Characteristics of water vapor sources and precipitation contributions to drought and wet events on the Chinese Loess Plateau

Rong Liu · Xin Wang · Zuoliang Wang · Rui Quan

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Abstract
In this paper, the standardized precipitation evapotranspiration index (SPEI) at the monthly scale was derived based on the ground observations to obtain different drought and wet events at the surface of the Loess Plateau in summer from 2000 to 2017. Using the National Centers for Environmental Prediction (NCEP) Final Analysis (FNL) data for the same period, backward simulations with the FLEXPART model were performed to obtain the water vapor transport characteristics and potential evaporative sources corresponding to different dry and wet events. Finally, the contribution of water vapor sources to precipitation on the Loess Plateau was obtained. The results show that the primary sources of water vapor on the Loess Plateau during dry and wet summer events are concentrated in the Loess Plateau and the Yunnan-Kweichow Plateau regions and sporadically distributed in the Altay region of Xinjiang, as well as at the junction of China, Kazakhstan and Mongolia. The evaporation extent and intensity in northern Xinjiang and Mongolia increase when the surface experiences wet-normal-dry events. The local internal circulation on the Loess Plateau contributes to 31.3% and 36.8% of the water vapor in drought and wet events, respectively. Influenced by the westerly wind belt and southwest monsoon, the precipitation contributions of the Yunnan-Kweichow Plateau are 11.2% and 13.1%, respectively, and those of Mongolia are 14.6% and 11.9%, respectively. The water vapor contributions from the Arabian Sea and Bay of Bengal in the south are insignificant. The results aid in understanding the mechanisms of drought and wet events on the Loess Plateau.

1 Introduction
China is an agricultural country that is also drought prone. It has been estimated that the annual food loss caused by drought accounts for 50% of the national food loss (Xu et al., 2022). The Loess Plateau, the second largest plateau in China, is a typical dryland agricultural region with frequent drought events. It is an essential part of China’s arid and semiarid regions, covering approximately 64 million ha and supporting approximately 100 million people (Lai et al., 2022). The average annual precipitation in the region is approximately 400 mm and provides critical value for ecological and crop maintenance and growth. Therefore, the ecological environment and agricultural production in this region are very sensitive to changes in precipitation.

This region is a typical climate change-sensitive zone and an ecologically and agriculturally vulnerable area. Understanding the water vapor transport and precipitation processes in such a unique area can provide scientific guidance for precipitation prediction and early warnings for local drought prevention and relief.

To better monitor and study drought, many researches have generally used available information such as temperature and precipitation to define drought indices, which are used to describe drought events, hence simplifying the complex drought phenomenon (Ault 2020). In past studies, the Palmer drought severity index (PDSI), standardized precipitation index (SPI), and standardized evapotranspiration index (SPEI) were widely used. The PDSI is based on the water balance principle, which integrates the effects of the water deficit and duration factors on drought events (Heim et al., 2002). However, the PDSI has some deficiency, such as the inability to accurately consider multiscale droughts due to fixed time scales, high computational complexity, and poor spatial comparability. Although many problems have been solved with the development of a self-calibrating PDSI, the fixed-time-scale
problem has not been properly addressed (Wells et al., 2004; Vicente-Serrano et al., 2011). In recent years, the concept that droughts can have multitemporal characteristics has been widely recognized. The SPI, a good solution for addressing the multitemporal scale of drought, is simple to calculate and can more accurately reflect drought trends. However, the SPI considers only precipitation factors and does not consider other factors that can affect drought (Chen and Sun, 2015). Based on the advantages and disadvantages of both indices, Vicente-Serrano et al. (2010) established the SPEI, which considers precipitation and evaporative processes. This index compensates for the shortcomings of the SPI, which does not consider temperature changes, and the PDSI, which does not consider multiple time scales. Therefore, the SPEI is an ideal indicator for current drought monitoring and research (Ault 2020; Wang et al., 2020).

The World Meteorological Organization (WMO) defines drought as a decrease in precipitation compared to the long-term average. Precipitation variability is an important determinant of drought events, while atmospheric circulation and water vapor transport are essential conditions for precipitation formation. The Loess Plateau is located in a transition zone from temperate semihumid to temperate semiarid and arid climate zones. Hence, atmospheric circulation and water vapor transport in this region are more complex and variable (Zhao et al. 2018a, b). Over the past half-century, the northern position of the monsoon edge has displayed a retreating southward trend, and the climate of the Loess Plateau has demonstrated a dramatic but consistent response (Zhang et al., 2019). By analyzing extreme rainfall events and atmospheric circulation indices, Zhao concluded that the possible reason for the decrease in rainfall on the Loess Plateau is the weakening of the East Asian summer monsoon, which prevented the rainfall belt from extending to northern China (Zhao et al. 2018a, b). Zhao et al. (2016) noted that all mechanisms of water vapor transport and the circulation structure on the Loess Plateau have a significant influence on changes in the north–south displacement pattern within the high-frequency area of heavy rainfall in eastern China. By analyzing the relationship between the Loess Plateau and different large-scale climate anomaly indices, Wang et al. (2019) concluded that El Niño-Southern Oscillation (ENSO) may influence summer precipitation on the Loess Plateau. In addition, it has been suggested that summer precipitation anomalies on the Loess Plateau are mainly associated with water vapor anomalies at the southern boundary (Chen and Huang, 2012), solar activity, El Niño intensity (Li et al., 2017), and remotely related wave trains originating from Western Europe (Orsolini et al., 2016). These studies have analyzed the causes of precipitation anomalies on the Loess Plateau from different perspectives and provided information for understanding the water cycle and land surface processes on the Loess Plateau. However, most of these studies were derived from the relationship between precipitation and reanalysis data and did not analyze the potential evaporative sources on the Loess Plateau or variations in precipitation contributions.

In recent years, Lagrangian methods have been increasingly used to study water vapor transport. The Flexible Particle Dispersion (FLEXPART) model based on the Lagrangian method can track the water vapor trajectory and identify the possible water vapor sources based on the water balance during transport, thus reducing numerical dissipation in the integration process. This model also considers convective and turbulent processes at small- and meso-scale, thereby reducing model error and improving the simulation accuracy (Sodemann et al., 2008). Hu et al. (2018) used FLEXPART to simulate the water vapor transport characteristics of the Loess Plateau over the last 30 years and concluded that east-central China, northwestern China, and eastern Central Asia are the primary sources of water vapor in the Loess Plateau region. The South and East China Sea contributes little to precipitation due to its distance from the plateau.

Due to the unique geological structure and topography of the Loess Plateau, soil erosion is severe, and the ecological outlook is not optimistic. The lives and properties of local people are seriously threatened by frequent droughts, hailstorms, locally heavy rainfall, flash floods, and mudslides. Currently, it is not common to link water vapor transport and drought events when assessing the sources of water vapor on the Loess Plateau and the contributions of different water vapor sources to precipitation on the Loess Plateau. Considering the capability of the Lagrangian method to simulate the backward trajectory of air masses and trace the relevant water vapor sources, water vapor transport is simulated based on the anomalous state of surface drought and wet conditions in summer on the Loess Plateau. The analysis focuses on the variability of different water vapor sources under different dry and wet events and their contributions to precipitation on the Loess Plateau. Through this study, we hope to understand the sources of precipitation that cause different dry and wet events from the perspective of water vapor transport and further understand the potential impact of water vapor transport differences on precipitation in the Loess Plateau region.

The remainder of the paper is organized as follows. The study area and data sets are briefly described in Sect. 2. The methodology is presented in Sect. 3. The results are summarized in Sect. 4. Finally, the discussion and conclusions are provided in Sects. 5 and 6.
2 Study area and materials

2.1 Study area

The Loess Plateau (100°52′～114°33′E, 33°41′～41°16′N) is located in the middle and upper reaches of the Yellow River (Fig. 1). The total area of this region is approximately 62.68 × 10 km²; it stretches from the Taihang Mountains in the east to the Sun Moon Mountains in the west and from the Qinling Mountains in the south to the Ordos Plateau in the north. The average annual temperature in the region is 2.2–15 ℃, and the annual precipitation totals 150–700 mm, with both temperature and precipitation gradually decreasing from southeast to northwest. The terrain is high in the northwest and low in the southeast, and the elevation is generally above 1000 m.

The soil on the Loess Plateau is mainly loess soil, with a general thickness of 50–300 m (Zhao et al. 2018a, b). The soil appears grayish-yellow, brownish-yellow, and brownish-red, with poor cohesiveness and weak resistance to wind erosion and water erosion. The unique geomorphological and climatic characteristics make it a very special region in the world.

2.2 Data sets

2.2.1 Observation data

The SPEI is based on monthly total precipitation and the monthly mean temperature. Therefore, the daily value dataset of Chinese terrestrial climate information (V3.0) provided by the National Meteorological Science Data Center (http://data.cma.cn/) is used in this paper. This dataset contains air pressure, air temperature, and precipitation data observed at Chinese meteorological stations since 1951. In this study, we mainly used the area-averaged daily mean temperature and 24-h cumulative precipitation data from the observed data at 67 stations on the Loess Plateau during the summer (June, July, and August) from 2000 to 2017 to calculate the SPEI. The accuracy of the daily average temperature data was 0.1 ℃. The accuracy of the 24-h cumulative
precipitation data was 0.2 mm. Before calculations were performed, the data outliers were removed, and the precipitation and temperature data were processed to the monthly scale.

2.2.2 Reanalysis of data

The National Centers for Environmental Prediction Final dataset from 2000 to 2017 was selected for the study. These data were used as the environmental inputs to drive the FLEXPART model for backward simulation. The data included wind, humidity, temperature, pressure, and boundary layer height, as well as information for other meteorological fields, with a spatial subscale of $1^\circ \times 1^\circ$ and a temporal resolution of 6 h. The data are available at 00:00, 06:00, 12:00, and 18:00 (UTC). There are 26 layers from 1000 to 10 hPa in the vertical direction, and the FNL data include five new layers at 1, 2, 3, 5, and 7 hPa in the vertical direction after 12:00 UTC on May 11, 2016.

3 Methodology

3.1 FLEXPART model and parameters

FLEXPART is a Lagrangian particle transport and diffusion model that was initially used to simulate the diffusion of pollutants and then later mainly applied to model gas exchange in the troposphere and stratosphere. Now, however, it is being increasingly applied for global and regional atmospheric water cycle analysis (Sun et al., 2014). The model can track the three-dimensional positions (latitude, longitude, and vertical height) of air masses and simulate atmospheric transport processes (Chen et al., 2012; Sun et al., 2018). The model has two modes, forward and backward, where the former is used to simulate the dispersion process of substances emitted from various emission sources and the latter is used to simulate the source of a substance in the study area and the transport process after emission from the source.

In this study, three simulations were conducted using the FLEXPART model to analyze drought events, wetting events, and normal conditions in the study area. The NCEP FNL data were used as inputs in all three simulations to drive the model. The time integration step of the model was set to 6 h. The vertical altitude range was set to 3000–16,000 m. The backward simulation time of the model was set to 10 days, i.e., backward tracking for 10 days from the particle release time, which is the average residence time of water vapor in the atmosphere (Trenberth, 1998). The model was run to output the 3D position of each air mass during the simulation, and the spatial interpolation of the reanalysis data was used to obtain certain physical information, such as the locations of potential vortices, specific humidity, and air density during the simulation (Liu et al. 2022a, b).

3.2 SPEI index

The SPEI developed to incorporate the advantages of both the SPI and PDSI (Vicente-Serrano et al., 2010). It integrates the effects of temperature and precipitation factors on drought and is therefore suitable for drought assessment in the context of global warming. The modeling method is as follows (Vicente-Serrano et al., 2010).

First, temperature-related evaporation is calculated.

$$\text{PET} = 16K \left( \frac{10^T}{T} \right)^m$$

(1)

where PET is potential evaporation, $T$ is the monthly average temperature, $I$ is the sum of the monthly heat index values $I$ for 12 months, and $I$ is calculated from the monthly average temperature with the formula shown in (2). Additionally, $m$ is a coefficient related to $I$ and calculated with the formula shown in (3), and $K$ is a correction function based on the latitude and month and determined with the formula shown in (4).

$$I = \left( \frac{T}{5} \right)^{1.514}$$

(2)

$$m = 6.75 \times 10^{-7}I^3 - 7.71 \times 10^{-5}I^2 + 1.79 \times 10^{-2}I + 0.492$$

(3)

$$K = \left( \frac{N}{12} \right) \left( \frac{NDM}{30} \right)$$

(4)

where NDM is the number of days in a month and $N$ is the maximum number of sunshine hours. After obtaining PET, the moisture deficit in month $i$ is calculated as follows.

$$D_i = P_i - \text{PET}_i$$

(5)

$D_i$ for different time scales $k$ is calculated as follows.

$$X_{ij}^k = \sum_{l=13-k+j}^{12} D_{l-1,j} + \sum_{l=1}^{j} D_{l,i} j < k$$

(6)

$$X_{ij}^k = \sum_{l=1}^{j} D_{l,i} j \geq k$$

(7)

where $i$ and $j$ represent the year and month, respectively. Next, a three-parameter log-logistic function is fitted to $X_{ij}^k$ with the following probability distribution function:

$$F(x) = \left[ 1 + \left( \frac{x - \mu}{\sigma} \right)^\beta \right]^{-1}$$

(8)

where $\alpha$, $\beta$, and $\gamma$ are the scale, shape, and position parameters, respectively.
P = 1 - F(x), and when \( P \leq 0.5 \), \( W = \sqrt{-2\ln(P)} \) and 

\[
\text{SPEI} = W - \frac{C_0 + C_1 W + C_2 W^2}{1 + d_1 W + d_2 W^2 + d_3 W^3}
\]  \hspace{1cm} (9)

When \( P > 0.5 \), \( W = \sqrt{-2\ln(1 - P)} \), and 

\[
\text{SPEI} = \frac{C_0 + C_1 W + C_2 W^2}{1 + d_1 W + d_2 W^2 + d_3 W^3} - W
\]  \hspace{1cm} (10)

The drought levels based on the SPEI are shown in Table 1 (Wu et al., 2011).

### 3.3 Method of water vapor source determination

In this study, the FLEXPART model is used to derive the regions responsible for moisture changes in air particles. These regions are determined by their specific humidity during air mass movement. First, it is assumed that the moisture variation during air mass movement is caused by precipitation from the air mass and evaporation from the surface. Surface evaporation causes an increase in moisture, and precipitation from an air mass causes a decrease in moisture. Thus, for a particle, the moisture balance is

\[
e - p = m \frac{\Delta q}{\Delta t}
\]  \hspace{1cm} (11)

where \( e \) is the moisture that evaporated from the surface into the air mass per unit time \( \Delta t \), \( p \) is the moisture lost from the air mass due to precipitation per unit time \( \Delta t \), and \( \Delta q \) is the change in specific humidity. It is also assumed that the three-dimensional atmosphere of a region in area \( A \) consists of \( N \) uniform air blocks, and the average moisture balance equation for the whole region can be derived from Eq. (11) as follows:

\[
E - P = \frac{\sum_{i=1}^{N} m_i \Delta q_i}{A}
\]  \hspace{1cm} (12)

### Table 1 Classification of drought levels corresponding to the SPEI

| Drought level       | SPEI          |
|---------------------|---------------|
| Extremely wet       | \( \text{SPEI} \geq 2 \) |
| Severely wet        | \( 1.5 < \text{SPEI} < 2 \) |
| Moderately wet      | \( 1 < \text{SPEI} \leq 1.5 \) |
| Mildly wet          | \( 0.5 < \text{SPEI} \leq 1 \) |
| Normal              | \( -0.5 < \text{SPEI} \leq 0.5 \) |
| Mildly drought      | \( -1 < \text{SPEI} \leq -0.5 \) |
| Moderately drought  | \( -1.5 < \text{SPEI} \leq -1 \) |
| Severely drought    | \( -2 < \text{SPEI} \leq -1.5 \) |
| Extremely drought   | \( \text{SPEI} \leq -2 \) |

where \( E \) and \( P \) are the surface evaporation and precipitation from the air mass, respectively. The resulting value is generally accurate when the value of \( N \) is sufficiently large. According to Eq. (12), the change in water content in an air mass is assessed based on the change in specific humidity during the movement of the air mass to determine whether the area is a moisture source. In other words, a positive or negative value of \( E - P \) is used to determine whether the area is a source of water vapor. When \( E - P \) is positive, the surface evaporation in the area is less than the precipitation from the air mass, and the surface is a source of water vapor. When \( E - P \) is negative, the surface evaporation in the area is larger than the precipitation from the air mass, and the surface is a sink of water vapor. Therefore, the strength of a moisture source or sink can be determined according to the magnitude of \( E - P \). An advantage of the algorithm is its concise method for calculating the atmospheric moisture budget without considering the role of convergence.

### 3.4 Method of precipitation contribution determination

When calculating the precipitation contributions of water vapor sources to the study area, the \( E - P \) of a source cannot be simply cumulatively determined. Particles undergo multiple evaporative and precipitation processes before being transported to the study area and are obstructed by topography. Therefore, the water vapor transported to the study area cannot be simply considered the sum of water vapor obtained from previous evaporation processes. The variations in water vapor during the transport process should be considered (Sun and Wang, 2014). Particles are first replenished by the evaporation of water vapor from a given water vapor source and then experience multiple evaporative and precipitation processes during the subsequent transport process, resulting in changes in the water vapor content. To address this problem, Sodemann et al. (2008) proposed a method that considers evaporative and precipitation processes along the particle trajectory and can be used to calculate the contribution of each particle along its trajectory to the study area. However, this method is only suitable for tracking multiple point sources of water vapor at a point location. It is not suitable for a source on a plane because it does not accurately distinguish between evaporation inside and outside a source area, which can lead to the misestimation of the water vapor contributions of different sources.

Sun and Wang (2014) improved this method by determining the amount of precipitation (\( R_{\text{total}} \)) associated with all particles within the study area based on the identification of water vapor sources and then backward tracing the trajectories of these precipitation-producing particles. The specific humidity (\( \Delta q \)) of particles associated with a water vapor source at an initial time (forward in time) is determined, and
then $\Delta q$ is iteratively determined in three cases: inside the water vapor source, inside the study area, and outside the water vapor source and study area. Finally, the contribution of a water vapor source $C$ is

$$C = \Delta q (\Delta p / q)$$

(13)

where $\Delta p$ is the difference in precipitation in the study area. The contribution of total precipitation $C_p$ in the study area is

$$C_p = C / R_{total}$$

(14)

4 Results

4.1 Drought characteristics

The main objectives of this study involve analyzing water vapor transport and water vapor sources. Meteorological drought events triggered by short-term precipitation deficits are most closely related to the SPEI. Therefore, the time series of monthly scale SPEI from 2000 to 2017 were plotted to show the evolutionary characteristics of drought and wet events (Fig. 2). Drought (wet) events were also identified based on SPEI values (Table 1).

When the SPEI value drops below 0 (increased above 0), the month is counted in the event cycle. Subsequent values of $-1$ or less than $-1$ (subsequent values of 1 or greater) denote the beginning of drought (wet) events. An event ends when the SPEI value returns a positive value (negative value). In addition, wet and drought events are evaluated based on the following criteria: the sum of the absolute values of the SPEI during an event represents the event severity, and the severity to duration ratio is the event intensity.

Figure 2 shows the SPEI time series at the monthly scale from 2000 to 2017, where negative values represent drought events and positive values represent wet events with 12 values per year (the horizontal coordinates in the figure represent SPEI-12). Drought and wet events frequently varied, with irregular oscillatory patterns. The highest frequency of drought events was 38% during the study period, and the frequencies of wet events and normal states were 28% and 34%, respectively. The frequencies of extreme, severe, moderate, and mild drought events were 2.3%, 6.5%, 14.8%, and 13.9%, respectively. In contrast, the frequencies of extreme, severe, and moderate wet events were 1.4%, 6.5%, and 6.9%, respectively. Among them, the frequency of extreme drought events was higher than that of extreme wet events, the frequencies of severe drought and severe wet events were equal, and the frequency of moderate drought events was higher than that of moderate wet events. Figure 3 shows that 81 drought events occurred during the study period, and the drought event with the highest intensity was in the summer of 2005, with a severity of 2.78. A total of 60 wet events occurred, of which the longest duration was eight months, from April to November 2003, with a severity of 6.78.

To analyze the information related to drought and wet events in summer, we analyzed the intensity of drought events in June, July, and August from 2000 to 2017 based on...
on the SPEI (Fig. 4). It was concluded that the most intense wet events occurred in the summer of 2003, and the most intense drought events occurred in the summers of 2005 and 2015. Considering that this study focuses on analyzing the differences in moisture sources and precipitation contributions between drought and wet events, we used summer 2003 and summer 2005 as study periods to investigate the corresponding wet and drought events, respectively. The summer of 2004 was selected as the normal state. These selections facilitate our analysis of the variations in water vapor sources and precipitation contributions over successive periods.

4.2 Water vapor pathways

To analyze the relationship between changes in water vapor transport and changes in wet and drought events, backward trajectory simulations of water vapor under different wet and drought event conditions on the Loess Plateau were performed using the FLEXPART model. The backward clustering trajectory simulations of air particles reaching the Loess Plateau (with a cluster number of 50) were conducted by selecting the summers of 2003, 2004, and 2005 as different periods of wet, normal, and drought events.

Figure 5 shows the clustering trajectories and their specific humidity variations in the three periods. In the figure, a, b, and c indicate wet, normal, and drought events, respectively. The small black box on each trajectory represents the starting point of the water vapor transport trajectory, the black circle represents the end point of water vapor transport, and the color change of the lines represents the specific humidity variation during water vapor transport. A change in specific humidity larger than zero (warm color) indicates water vapor replenishment, and a value less than zero (dark color) indicates water vapor loss. Since the water vapor content varies with latitude, longitude, and elevation, the dense trajectories in Fig. 5 do not represent intense water vapor transport. To better understand the differences between wet and drought events, we define 50 clusters, which means that there are only 50 paths in Fig. 5. These 50 paths are the most concentrated paths of particle motion. In addition to these 50 paths, there are other paths. However, for clarity, we do not show or analyze those paths in the figure.

Since the summers are consecutive, the paths of water vapor transport do not vary much among the three periods. The western branch is mainly from the central and northern US, the mid-latitude sea area of the North Atlantic, northern Africa, and central Eurasia. The northern branch mainly comes from the western Siberian plains and the southern part of the Central Siberian Plateau. The southern branch comes mainly from the northern Arabian Sea, the Indian Peninsula, the northern part of the South-Central Peninsula, and the northwestern part of Saipan.

The specific differences are related to the air masses during wet events (Fig. 5a), with paths that display a relatively westerly starting point. There are five paths in the northern US, one of which comes from the Pacific Ocean in the western part of the North American continent and crosses the entire North American continent, the Atlantic Ocean, northern Africa, and Eurasia from mid-latitude 130°W to the Loess Plateau region of China near 110°E. Compared to the normal state (5b) and the drought event case (5c), the air mass is more replenished during wet event movement. With the junction of northern Africa and Eurasia as the dividing line, water vapor changes from a state of loss to one of evaporation compensation. This transport path is warmer in

Fig. 4  Drought event intensity in summer (June–August) from 2000 to 2017 (the blue dashed rectangle is the event that was selected)
color between Eurasia and the Loess Plateau. At the time of a drought event (5c), the starting points of the air masses are more concentrated in the mid-latitudes of the Atlantic Ocean and the northern part of the African continent. In addition, there are fewer air blocks from the Indian Peninsula than in the other two states. During drought events, air masses are more concentrated in the Bay of Bengal and the South-Central Peninsula area, and new masses emerge from the vicinity of the South China Sea. The air masses from the northern branch are less abundant than those in the other two
states, and the water vapor is replenished during air mass movement. Air masses from the northern branch are most abundant during wet events, and the number of air masses during the normal and drought states is approximately equal.

The study area is located at the intersection of the East Asian summer monsoon margin and the Qinghai-Tibet Plateau, an area influenced by both westerly winds and monsoons. By comparing the water vapor transport paths in the three periods, this work finds that the water vapor transport is most visible in the latitudinal direction, which indicates that the Loess Plateau is more influenced by the westerly wind belt than the monsoon. The westerly winds and south-west monsoon are the strongest during wet events. During drought events, the air parcels carrying water vapor from the Arabian Sea and the Bay of Bengal weaken under the influence of the south-western monsoon, thus reducing the north–south water vapor transport.

4.3 Water vapor sources

Although the particle trajectory (Fig. 5) represents the path of an air mass in the study area during the target time period and the variation in specific humidity during particle motion, it does not give an accurate quantitative representation of the corresponding water vapor source. Therefore, the distribution and intensity of potential sources of water vapor evaporation in different periods are obtained according to the Sect. 3.3.

Figure 6 is a map of the sources of water vapor in the Loess Plateau during summer for wet events (a), normal conditions (b), and drought events (c). In red areas, i.e., the areas that contribute to precipitation on the Loess Plateau, evaporation is greater than precipitation during air mass movement. In blue areas, evaporation is less than precipitation during the motion of the air mass, indicating a loss of water vapor during particle motion, which eventually becomes precipitation that falls to the land surface. Similar to the water vapor transport paths, the water vapor source areas do not differ significantly in the three periods because the study period spans three consecutive years. However, there are differences in the intensity and extent of sources.

The potential evaporation sources in the three periods are mainly concentrated in central China, including in the Alashan Plateau, Loop Plain, Loess Plateau, Qinling Mountain and Sichuan Basin regions, as well as on the eastern side of the Yunnan-Kweichow Plateau. The most vital evaporation sources are concentrated in the Loess Plateau and Loop Plain regions. From the perspective of the extent of sources, only sporadic sites occur in northern Xinjiang, and no sites occur in Mongolia during wet events. However, for normal and drought events, potential evaporation source sites occur in northern Xinjiang and central and southern Mongolia; hence, the source area for drought events is larger than that for wet events. This finding indicates that the extent and intensity of the corresponding source sites of water vapor transport in northern Xinjiang and Mongolia gradually increase when the surface experiences wet-normal-drought conditions. During the wet-normal-drought evolution, a more pronounced evaporation process exists at the border between Kazakhstan and Xinjiang. For drought events, northern Pakistan is newly added as an evaporation source, indicating that this region contributes water vapor to the Loess Plateau. During wet events, the largest area of evaporation source is found on the North China Plain in eastern China, especially in the Shandong Peninsula region. Evaporation intensity is strongest in the Alashan Plateau, Loop Plain, Loess Plateau and Shandong Peninsula areas during wet events and in central and southern Mongolia during drought periods. In all three periods, the evaporation intensity in northern Xinjiang is much greater than that on the Tibetan Plateau.

It is worth noting that the water vapor sources in the western part of the southern foothills of the Himalayas, the Arabian Sea, and the Bay of Bengal are not apparent for the three events. By combining the trajectories of particles in Fig. 5, it can be concluded that although there are air masses released in these regions, the air masses are obstructed by the height of the Himalayas and do not reach the Loess Plateau. This phenomenon again demonstrates that the water vapor on the Loess Plateau in summer is influenced most by the westerly wind.

4.4 Precipitation contribution

Water vapor is involved in several precipitation and evaporation processes from a source to the study area, resulting in changes in moisture content. In particular, the study area is in the northeastern part of the Tibetan Plateau, and the unique topography of the Tibetan Plateau complicates water vapor transport. Therefore, to estimate the precipitation contribution of different water vapor sources during drought and wet events, the representative water vapor sources were divided into eight regions, as shown in Fig. 7. The eight regions are not named strictly according to their areas but are mainly based on location. These regions are the Loess Plateau region (33.68–41.27°N), the northern Tibetan Plateau region (33.68–41.27°N, 65–100.86°E), the southern Tibetan Plateau region (25–33.68°N, 65–100.86°E), the Yunnan-Kweichow Plateau region (25–33.68°N, 100.86–114.55°E), the Arabian Sea region (7–25°N, 45–80°E), the Bay of Bengal region (7–25°N, 45–80°E), and the Mongolia region (41.27–60°N, 65–125°E).

Figure 8 shows the contributions of water vapor from different sources to summer precipitation on the Loess Plateau for three types of events (in sequence, wet, normal, and drought events). The local water vapor internal circulation
on the Loess Plateau contributes the most water vapor in all three periods, with precipitation contributions of 36.8%, 33.4%, and 31.3%, respectively. The same conclusion can be found by assessing the data in Fig. 6, which shows that the intensity of the internal circulation of water vapor on the Loess Plateau decreases sequentially in the three periods. However, this region still displays the greatest contribution compared to other source areas. The Arabian Sea contributes the least amount of precipitation in all three periods, with values less than 1%, 0.48%, 0.22%, and 0.43%, respectively. The same conclusion can be drawn by referencing Fig. 6, which demonstrates that the Arabian Sea is not an important source of evapotranspiration in the three events, with a minimal contribution.

As Fig. 6 shows that the evaporation intensity in Mongolia and the northern Xinjiang region during drought events is much stronger than that during the other two types of events. Hence, in Fig. 8 precipitation contributes the most during drought events, with a contribution of 14.6%. In contrast, the contributions of precipitation during normal and wet events are 13% and 11%, respectively. Because the westerly wind is more powerful during wet events than during other events, the meridional transport of water vapor over the Tibetan Plateau is stronger than north–south transport. The water vapor over the southern part of the Tibetan Plateau mainly comes from the Arabian Sea and the Bay of Bengal. The ocean is comparatively farther away from the Loess Plateau, the transport journey is topographically complex, and several evaporation-precipitation processes occur. Therefore, the northern part of the Qinghai-Tibet Plateau contributes more water vapor than the southern part during the three types of events.

The contributions of precipitation in the northern part of the Tibetan Plateau during the three types of events are 8.01%, 9.37%, and 9.72%, respectively. The contribution from the northern part of the Qinghai-Tibet Plateau is more prominent in wet events than in drought events, with contributions of 5.11% and 4.45%, respectively. In addition, the YKP region, where the Sichuan Basin and the eastern edge of the Yunnan-Kweichow Plateau are located, contributes 13.05%, 13.90%, and 11.21% to precipitation in the different events, respectively. The same conclusion can be drawn from Fig. 6; notably, the YKP has a more significant and broader evaporation intensity than the other regions. The contribution of the EC region, where the North China Plain is located, does not differ much in the three periods, with values of 2.76%, 3.33%, and 3.31%, respectively. This result is likely because the Loess Plateau is in inland China, far from the Pacific Ocean. Most air masses with water vapor from the Pacific Ocean become rain in southern and eastern China; therefore, less water vapor can reach the Loess Plateau.

5 Discussion

Many studies have conducted work on water vapor transport, but most of the works have focused on precipitation anomalies (Makarieva et al., 2013; Liu et al. 2022a, b). Therefore, this paper does not focus on the specific precipitation events, it extracts the drought and wet events based on drought index data instead. The water vapor transport characteristics are simulated for different events to analyze the evolution of drought and wet events from the perspective of moisture transport. This is the difference between this work and that of other researchers.

This study shows that there are differences in water vapor transport to the Loess Plateau in different periods, but the observed differences are smaller than those reported by other scholars who analyzed water vapor transport to the Loess Plateau based on precipitation anomalies. This work suggests that the eastern ocean does not contribute significant water vapor from the perspective of dry and wet events. Notably, this study clustered the 50 most obvious water vapor transport routes, which supported this result. Additionally, because the Loess Plateau is located in a typical arid and semiarid region, water vapor reaches the surface in the form of precipitation and then evaporates through vegetation and the soil before a drought or wet soil state is reached. There is a time lag between the precipitation process and a dry or wet soil state. The monthly SPEI is the most closely related to atmospheric water vapor transport, and sensitive to the atmospheric water vapor transport. This index is calculated based on precipitation and evaporation, so the analysis from the perspective of wet and drought events encompasses the connection between the surface and the atmosphere.

Compared with traditional research methods, such as water vapor flux analysis and the Eulerian model, the Lagrangian model is used in this paper to simulate water vapor transport; it can clearly show the water vapor transport trajectories and potential water vapor sources. However, the main drawback of this method is that evaporation and precipitation cannot be separated. In the simulation of water vapor transport, precipitation and evaporation are considered together. The variation in specific humidity determines the values of precipitation and evaporation, which can lead to inaccurate results. The results can be improved in the future by combining this proposed approach with observations. In addition, NCEP FNL data are used to drive the model, with some data uncertainty in the Loess Plateau region. Thus, the model simulation results and the actual conditions may
differ to some extent. Therefore, different numerical models should be used in follow-up work to combine different data types, and comprehensive analyses can be conducted with the actual observations.

6 Conclusion

In this paper, we focus on the variations in water vapor sources and precipitation contributions in the Loess Plateau region from the perspective of different drought and wet events. The following conclusions are obtained.

(1) There are differences in water vapor sources during summer wet, normal, and drought events on the Loess Plateau surface. The sources with the most vital evaporation capacities for all three events are concentrated on the Loess Plateau and the Loop Plain. The evaporation intensity in northern Xinjiang and Mongolia is weaker during wet events and stronger during drought events. Northern Pakistan is the source of evaporation during drought events, although it disappears as a source during wet events. The evaporation intensity is higher in the Alashan Plateau, Loop Plain, Loess Plateau, and Shandong Peninsula areas during wet events than during drought events. For the three types of events, the evaporation intensity in northern Xinjiang is much greater than that on the Qinghai-Tibet Plateau.

(2) The precipitation contribution of the Loess Plateau depends mainly on water vapor transport from inland China. Most of the contribution on the Loess Plateau is from internal water vapor circulation, and the Arabian Peninsula makes essentially no precipitation contribution. The northern part of the Qinghai-Tibet Plateau contributes more water vapor than the southern part. The precipitation contribution of the EA region is unchanged in the three periods.

Author contribution Rong Liu: conceptualization, funding acquisition writing-original draft, writing-review. Xin Wang: data curation, formal analysis, project administration. Zuoliang Wang: methodology, resources, validation. Rui Quan: resources.
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Data availability For download of the model, please link to https://www.flexpart.eu/

“Daily Data Set of Surface Climate in China (V3.0)” provided by the National Meteorological Data Service Center (http://data.cma.cn/).

Code availability Will be available on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

Ethics approval No ethical issues involved. No ethics committee approval was required for this paper.

Consent to participate The authors declare that they have consent to participate.

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