; Li et al. 2019). However, these studies mainly focus on MD and do not consider the drought propagation from MD to HD. In view of this, this work aims to simultaneously investigate two types of droughts and reveal their relationship in the ULMR from 1961 to 2015. The objectives of this study are (1) to analyze the characteristics of MD and HD based on the SPI and the SSI, (2) to determine the propagation from MD to HD, and (3) to quantify the relationship between MD and HD in different time scales. The research results are expected to be helpful for developing an early warning system for HD and water resource management in the ULMR.

MATERIALS AND METHODS

Study area

The ULMR refers to the catchment areas above the Jiuzhou hydrological station (25°47′N, 99°13′E) and spans an area of 8.42 × 10⁴ km², occupying 10.4% of the total drainage area of the Lancang–Mekong Basin (Figure 1). The elevation of the ULMR remarkably decreased from 6,968 m in the north to 1,300 m in the south. Varying with regard to both latitude and elevation, the mean annual precipitation increases from north to south, ranging from 413 to 1,043 mm, and the mean temperature differs from approximately –2 to 15 °C. The ULMR is dominated by the westerlies in winter and the Indian monsoon in summer (Fan & He 2015). The wet season receives more than 80% of the annual precipitation from the monsoon between May and October (Shi et al. 2013). Accordingly, the ULMR has strong seasonal runoff variability, and the dry season (November to April) is prone to HD.

The monthly precipitation data received from 15 meteorological stations from 1961 to 2015 were provided by the China Meteorological Data Sharing Service System (http://data.cma.cn). The monthly streamflow observations were obtained from the Jiuzhou and Gongguqiao hydrological stations. The Jiuzhou station started its operations in 1954 and ceased them in 2010. The Gongguqiao station is located 26 km downstream of the Jiuzhou station and has been operating since 2008. Therefore, the streamflow data at the Jiuzhou station were extended to 2015 based on the regression relationship between these two stations’ observations recorded in 2009–2010.

Drought indices

The SPI was calculated by fitting a cumulative probability density function to the precipitation data and then converted to a standard normal distribution of the actual SPI value using an equal probability transformation (Mckee et al. 1993). Gamma is usually selected to fit the precipitation data (Stagge et al. 2015). The SSI operates on the same principle as that of the SPI and uses streamflow data to quantify HD (Vicente-Serrano et al. 2012). It is worth noting that the streamflow commonly presents higher spatial variability than the precipitation; therefore, various probability distributions have been adopted in different areas (Huang et al. 2016; Li et al. 2020a). To choose a suitable distribution function, seven distribution functions, namely norm, log-normal (LN), Gumbel, extreme value distribution (EV2), generalized extreme value (GEV), Pearson type III (P3), and log-P3 (LP3), were fitted to the monthly streamflow. These distribution functions were compared based on the Akaike information criterion (AIC) and the Bayesian information criterion (BIC) (Laio et al. 2009). The results revealed that the P3 distribution exhibited the smallest statistical AIC and BIC values (Table 1). Therefore, the P3 distribution was selected as most suitable for calculating the SSI in the ULMR.

Identification of drought event

The run theory was applied to identify the drought events (Yevjevich 1967). Given a threshold, the length of the negative run was recorded as the drought duration, the cumulative amount of negative run was recorded as the drought magnitude, and the ratio of magnitude to duration was recorded as the drought intensity (Mishra & Singh 2010; Hassan et al. 2014). In this study, drought events were identified according to Wu et al. (2017), who defined three different types of drought events (single
month, consecutive months, and merged drought events) based on the SPI/SSI and three given threshold levels. The number of events, duration, magnitude, and intensity were calculated for historical MD and HD at different accumulation periods (1, 3, 6, and 12 month).

Statistical methods
The Mann–Kendall (MK) and Sen’s slope were employed to estimate the trends of time series, which are widely used in hydroclimate studies (Sen 1968; Kendall 1975; Li et al. 2019; Zhou et al. 2021b). A trend-free pre-whitening (TFPW) procedure was employed to eliminate the influence of serial correlation on the MK test (Yue et al. 2002). Moreover, Pettitt’s test was conducted to identify the change points in the time series (Pettitt 1979).

Correlation analysis was performed to quantitatively identify the correlation between the SPI and the SSI at different time scales. The SPI accumulation periods of 1–24 months and SSI-1 time series were cross-correlated using the Pearson correlation to analyze the most appropriate SPI accumulation period best characterized the SSI-1. The SPI accumulation

**Figure 1** | Location of meteorological and hydrological stations in the UMLR.

**Table 1** | Model selection criteria of seven distribution functions

| Model | Norm | LN | GUMBEL | EV2 | GEV | P3 | LP3 |
|-------|------|----|--------|-----|-----|----|-----|
| AIC   | 11,520 | 11,108 | 11,286 | 11,106 | 11,103 | 10,987 | 11,070 |
| BIC   | 11,529 | 11,117 | 11,295 | 11,115 | 11,117 | 11,001 | 11,084 |
period with the strongest correlation coefficient with SSI-1 was used to determine the PT (Barker et al. 2016; Huang et al. 2017; Ma et al. 2019).

The relationships between MD and HD were quantitatively investigated using the wavelet analysis, which has been widely used in hydrological research (Feng et al. 2020; Wang et al. 2020b; Ma et al. 2021). The continuous wavelet transform (CWT) is a type of wavelet transform useful for feature extraction that can detect the intermittent oscillation period of time scales. Moreover, the cross-wavelet transform (XWT) can efficiently reveal the resonance frequency in the time-frequency domain and phase shift of two time series. However, the XWT only reflects the regions where the two time series exhibit a higher common power value in space. The wavelet coherence (WTC) can help identify similar spectral characteristics of two time series in areas where the common power is low, which is compensated for the insufficiency of the XWT. Detailed information on the procedures have been provided in previous studies (Torrence & Compo 1998; Grinsted et al. 2004).

RESULTS

Variations of annual precipitation and streamflow

Figures 2 and 3 present the results of the TFPW-MK and Pettitt tests for annual precipitation and streamflow. The annual precipitation and streamflow exhibited a statistically non-significant trend from 1961 to 2015, with a rate of $-4.76 \text{ mm decade}^{-1}$ and $2 \text{ m}^3 \text{ s}^{-1} \text{ decade}^{-1}$, respectively. No statistically significant changes were detected in two time series. These results implied that the streamflow regime of the ULMR remained stable in the changing environment, although the hydrological variables exhibited a noticeable interannual and decadal fluctuation.

The evolution characteristics of drought

To explore the temporal evolution of droughts, a Hovmöller diagram of the SPI and the SSI at 1- to 24-month time scales between the period 1961 and 2015 was generated (Figure 4). Generally, with an increase in the time scales, the cumulative effects of the SPI and the SSI became more obvious with longer wet and dry periods. From 1961 to 2015, the SPI and the SSI exhibited similar temporal changing patterns, thereby exhibiting a distinct alternation between dry and wet episodes. The main persistent drought episodes identified were 1967–1973, 1981–1984, 1994–1996, 2006–2009, and 2014–2015, whereas the continuous wet periods during 1961–1966, 1979–1981, 1988–1993, and 1998–2005 were documented. Historical drought confirmed a close relationship between MD and HD; however, their occurrence times were usually not synchronized. For example, MD and HD occurred simultaneously in 1968–1969 and 2006–2007; HD lagged behind MD within 1 year in 1986–1987 and 1972–1973; and HD occurred for a long time after MD in 1982–1985.

The statistical results of historical drought duration, magnitude, and intensity based on the SPI and the SSI are presented in Table 2. The drought duration and magnitude of both MD and HD increased with an increase in the time scale. Additionally, the duration and magnitude of HD were greater than those of MD. For example, the average duration of HD at 1-, 3-, 6-, and

![Figure 2](http://iwaponline.com/jwcc/article-pdf/13/2/421/1013802/jwc0130421.pdf)
12-month time scales were 10.87, 14.6, 16.75, and 19.06 months, respectively, which are 6.12, 4.82, 3.98, and 1.64 months longer than the mean duration of MD, respectively. Regarding drought intensity, HD was found to be less severe than MD at shorter time scales (1 month); however, it was more severe than HD at longer time scales (12 months).

**Figure 3** | Pettitt test of annual precipitation (a) and streamflow (b) from 1961 to 2015.

**Figure 4** | The Hovmöller diagram of the SPI (a) and the SSI (b) at 1- to 24-month time scales from 1961 to 2015.
Propagation from MD to HD

Generally, MD leads to the origination of HD; however, there are amounts of MD that do not trigger HD because of underlying surface conditions as well as groundwater supply (Guo et al. 2020). Here, we used the response rate to describe the propagation of MD to HD. The response rate was defined as the percentage of MD that propagated to HD through the hydrological cycle (Sattar et al. 2019). A higher percentage of propagation means that HD is more sensitive to MD, and vice versa. According to Table 2, the response rates for the 1-, 3-, 6- and 12-month accumulation periods were 44, 69, 77, and 89%, respectively, which implies that MD more likely propagated to HD with increasing time scales.

To detect the PT from MD to HD, the Pearson correlations between the SPI-n (1–24 months) and SSI-1 were investigated. The Pearson correlation coefficients at various time scales are shown in Figure 5. It can be seen that the correlation coefficients between the SPI-n and SSI-1 varied at different time scales, ranging from 0.29 to 0.58. The strongest correlations (0.58) between the SPI-n and SSI-1 were noted at the accumulation period of 7 months. Therefore, the PT from MD to HD in the ULMR was approximately 7 months. Additionally, the PT from MD to HD exhibited a remarkable seasonal variability (Figure 6). For instance, a shorter PT was recorded in the warm and wet seasons (June to September), while a longer PT was recorded in the cold and dry seasons (December to February). Generally, the PT in summer is of approximately 2 months, which is relatively shorter than that of autumn (2–4 months) and spring (3–6 months). However, the PT in winter (18–20 months) is longer than that in all other seasons.

Relationship between MD and HD

The highest correlation coefficient between the SPI-n and SSI-1 was obtained at an accumulation period of 7 months, as mentioned in the Section ‘Propagation from MD to HD’. Therefore, the relationship between MD and HD can be further explored based on the SPI-7 and SRI-1 using the CWT, XWT, and WTC. The SPI-7 exhibited significant periodicities of 10–24 months, 28–32 months, 20–28 months, and 16–32 months during 1961–1972, 1979–1984, 1993–2002, and 2004–2012, respectively.

**Table 2 | Historical drought characteristics of SPI and SSI at 1-, 3-, 6- and 12-month time scale**

| Index | Time scale | Number of events | Duration | Magnitude | Intensity |
|-------|------------|------------------|----------|-----------|-----------|
| SPI   | 1          | 71               | 4.75     | 3.32      | 0.83      |
|       | 3          | 36               | 9.78     | 7.03      | 0.71      |
|       | 6          | 26               | 12.77    | 10.06     | 0.78      |
|       | 12         | 19               | 17.42    | 14.14     | 0.66      |
| SSI   | 1          | 31               | 10.87    | 8.42      | 0.77      |
|       | 3          | 25               | 14.60    | 10.87     | 0.70      |
|       | 6          | 20               | 16.75    | 13.56     | 0.72      |
|       | 12         | 17               | 19.06    | 16.01     | 0.74      |

**Figure 5 | The Pearson correlation coefficients between the SPI and the SSI-1. The red triangle denotes the strongest correlation.**
Figure 6 | The Pearson correlation coefficients between the SPI-n (1–24 months) and the SSI-1. The black dot denotes the strongest correlation.

Figure 7 | CWT of the SPI-7 (a) and the SSI-1 (b). The thick contours denote a 95% confidence level against red noise, and the thin lines being cone of influence (COI), in which the effect of zero padding may distort the picture. The color bar on the right denotes the wavelet energy.
Additionally, the wavelet power with 95% confidence in the period of 2–6 months exhibited a larger value but a shorter duration, thereby reflecting an intermittent quasi-periodic oscillation. Similar to the SPI-7, SSI-1 also exhibited periodic characteristics, including 50–64 months, 22–32 months, 20–30 months, and 48–56 months during 1969–1980, 1981–1988, 1992–1995, and 2002–2007, respectively (Figure 7(b)). The figure also indicates a 128–192 months cycle for a long duration between 1965 and 1993. There were also intermittent quasi-periodic oscillations with large values and short durations recorded from 2 to 6 months, which were the same for the SPI-7.

As shown in Figure 8(a), there was a statistically significant correlation noted between the SPI-7 and SSI-1 in the 12–20 months period from 1961 to 1967, 20–24 months period from 1968 to 1971, 24–32 months period from 1979 to 1989, 12–32 months period from 1992 to 2001, and 20–56 months period from 2002 to 2012. Moreover, the phase angle relationships indicated that the SSI-1 was positively correlated with the SPI-7 and lagged behind the SPI-7 variations by approximately 1–3 months. Figure 8(b) indicates that the SSI-1 was significantly positively correlated with the SPI-7 in most parts of the area. Oscillations in the SSI-1 can be well captured by the SPI-7 at periods varying from 12 to 192 months. Additionally, the region with lower power in the XWT was detected as it exhibited higher coherence in the WTC. Overall, there was a positive correlation noted between MD and HD, suggesting that MD plays an important role in the evolution of HD, and the occurrence of HD had a lag time compared with MD in the ULMR.

(Figure 7(a)).
DISCUSSION

The SPI and the SSI were used to study the relationship between MD and HD in the ULMR between 1961 and 2015. There were no significant changes in the annual precipitation and streamflow in the ULMR (Table 1); however, the ULMR experienced successive alternations of wet and dry episodes, and it was most frequently hit by drought events during 1967–1973, 1981–1984, 1994–1996, and 2006–2017 (Figure 4). The results were in agreement with those reported by Zhao et al. (2018), who detected an extreme drought in 2006, severe drought in 2011, and prolonged drought from 2009 to 2010 in Southwestern China based on the Gravity Recovery and Climate Experiment (GRACE) data. With an increase in the time scale, the average drought duration and magnitude increased for both MD and HD. The duration and magnitude of MD were both lengthened and amplified in HD, suggesting a non-linear relationship between MD and HD, which is concordant with previous studies (Barker et al. 2016; Yang et al. 2017; Wu et al. 2018b). Specifically, short-term and mild MD may not trigger HD, whereas a series of MDs can merge resulting in a prolonged HD. For example, the response rates of HD to MD were 44, 69, 77, and 89% for 1-, 3-, 6- and 12-month accumulation periods, respectively, thereby indicating that MD more likely propagated to HD with increasing time scales.

The Pearson correlation analysis revealed that the PT from MD to HD was estimated as 7 months in the ULMR, shorter in the warm and wet season, and longer in the cold and dry season (Figures 5 and 6). The seasonality of PT can be attributed to high precipitation and evapotranspiration in summer and autumn, by contrast, less precipitation and accumulation of snow in winter, and consequently, its melting in spring (Huang et al. 2017; Wu et al. 2018c; Wang et al. 2020b). In general, the relatively long PTs seen in winter in most catchments are because of the water stored in the soil during the preceding months (Barker et al. 2016). Previous studies have shown that the PT from MD to HD usually exhibits spatial heterogeneity and seasonality. Huang et al. (2017) found that the PT differs in the spring (6 months), summer (3 months), autumn (9 months), and winter (12 months) in the Wei River Basin. Wang et al. (2020b) demonstrated that the PT was shorter in summer (3 months) and longer in winter (12 months) in the Yellow River Basin. Li et al. (2020a) revealed that PT varied with seasons in the upper Shaying River Basin. Ding et al. (2021) further indicated that moist environments exhibit a stronger propagation relationship than arid environments. It should be noted that the maximum Pearson correlation was used to identify the PT in these studies, which only consider the linear relationships between MD and HD. The non-linear dependence must be carefully considered together with the linear dependence to better understand the propagation characteristics in the future (Zhou et al. 2021a).

The relationship between MD and HD was further investigated by applying XWT and WTC. There was a positive correlation between MD and HD; these two types of drought exhibited similar resonance frequency and phase-shift characteristics, and HD lagged behind MD (Figures 7 and 8). Previous studies have shown that XWT and WTC can reveal the internal correlation between MD and HD (Li et al. 2020a; Wang et al. 2020b). The use of XWT and WTC in this study confirmed the close connection between MD and HD from a statistical point of view; however, it ignored the physical mechanisms on the propagation from MD to HD. Both climate and catchment characteristics play a vital role in the propagation of MD to HD (Huang et al. 2017). The evolution of drought and propagation was strongly controlled by climate factors, such as El Niño Southern Oscillation, Arctic Oscillation, Pacific Decadal Oscillation, and sunspot (Huang et al. 2017; Wang et al. 2020a; Zhou et al. 2021b). Meanwhile, the drought propagation was influenced by anthropogenic activities in the modified and regulated basins. For example, land-use change (Wu et al. 2018c), irrigation (Ma et al. 2019), reservoirs, and water diversion (Wang et al. 2019) can disrupt the relationship between MD and HD. Therefore, the key issue of how and to what extent do the artificial influences affect HD propagation needs to be addressed in the whole Lancang–Mekong River Basin in future research.

CONCLUSION

This study revealed the evolution characteristics of MD and HD in the ULMR during 1961–2015. In addition, the PT from MD to HD and the link between MD and HD were quantitatively investigated. The main findings are as follows:

(1) There were no significant changes in the annual precipitation and streamflow in the ULMR during 1961–2015. However, ULMR has experienced successive alternations of wet and dry episodes. With an increase in time scale, the average drought duration and magnitude increased for both MD and HD. Additionally, the duration and magnitude of MD were both lengthened and amplified in HD.

(2) The response rates of HD to MD were 44, 69, 77, and 89% for 1-, 3-, 6- and 12-month accumulation periods, respectively, thereby indicating that MD more likely propagated to HD with an increase in the time scale. Moreover, the PT from MD to HD was estimated to be 7 months in the ULMR, which varied in spring (3–6 months), summer (2 months), autumn (2–4 months), and winter (18–20 months).
Furthermore, following the advances in artificial intelligence, machine learning as a data-driven method is a suitable alternative for HD forecasting (Shamshirband et al. 2020; Bai et al. 2021; Ma et al. 2021).

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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