Water Resources Research

RESEARCH ARTICLE
10.1029/2022WR032846

Key Points:

- Drought intensity propagation index and drought duration propagation index for quantifying drought propagation characteristics are proposed
- Dividing drought propagation partition
- Discovery of drought propagation close peer-to-peer in areas with strongest land-atmosphere coupling

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Citation:
Li, Q., Ye, A., Zhang, Y., & Zhou, J. (2022). The peer-to-peer type propagation from meteorological drought to soil moisture drought occurs in areas with strong land-atmosphere interaction. *Water Resources Research*, *58*, e2022WR032846. https://doi.org/10.1029/2022WR032846

Received 19 MAY 2022
Accepted 20 AUG 2022

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Data curation: Qiaoqiao Li
Funding acquisition: Aizhong Ye
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The Peer-To-Peer Type Propagation From Meteorological Drought to Soil Moisture Drought Occurs in Areas With Strong Land-Atmosphere Interaction

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Abstract Meteorological and soil drought is disastrous to natural and social systems. It is expected that the occurrence of meteorological and soil drought compound events will become more frequent and extreme in the future. The propagation process of meteorological drought to soil drought plays an essential role in the occurrence of drought. However, the drought propagation process is not clear, especially the quantification of drought characteristic propagation process is rarely realized. This study constructs drought intensity propagation index (DIP) and drought duration propagation index (DDP), and then puts forward drought propagation partition in China. Furthermore, this study preliminarily discussed the driving factors of drought propagation and the relationship between land-atmosphere interaction and main drought propagation partition (arid type drought propagation area, peer-to-peer type drought propagation area, and humid type drought propagation area). The results show that DDP and DIP are significantly negatively correlated in China from 1981 to 2020. From southeast to northwest, the propagation of drought intensity from meteorological drought to soil drought gradually increased and the propagation of drought duration gradually decreased. We further concluded that 68% of regions with similar intensity and duration of meteorological drought and soil drought (peer-to-peer type drought propagation area) are concentrated in semiarid and dry subhumid, which is exactly the area with strong land-atmosphere interaction. In all land use types, grasslands are most prone to peer-to-peer propagation of drought. This study further reveals the law and mechanism of drought propagation and provides a new idea and attempt to clarify the drought propagation process.

1. Introduction

In the context of global change, drought and flood disasters are the most complex natural phenomena. Their occurrence process has the characteristics of gradualness, wide influence range, and large loss. They are considered one of the world's most serious natural disasters (Zheng, 2000), causing widespread concern among scholars and proposing positive drought mitigation methods. (Ahmadi et al., 2019; Engström et al., 2020; Xiao et al., 2012; Zelenhasić & Salvai, 1987). With the impact of climate change, especially in extreme climates (Li et al., 2018), there is an increasing trend in the frequency and duration of major drought events (Panagoulia & Dimou, 1998).

Soil drought and meteorological drought are two major physiological stressors leading to widespread vegetation death and reduced terrestrial carbon uptake (Zhou, Li, et al., 2019; Zhou, Williamsa, et al., 2019). Meteorological drought is the cause of other drought types (Li et al., 2016), which is the most important factor causing soil moisture loss and soil drought (Mishra & Singh, 2010; Mishra et al., 2015). Soil drought is the frontier problem of drought. Soil moisture is a key component of the hydrological cycle, which is often used in related research on soil drought. The occurrence mechanism and prediction of soil drought have achieved phased results (Song et al., 2022; Zarekarizi et al., 2021). Both usually happen at the same time, and future compound events are expected to be more frequent and extreme, which will severely limit the continent's ability to act as carbon sinks (Novick et al., 2016). Therefore, studying the coupling relationship between meteorological drought and soil drought characteristics is also more important.

The concept of drought propagation was first introduced by Changnon (1987) as a hypothetical framework. Eltahir and Yeh (1999) first created the term and applied it to the propagation from meteorological drought to hydrological drought (Heudorfer & Stahl, 2017). Van Loon (2013) pointed out that drought propagation is the change of drought signal from abnormal meteorological conditions to hydrological drought in the land part of the whole hydrological cycle. Over the past decade, the study of drought propagation has been a frontier issue

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in hydrology. Due to the limitation of data and the complexity of technology, the research on drought propagation is limited to some extent (Zhao, 2020). The complexity of the propagation process leads to uncertainty and misunderstanding about how drought changes and whether it will change in the future. At present, the research on drought propagation mainly focuses on the propagation of meteorological drought to hydrological drought (Ahmadi & Moradkhani, 2019; Apurv et al., 2017; Niu et al., 2015; Schumacher et al., 2022; Van Loon, 2006; Van Loon et al., 2016; Zhou, Li, et al., 2019; Zhou, Williamsa, et al., 2019; Zhou, Wu, et al., 2019). The propagation from meteorological drought to soil drought depends on many processes that affect the balance of surface water, which is more complex than the propagation of meteorological drought to hydrological drought (Berg & Sheffield, 2018). Therefore, we can learn from previous results to increase the research on the propagation process of meteorological drought to soil drought.

Recent studies on the propagation of meteorological drought to soil drought have been gradually discovered (Xu et al., 2021; Zhang et al., 2021; Zhu et al., 2021). The current research mainly focuses on the correlation, propagation time, and influencing factors of meteorological drought to soil drought at different spatiotemporal scales. Studies have shown that the propagation time of meteorological drought to soil drought is 1–7 months. With the different research spatial scales, the influencing factors of meteorological drought to soil drought are different, including vegetation cover, Arctic oscillation, groundwater drought, and ENSO (Huang et al., 2015; Xu et al., 2021; Zhang et al., 2021; Zhou et al., 2021a, 2021b, 2021c; Zhu et al., 2021). However, in the past, when studying the correlation and propagation time of meteorological drought to soil drought, the whole dry-wet sequence is usually used for calculation, which is affected by the wetting sequence to some extent. A complete drought process encompasses five stages drought occurrence, development, persistence, mitigation, and lifting (Mo, 2011; Van Loon & Van Lanen, 2012). During the development of drought events, drought intensity, drought duration, and drought degree are the main characteristic indexes for evaluating drought. Using drought characteristic indexes to study drought propagation can better reflect the essence of drought propagation, and the propagation law and mechanism of drought characteristics between different drought types remain to be clarified.

Zhou, Li, et al. (2019) proposed the Drought Propagation Intensity Index (DPI), studied the propagation intensity of meteorological drought to hydrological drought in the Shiyang River basin, and obtained the calculation results in line with the actual situation and further application (Li, Zhou, et al., 2021). But obvious defects appeared when applied to a wide range. The reason is that when calculating DPI, the selected timescale is 12 months, and an excessive timescale will smooth the drought propagation characteristics. In China, the time of meteorological drought propagation to soil drought is different, and the average renewal period of soil moisture is 1 year (Lu, 2009). Drought propagation time should be considered when calculating drought propagation. In addition, drought duration is one of the main drought characteristic indexes, and the propagation strength of meteorological drought duration to soil drought duration will directly affect food security and ecosystem stability. Therefore, it is necessary to study its propagation characteristics (Zhu et al., 2021).

This study further developed the drought intensity propagation index (DIP) and drought duration propagation index (DDP), focusing on the study of drought intensity and drought duration in meteorological drought to soil drought propagation and divided the drought propagation partition in China. Furthermore, this study preliminarily discussed the driving factors of drought propagation. This study further reveals the law and mechanism of drought propagation and provides a new idea and attempts to clarify the drought propagation process.

2. Material and Methods

2.1. Data

2.1.1. Precipitation and Soil Moisture

In order to fully understand the temporal and spatial characteristics of drought propagation and improve the reliability of research results, it is necessary to ensure that the selected data have high spatial resolution and long-term time series. Data assimilation provides strong support for obtaining long-term, high-resolution, and accurate soil moisture data and greatly improves the skill of drought monitoring (Gavahi et al., 2020, 2022; Muñoz-Sabater et al., 2021; Xu et al., 2020). Therefore, this study uses the ERA5-land reanalysis data set provided by European Centre for Medium-Range Weather Forecasts. The spatial resolution of $0.1 \times 0.1°$, and the available period is 1981–2020. This data set is a series of improvements to the ERA-5 data set, which enables ERA-5 data sets to be more accurately applied to all types of land applications (Pelosi et al., 2020; Zhou et al., 2021b, 2021c). Among many data products, ERA5-Land has comprehensive application potential in China (Li, Ye, et al., 2021). Based on the precipitation and soil moisture data of the ERA5-Land data set, the standardized precipitation index (SPI) and standardized soil moisture index (SSMI) at different timescales were calculated (Husak et al., 2007; Zhou et al., 2021b, 2021c).

2.1.2. DEM

The MERIT digital elevation models (DEMs) were developed by removing multiple error components (absolute bias, stripe noise, speckle noise, and tree height bias) from the existing spaceborne DEMs (SRTM3 v2.1 and AW3D-30m v1). It represents the terrain elevations at a 3 s resolution (~90 m at the equator) and covers land areas between 90°N and 60°S, referenced to EGM96 geoid, and we use this DEM data set to calculate the slope.

2.1.3. Land Use Data

This study chose the ESACCI product to classify different land use types without considering the change in land cover during the study period (Zhou et al., 2021a). Four main types of land use, including construction land, forest, agriculture, and grassland, were studied. The land cover map with a resolution of 0.1° is determined based on the dominant land use types within each grid unit in ESACCI of 300 m.

2.1.4. Normalized Difference Vegetation Index (NDVI)

The normalized difference vegetation index (NDVI) data set is the latest release of the long sequence (1981–2015) NDVI product of NOAA Global Inventory Monitoring and Modeling System (GIMMS), version number 3g.v1. The temporal resolution of the product is twice a month, while the spatial resolution is 1/12 of a degree. The temporal coverage is from July 1981 to December 2015 (Ma et al., 2019; Pinzon & Tucker, 2014; Tucker et al., 2005). We use the average NDVI from 1981 to 2015.

2.1.5. Actual Evapotranspiration (AET)

This study chose the average terrestrial evapotranspiration across China data set, which is based on the evapotranspiration complementary method. The input data include China Meteorological Forcing Dataset downward short-wave radiation, downward long-wave radiation, air temperature, air pressure, GLASS surface emissivity and albedo, ERA5-land surface temperature and air humidity, National Centers for Environmental Prediction scattering radiation rate, etc. The spatial range is China's land area, with monthly temporal resolution and 0.1° spatial resolution (Ma et al., 2019).

2.1.6. Frozen Soil

The Frozen soil map of China (2000) data was released by the National Qinghai-Tibet Plateau Data Center. Based on the analysis of the existing frozen soil maps, a new distribution map of frozen soil is prepared, which integrates the existing frozen soil maps and the simulation results of permafrost distribution in the Qinghai-Tibet Plateau. The data acquisition time of each part of the country is unified, which reflects the distribution of frozen soil in China around 2000 (Ran & Li, 2018).

2.2. Methods

2.2.1. Standardized Precipitation Index (SPI) and Standardized Soil Moisture Index (SSMI)

The selection and construction of drought indicators need to determine the probability distribution of data. Probability distribution functions commonly used in drought index construction include Pearson type III, gamma distribution, empirical cumulative probability distribution, Log-Logistic distribution, normal distribution, etc. (Qin et al., 2015). Precipitation distribution is a skewed distribution, and soil moisture obeys normal distribution (Mc Kee et al., 1993; Mishra et al., 2015; Zhou, Li, et al., 2019; Zhou, Wu, et al., 2019). The Γ distribution probability is chosen to describe the change in precipitation when calculating the SPI and then was transformed into a standard normal distribution for the actual SPI values using an equal probability transformation. (Mc Kee et al., 1993; Wu et al., 2017). Husak et al. (2007) proposed the specific calculation steps of SPI. Jung et al. (2020) and Zhou, Wu, et al. (2019) proposed the specific calculation steps of SSMI. SSMI and SPI have multiple timescales, and different timescales reflect different drought and flood conditions (Wang & Zhang, 2012; Ye, 2014).

2.2.2. Propagation Time (PT)

The propagation time can be defined as the time length from dry-wet meteorological propagation to dry-wet soil (Ding et al., 2021; Han et al., 2019; Huang et al., 2015, 2017; Xu et al., 2021; Zhang et al., 2021; Zhou et al., 2021b, 2021c). In this study, Pearson correlation coefficient (PCC) was selected to determine the propagation time of meteorological drought to soil drought. PCC between meteorological drought (SPI1, SPI2, ..., SPIn) at different timescales and soil drought (SSMI1) at a 1-month timescale was calculated. The SPI accumulation period(n) corresponding to the maximum Pearson correlation coefficient was used as the PT of meteorological drought to soil drought (PT). Some studies have shown that the average renewal cycle of soil moisture is 1 year (Lu, 2009), so the maximum propagation time selected in this paper is 12 months ($n \leq 12$), and the sequence length at each timescale is 468 months.

2.2.3. Drought Intensity Propagation Index (DIP) and Drought Duration Propagation Index (DDP)

The drought propagation index is a parameter that quantitatively expresses the propagation process of specific drought characteristics between two drought types. Drought intensity and drought duration are two essential attribute characteristics of drought events. Therefore, to describe the propagation process of meteorological drought to soil drought more clearly, this paper proposes a DDP and improves the algorithm and significance of the drought propagation intensity index. DIP represents the propagation degree of meteorological drought intensity to soil drought intensity, and DDP represents the propagation degree of meteorological drought duration to soil drought duration. Together they made a more comprehensive expression of the drought propagation process.

The specific calculation processes are as follows:

$$\mathrm{DIP} = \frac{\mathrm{SI}_{\mathrm{SSMI1-Ln}}}{\mathrm{MI}_{\mathrm{SPIn-Ln}}}(\mathrm{MI} \neq 0) \tag{1}$$

$$\mathrm{DDP} = \frac{\mathrm{SD}_{\mathrm{SSMI1-Ln}}}{\mathrm{MD}_{\mathrm{SPIn-Ln}}}(\mathrm{MD} \neq 0) \tag{2}$$

The principle of this method is that if the propagation of meteorological drought to soil drought is peer-to-peer, that is, soil drought is only affected by meteorological drought, and soil drought will also produce feedback to meteorological drought, the intensity and duration of meteorological drought are consistent with those of soil drought, and the ratio of the two is about 1. If the propagation of meteorological drought to soil drought is affected by other factors, the ratio of the two deviates from 1.

Where, DIP is the drought intensity propagation index, n represents the propagation time (PT) of meteorological drought to soil drought at the grid point. The sequence lengths of SPIn and SSMI1 at each timescale are 468 months, represented by Ln. For example, when $n = 1$, the sequence of dry-wet meteorological and dry-wet soil is the time series from January 1981 to December 2019 in SPI 1 month timescale and SSMI 1 month timescale, respectively, which are abbreviated as SPI1-L1 and SSMI1 -L1; when $n = 2$, the sequence of dry-wet meteorological and dry-wet soil is the time series from February 1981 to January 2020 in SPI 2 months timescale and SSMI 1 month timescale, respectively, which are abbreviated as SPI2-L2 and SSMI1-L2; and in this way, when $n = 12$, the sequence of dry-wet meteorological and dry-wet soil is the time series from December 1981 to November 2020 in SPI 12 months timescale and SSMI 1 month timescale, respectively, which are abbreviated as SPI12-L12 and SSMI1-L12.

$\mathrm{MI}_{\mathrm{SPIn\text{-}Ln}}$ is the average value of drought sequence in SPIn-Ln dry-wet sequence. $\mathrm{SI}_{\mathrm{SSMI1\text{-}Ln}}$ is the average value of drought sequence in SSMI1-Ln dry-wet sequence. DDP is the drought duration propagation index, $\mathrm{MD}_{\mathrm{SPIn\text{-}Ln}}$ is the total drought duration in SPIn-Ln dry-wet sequence, and $\mathrm{SD}_{\mathrm{SSMI1\text{-}Ln}}$ is the total drought duration in SSMI1-Ln dry-wet sequence.

The direction of drought propagation is defined as the propagation of meteorological drought to soil drought. When DDP and DIP were close to 1 in the range of [0.9, 1.1), the propagation from meteorological drought to hydrological drought is peer-to-peer. And soil drought was mainly affected by meteorological drought. When DDP and DIP are not close to 1, the propagation process of meteorological drought on soil drought is affected by other factors, which can be divided into two situations, DDP and DIP are greater than 1, that is, the intensity and total duration of soil drought are greater than those of meteorological drought, which is the strong propagation of meteorological drought to soil drought. DDP and DIP were less than 1, that is, the intensity and total duration

Table 1
Classification of Drought Propagation Index

DIP or DDP	Index range	DIP or DDP	Index range
		[0.9,1.1)	Peer-to-peer
(1.1,1.2]	Mildly strong	[0.8,0.9)	Mildly weak
(1.2,1.3]	Moderately strong	[0.7,0.8)	Moderately weak
(1.3, +∞)	Extra strong	(0,0.7)	Extra weak

Note. DDP, drought duration propagation index; DIP, drought intensity propagation index. When the meteorological drought value is 0 and the soil drought value is not 0, the drought propagation index is defined as Extra strong.

of soil drought were less than meteorological drought, which was the weak propagation of meteorological drought to soil drought. The drought propagation index is graded in Table 1.

Compared with the existing researches, the innovation of research methods in this paper is mainly reflected in the following aspects: (a) Two indicators (DIP and DDP) were proposed to study the drought propagation process. (b) In calculating the DIP and the DDP, the PT of any pixel meteorological drought propagation to soil drought is fully considered. (c) When calculating the intensity and duration of drought, the data of the whole sequence of each timescale are used to participate in the calculation, instead of selecting seasonal and annual values as values of different timescales. (d) Improving the classification criteria for drought propagation indices. The comparison before and after the improvement of the drought propagation index and the calculation process of the drought propagation index are presented in Figure 1.

2.2.4. Bivariate Local Spatial Autocorrelation

The bivariate spatial autocorrelation method proposed by Anselin (1995) can effectively reflect the correlation and dependence characteristics of the spatial distribution of the two types of variables (Xu et al., 2019), which is considered to be one of the most widely used methods to estimate the spatial autocorrelation of each index (Getis, 2010; Li et al., 2020).

Bivariate Local Moran's I represents the local correlation between the independent variables of region i and the dependent variables of region j. The treatment of the bivariate Local Moran's I closely follows that of its global counterpart (Anselin, 2019; Anselin & Xun, 2020; Anselin et al., 2002). In essence, it captures the relationship between the value for one variable at location i, x_i, and the average of the neighboring values for another variable, that is, its spatial lag $\sum_{j=1}^{n} W_{ij} y_j$. Apart from a constant scaling factor (that can be ignored), the statistic is the product of x_i with the spatial lag of y_j (i.e. $\sum\limits_{j=1}^{n} W_{ij} y_j$), with both variables standardized, such that their means are zero and variances equal one:

$$I_i = C x_i \sum_{j=1}^{n} W_{ij} y_j \tag{3}$$

Where w_{ij} are the elements of the spatial weights matrix. The clustering pattern can be divided into high-high (H-H) aggregation, that is, the independent variables of space unit i and the dependent variables of adjacent unit j are larger; low-low (L-L) aggregation, that is, the independent variables of space unit i and the dependent

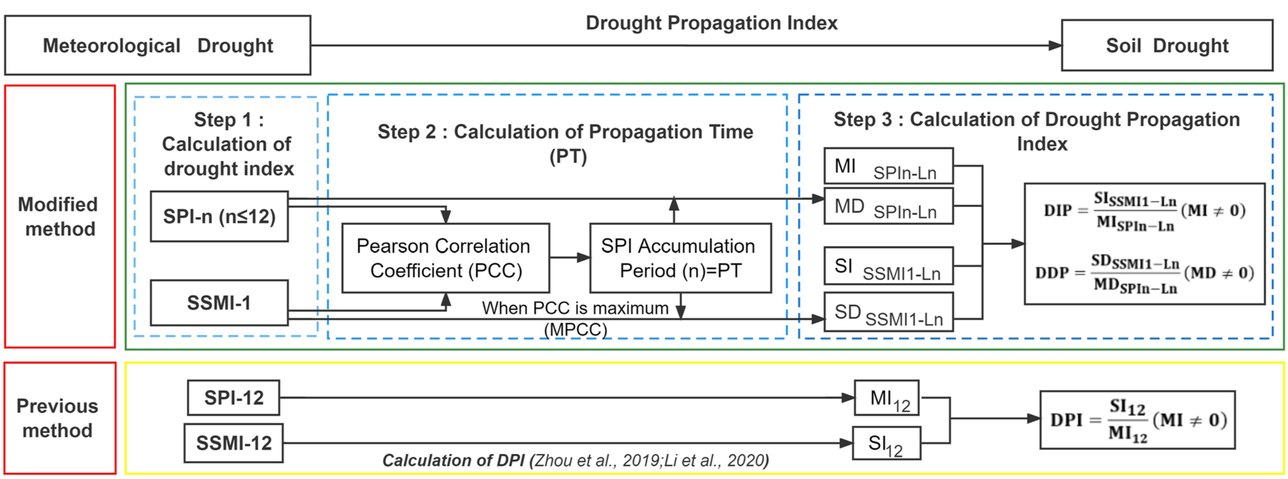

Figure 1. The comparison before and after the improvement of drought propagation index and the calculation process of drought propagation index.

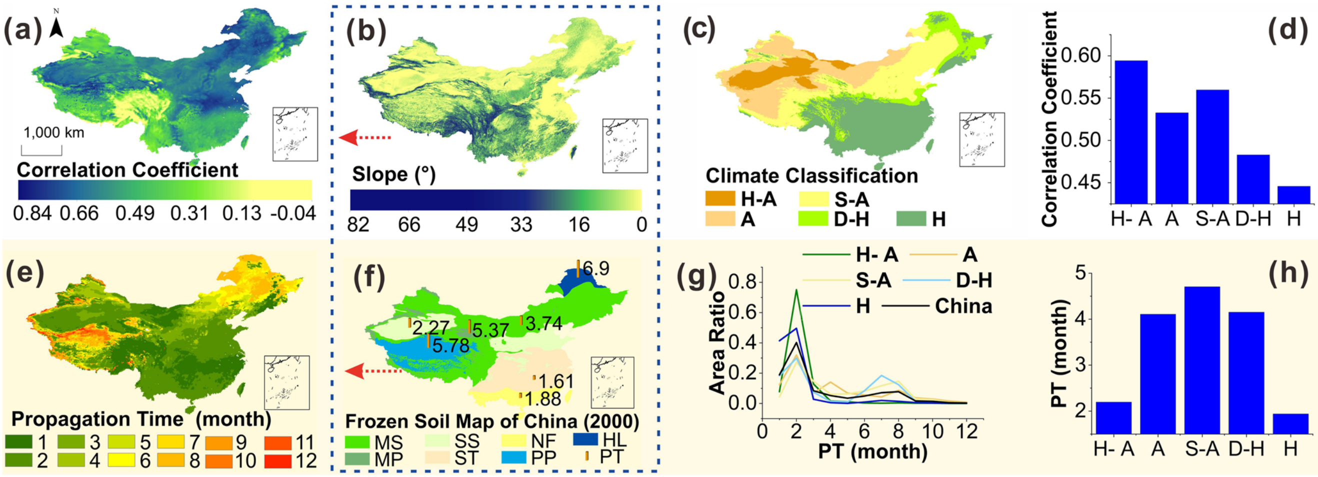

Figure 2. (a) Maximum correlation coefficient (MCC) between dry-wet meteorological and dry-wet soil; (b) slope map; (c) climate region (H-A: hyper arid, A: arid, S-M: semiarid, D-H: dry subhumid, and H: humid); (d) average MCC between dry-wet meteorological and dry-wet soil in each climate region; (e) propagation time (PT) from dry-wet meteorological to dry-wet soil; (f) frozen soil map and average propagation time in each frozen soil (HL: high latitude permafrost; PP: plateau permafrost region; MP: mountain permafrost regions; MS: middeep seasonal frozen soil (>1 m); SS: shallow season frozen soil (<1 m); NF: nonfrozen ground; and ST: short-term frozen soil); (g) propagation time in each climate region; and (h) average propagation time in each climate region.

variables of adjacent unit *j* are small; low-high (L-H) aggregation means that the independent variable value of spatial unit *i* is small and the dependent variable value of adjacent unit *j* is large; and high-low (H-L) aggregation means that the independent variable value of spatial unit *i* is large and the dependent variable value of adjacent unit *j* is small.

3. Results

3.1. Propagation Time of Dry-Wet Meteorological to Dry-Wet Soil

The DIP represents the degree of meteorological drought intensity propagation to soil drought intensity, and the DDP represents the degree of meteorological drought duration propagation to soil drought duration. Before getting DIP and DDP, it is necessary to consider the maximum correlation coefficient (MCC) between dry-wet meteorological and dry-wet soil and the propagation time of dry-wet meteorological propagation to dry-wet soil (PT). MCC represents the degree of influence of dry-wet meteorological on dry-wet soil (Figure 2a). In China, more than 98% of the regional dry-wet meteorological were significantly correlated with dry-wet soil ($p < 0.01$). MCC distribution was highly similar to slope distribution (Figure 2b), and there was a significant negative correlation between them ($P < 0.01$). In areas with a large slope, the runoff will be generated by rapid flow after rainfall, resulting in less influence of dry-wet meteorological on dry-wet soil (Huang et al., 2015; Xu et al., 2019). The uncorrelated areas are mainly concentrated in glacier areas and permafrost areas, and their existence seriously hindered the influence of dry-wet meteorological on dry-wet soil. In terms of climate region (Figures 2c and 2d), the correlation between dry-wet meteorological and dry-wet soil in dry regions is greater than that in wet regions. This is because vegetation coverage is high in humid areas (Zhou et al., 2021a), and moisture stored in soil has a certain buffering effect on the change of dry-wet meteorological (Huang et al., 2015). In dryland, the change of soil moisture mainly depends on the change of dry-wet meteorological.

PT can be defined as the time length from dry-wet meteorological propagation to dry-wet soil, mainly representing the time that dry-wet meteorological can effectively affect the dry-wet soil (Figure 2e). In China, the average PT is 3.4 months. Among them, PT is mainly 2 months, accounting for 40% of China's area, mainly distributed in the southern and northwestern desert areas of China; followed by 1 month and 3 months, mainly distributed in the south and northwest of China. The area with PT for more than 3 months is mainly distributed in the northern part of the Qinghai-Tibet Plateau and northeast China, accounting for 32.5% of China's area. The distribution range of this area is highly consistent with the permafrost area (Figure 2f). The existence of permafrost hinders the propagation of dry-wet meteorological to dry-wet soil. From the high-latitude permafrost region to the seasonal permafrost region to the nonpermafrost region, the drought propagation time decreases obviously (Figure 2f).

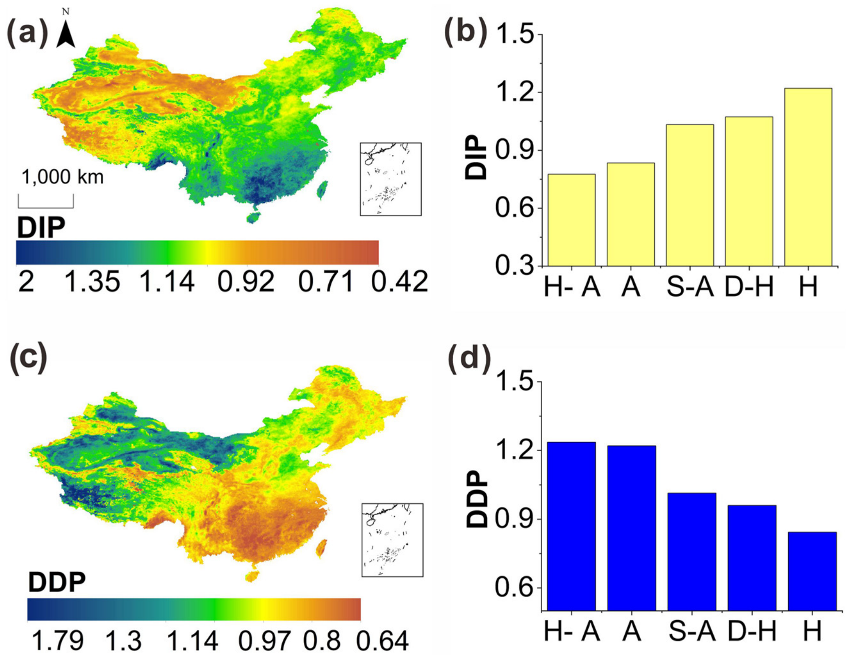

Figure 3. (a) Drought intensity propagation index (DIP); (b) DIP in each climate region; (c) drought duration propagation index (DDP); and (d) DDP in each climate region.

For the climate zone, the PT of each climate zone is mainly 2 months (Figures 2c and 2g). The PT in the semi-arid area was the longest, followed by a gradual decrease in PT in the arid and humid areas (Figures 2c and 2h). The reason for it being longest is that the area of PT in this area has two peaks over time and the second peak is 8 months, which is mainly distributed in the high-latitude permafrost and middeep season permafrost and plateau permafrost regions (Figure 2f).

3.2. The Propagation of Intensity and Duration of Meteorological Drought to Soil Drought

Figures 3a and 3c show the distribution characteristics of the propagation of intensity and duration of meteorological drought to soil drought, respectively, which characterizes the influence of meteorological drought intensity and duration on soil drought intensity and duration. In China, the average DIP was 1.031 and the average DDP was 1.016, there is peer-to-peer propagation from meteorological drought to soil drought (Figures 3a and 3c). There is a negative correlation between DDP and DIP in China ($P < 0.01$), DIP gradually changed from strong propagation to weak propagation from southeast to northwest, and DDP gradually changed from weak propagation to strong propagation.

In terms of climate region (Figures 3b and 3d), DIP gradually increased from hyper arid to humid and DDP gradually decreased. In semiarid and dry subhumid areas, there is peer-to-peer propagation from meteorological drought to soil drought, soil drought is greatly affected by meteorological drought and has strong sensitivity. When the meteorological drought changes in extreme arid areas, arid areas, and humid areas, the soil drought will basically remain in the original state, and the intensity and duration of meteorological drought have no obvious effect on soil drought.

3.3. Drought Propagation Partition in China

Based on the classification of DIP and DDP (Table 1) and climate region (Figure 2c), the drought propagation partition in China was divided into seven regions (Figure 4a). I VII and IV represent the main characteristic regions of meteorological drought propagation to soil drought, respectively. About 85.8% of Region I is distributed in hyper arid and arid regions of China, mainly in desert areas and the western part of the Qinghai-Tibet Plateau, which is named the Arid type drought propagation area. The intensity of meteorological drought propagation to

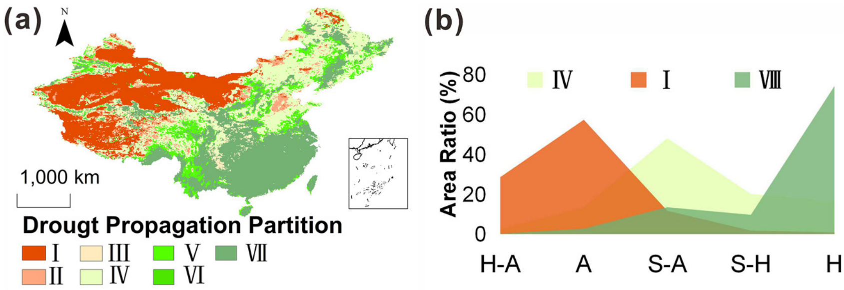

Figure 4. (a) Drought propagation partition in China (I, drought intensity propagation index (DIP) propagation weak, drought duration propagation index (DDP) propagation strong (arid type drought propagation area); II, DIP peer-to-peer propagation, DDP propagation strong; III, DIP peer-to-peer propagation, DDP propagation weak; IV DIP and DDP peer-to-peer propagation (peer-to-peer type drought propagation area);V, DDP peer-to-peer propagation, DIP propagation strong;VI DDP peer-to-peer propagation, DIP propagation weak; and VII DIP propagation strong, DDP propagation weak (humid type drought propagation area) and (b) The area ratio of main drought propagation partitions (I, IV, and VII) in each climatic region.

soil drought is weak (DIP <0.9) and drought duration propagation is strong (DDP >1.1). The soil drought intensity in this region is small but the drought duration is long. The main land use type is bare land. The soil types are mainly desert soil and arid soil, and the soil has been in a drought state for a long time; 74% of Region VII is distributed in humid regions of China, which is named the humid type drought propagation area. The intensity of meteorological drought propagation to soil drought is strong (DIP <1.1), drought duration propagation is weak (DDP <0.9). Although the duration of soil drought is less than meteorological drought, the intensity and destructiveness of soil drought are great. 68% of Region IV is distributed in semiarid and dry subhumid regions of China and is named the Peer-to-peer type drought propagation area. In this region, DIP and DDP are close to 1, and the propagation from meteorological drought to soil drought is peer-to-peer. Changes in soil drought in the region are more sensitive to changes in meteorological drought (Figures 4a and 4b).

3.4. Driving Factors of Drought Propagation

The driving factors of meteorological drought to soil drought are very complex. In the context of global change, changes in any link of the water cycle caused by natural factors and human activities will affect the propagation process (Apurv et al., 2017; Huang et al., 2015; Pan et al., 2019; Zhang et al., 2021; Zhu et al., 2021). In natural factors, we choose precipitation (P), actual evapotranspiration (AET), temperature (T), frozen soil, slope, digital elevation model (DEM), and NDVI as representatives. In the land use types, we choose four types, construction land, forest, agricultural land, and grassland as representatives (Figure 5g). The results showed that the above influencing factors had an important impact on the drought propagation process ($P < 0.01$) (Table 2). Among them, AET and NDVI were the most important driving factors affecting the drought propagation process, and we observed significant positive correlations between them and DIP, negatively correlated with DDP ($P < 0.01$). Next, the correlation coefficients between DIP, DDP, and natural factors from large to small are P, frozen soil, slop, and DEM. Therefore, we focus on the impact of AET and NDVI on drought propagation in space, which can reflect climate factors and vegetation factors, respectively (Figure 5).

In the northwest and southern regions, the AET and NDVI had significant effects on the drought propagation process, both of them showed a significant synergistic relationship with DIP and a significant trade-off relationship with DDP (Figures 5d and 5e). AET and NDVI values were moderate in semiarid and dry subhumid, and they had no significant synergy and trade-off with DDP and DIP. The peer-to-peer type drought propagation area is mainly distributed in the region, indicating that the soil drought in this region is mainly affected by meteorological drought, and the response to meteorological drought is obvious (Figure 5f).

In terms of the average value of China (Figure 5h), among all land use types, the DIP from large to small is construction land, forest, agriculture, and grassland; and the DDP from large to small is grassland, agriculture, construction land, and forest. Among them, the drought propagation of grassland was closest to peer-to-peer,

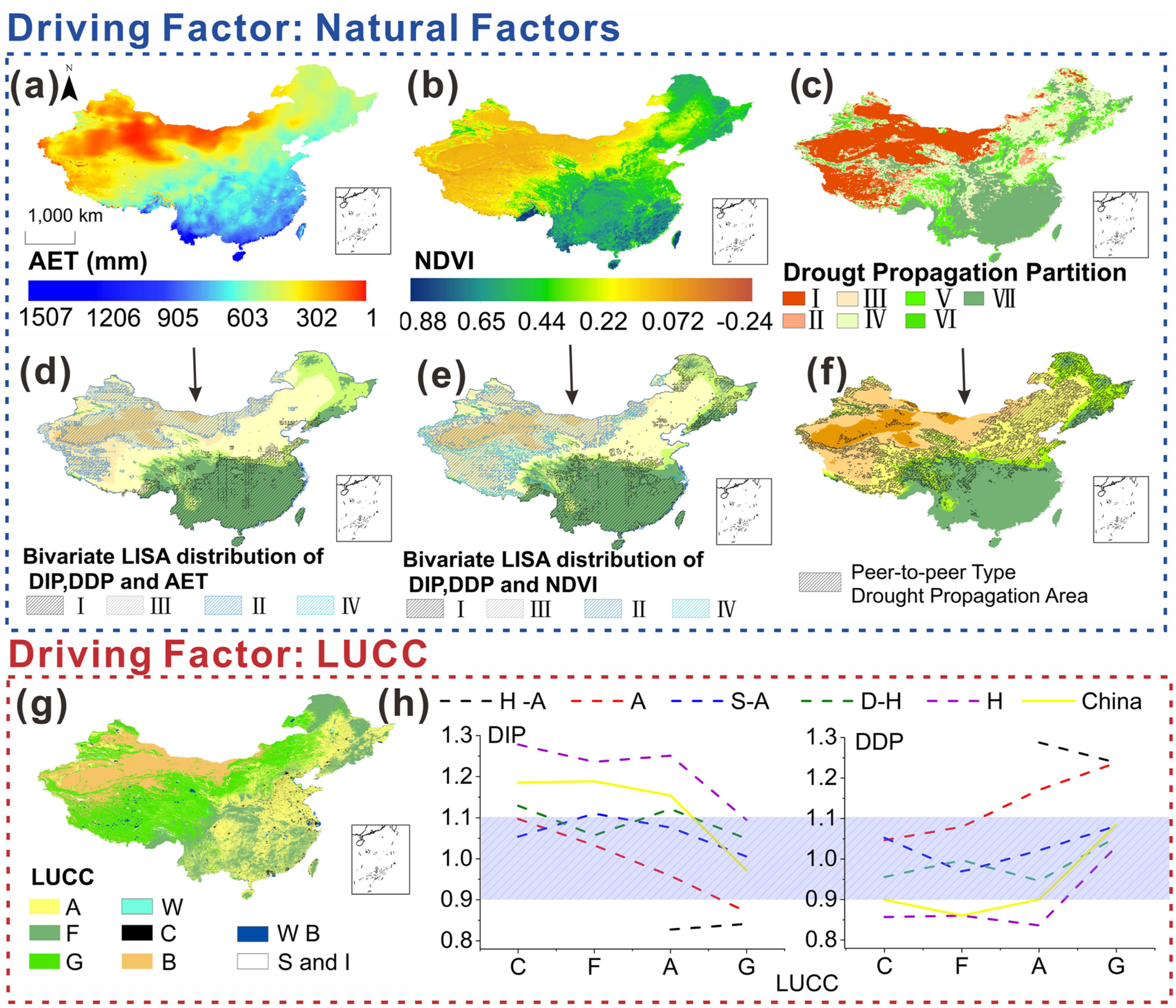

Figure 5. Driving factors of drought characteristic propagation: Natural factors: (a) Average terrestrial evapotranspiration across China; (b) dryland normalized difference vegetation index (NDVI); (c) division of drought characteristic propagation; (d) bivariate LISA distribution of drought intensity propagation index (DIP), drought duration propagation index (DDP), and actual evapotranspiration (AET) (DDP, DIP, and AET: I, L-H-H; II, H-L-L; III, L-H-H; and IV, H-L-L); (e) bivariate LISA distribution of DIP, DDP, and NDVI (DDP, DIP, NDVI: I, L-H-H; II, H-L-L; III, L-H-H; and IV, H-L-L); (f) peer-to-peer type drought propagation area; LUCC (Land use and cover change); (g) distribution of LUCC in China (C, Construction land; F, Forest; A, Agriculture; G, Grassland; W, Wetlands; B, Bare areas; W, Water bodies; and S and I, Permanent snow and ice); and (h) DIP and DDP in different land use types in each climate region.

especially in arid, semiarid, dry subhumid, and humid areas, where DIP and DDP were closest to 1. In addition, in semiarid regions, the intensity and duration of meteorological drought in each land use type are close to peer-to-peer.

Table 2
Correlation Coefficients Between DIP, DDP, and Natural Factors

	AET	P	T	NDVI	Frozen soil	Slop	DEM
DIP	0.780**	0.753**	0.335**	0.744**	−0.466**	0.297**	0.296**
DDP	−0.744**	−0.718**	−0.325**	−0.747**	0.482**	−0.283**	−0.260**

Note. AET, actual evapotranspiration; DDP, drought duration propagation index; DEM, Digital Elevation Models; DIP, drought intensity propagation index; NDVI, normalized difference vegetation index. **, $p < 0.01$.

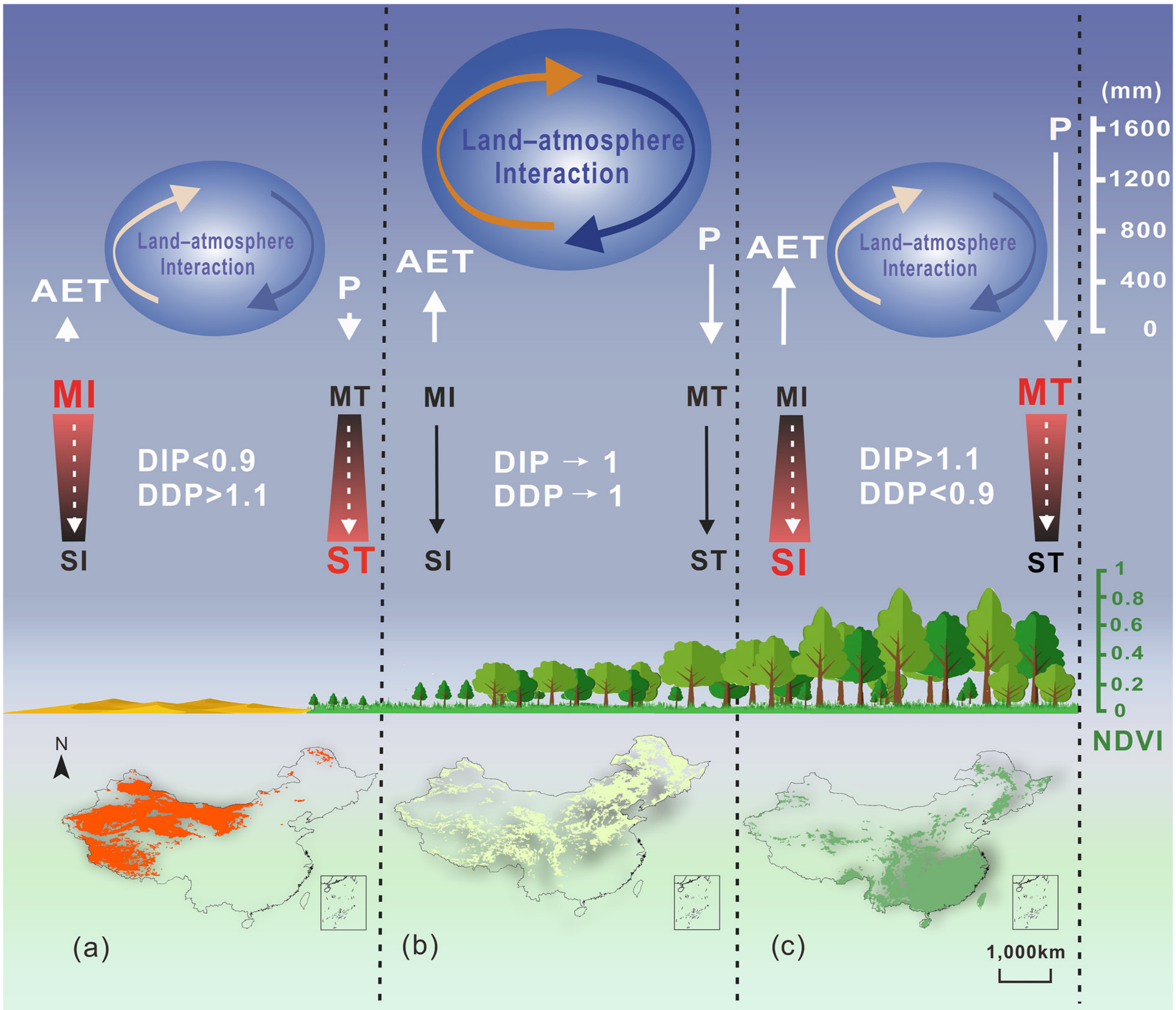

Figure 6. Relationship between land-atmosphere interaction and main drought propagation partition. (a) Arid type drought propagation area; (b) peer-to-peer type drought propagation area; and (c) humid type drought propagation area.

4. Discussion

Meteorological drought is the cause of other drought types (Li et al., 2016) and is the most important factor causing soil moisture loss and soil drought. Local soil moisture deficits have also been shown to promote precipitation deficits, particularly in transitional regimes between humid and arid climates (Guo et al., 2006; Koster et al., 2004). The relationship between soil moisture and evapotranspiration is a key physical process between the land-atmosphere interface and a breakthrough in the study of land-atmosphere interaction (Dirmeyer et al., 2009; Gao, 2018; Koster & Suarez, 2001; Koster et al., 2003; Seneviratne, Luthi, et al., 2006; Seneviratne, Koster, et al., 2006). It can be seen from Section 3.4 that there is a clear spatial correspondence between the drought zones in China and influencing factors such as precipitation, evapotranspiration, and precipitation, especially in the three main drought propagation zones (Figure 6).

In arid type drought propagation areas, there is a lack of water and more energy on land (Figure 6a). The AET is determined by water, and there is little water added to soil moisture (Gao, 2018; Liu et al., 2010; Zhang et al., 2001). Small-scale precipitation cannot penetrate into the soil due to evaporation, interception, and other factors to alleviate drought (Wang, 2014). The soil's ability to remember extreme dry-wet conditions allows unusually persistent timescales from week to month, even seasonal (Koster & Suarez, 2001; Orlowsky & Seneviratne, 2010; Wu & Dickinson, 2004). Therefore, the soil in arid regions will continue to maintain a drought state, and the duration of soil drought is longer than that of meteorological drought. Soils in the region may even be sandy, evapotranspiration is basically stagnant, and changes in soil moisture will not affect precipitation (Gao, 2018). The feedback between land and air is weak. Soil drought is not sensitive to changes in meteorological drought, and high-intensity meteorological drought does not cause high-intensity soil drought. So, in the arid type drought propagation area, the intensity of meteorological drought propagation to soil drought is weak (DIP <0.9), and drought duration propagation is strong (DDP >1.1).

In the humid type drought propagation area, under extremely humid conditions, the land moisture in the wet area is sufficient, and the main factor determining the actual evaporation change is the energy available (Figure 6c). AET in the region is close to potential evapotranspiration (ET_0), precipitation is greater than AET, and some precipitation will supplement soil moisture (Dirmeyer et al., 2006; Gao, 2018; Muñoz-Sabater et al., 2021). Water in the soil can meet or exceed the requirements of surface evaporation and vegetation, soil moisture has no strong binding force on evapotranspiration, on the contrary, it may also be affected by evapotranspiration (Gao, 2018). The soil in the moist region will continue to be moist, and the duration of drought is shorter than that of a meteorological drought. The main land use types in this region are forest and construction land. The roots of plants are well developed, and they are more resistant to the change of dry-wet surface soil, which has a buffer effect on the occurrence of meteorological drought (Huang et al., 2015; Zhou et al., 2021a). The occurrence of meteorological drought does not necessarily cause soil drought, but once meteorological drought causes soil drought, the intensity of soil drought is large and the harm is high. So, in the humid type drought propagation area, the intensity of meteorological drought propagation to soil drought is strong (DIP <1.1) and drought duration propagation is weak (DDP <0.9).

The peer-to-peer type drought propagation area, 68% of which is concentrated in semiarid and dry subhumid (Figure 6b), which is also proved to be an area with strong land-atmosphere interaction (Dirmeyer, 2011; Gao, 2018; Hua et al., 2013; Wei et al., 2008). The reason is that, as mentioned above, in the arid type drought propagation area, evaporation is controlled by water conditions, and in the humid type drought propagation area, evaporation is limited by energy. Only when there is a peer-to-peer type drought propagation area, the soil moisture will reflect the control effect on evaporation because the land-atmosphere interaction effect further plays a role in regulating thermal conditions and affecting precipitation (Bellucci et al., 2015; Seneviratne et al., 2010). In these regional hotspots, soil moisture exerts control on the surface energy partitioning and hence on moist convection (Dirmeyer et al., 2006; Guo et al., 2006). Therefore, the influence of evaporation on the process of drought propagation in this region is not obvious. Precipitation is between AET and ET_0, and some precipitation will affect soil moisture. Through the land-atmosphere interaction, meteorological drought can directly affect soil drought and soil drought, in turn, can significantly affect meteorological drought. Both feedbacks are strong and direct. At the same time, the main land use in the region is grassland, which is further conducive to the process of drought propagation. So, in the peer-to-peer type drought propagation area, DIP and DDP are close to 1, and the propagation from meteorological drought to soil drought is peer-to-peer.

5. Conclusions

The propagation process of meteorological drought to soil drought plays an important role in the occurrence of drought. In this study, the DDP was constructed, and the propagation time was introduced into the calculation of the DIP and the DDP to further quantify the drought propagation process accurately and comprehensively. At the same time, according to the distribution characteristics of DDP and DIP, seven drought propagation partitions in China were divided and three main drought propagation partitions were named (arid type drought propagation area, peer-to-peer type drought propagation area, and humid type drought propagation area) according to their distribution relationship with climate region. We further concluded that 68% of regions with similar intensity and duration of meteorological drought and soil drought (peer-to-peer type drought propagation area) are concentrated in semiarid and dry subhumid, which is exactly the area with strong land-atmosphere interaction. Through the land-atmosphere interaction, meteorological drought can directly affect soil drought and soil drought, in turn, can significantly affect meteorological drought. Both feedbacks are strong and direct. At the same time, the main land use in the region is grassland, which is further conducive to the process of drought propagation.

We provide a new idea and attempt to clarify the drought propagation process. In future studies, more drought characteristics can be considered or multiple drought propagation indexes can be coupled together to better study the propagation process between droughts.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The data used in this study are publicly available. They are described in detail below. Precipitation and soil moisture data set use the ERA5-land reanalysis data set provided by European Centre for Medium-Range Weather Forecasts. The spatial resolution of 0.1 × 0.1° and the available period is 1981–2020 are publicly available at (https://cds.climate.copernicus.eu/cdsapp%23%21/dataset/reanalysis%2Dera5%2Dland%2Dmonthly%2D-means%3Ftab%3Dform). The MERIT Digital Elevation Models (DEM) are publicly available at (http://hydro.iis.u-tokyo.ac.Jp/~yamadai/MERIT_DEM/%20index.html). The ESACCI Global Land Cover products are publicly available at (https://www.esa-landcover-cci.org/). The Normalized Difference Vegetation Index (NDVI) data set are publicly available at (https://data.tpdc.ac.cn/en/data/9775f2b4-7370-4e5e-a537-3482c9a83d88/). The Actual Evapotranspiration (AET) data choose the average terrestrial evapotranspiration across China data set are publicly available at (http://data.tpdc.ac.cn/zh-hans/data/b6d9f525-5b76-48b0-82db-bb2963465cac/). The Frozen soil map of China (2000) data released by the National Qinghai-Tibet Plateau Data Center are publicly available at (http://data.tpdc.ac.cn/zh-hans/data/582234a6-4f57-4899-a37f-7Ad51bab63e8/).

Acknowledgments
This study was supported by the Natural Science Foundation of China (Nos. 51879009, 41875131, and 42171022), the Second Tibetan Plateau Scientific Expedition and Research Program (No.2019QZKK0405), and the National Key Research and Development Program of China (No. 2018YFE0196000).

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