Tracing anomalies in moisture recycling and transport to two record-breaking droughts over the Mid-to-Lower Reaches of the Yangtze River

Yansong Guan[1], Xihui Gu[2,3,4,5,6,7*], Louise J. Slater[5], Lingfeng Li[2], Dongdong Kong[2,4], Jianyu Liu[8], Xiang Zhang[3], Xuesong Yan[1*]

1. School of Computer Science, China University of Geosciences, Wuhan 430074, China;
2. Department of Atmospheric Science, School of Environmental Studies, China University of Geosciences, Wuhan 430074, China;
3. National Engineering Research Center of Geographic Information System, School of Geography and Information Engineering, China University of Geosciences, Wuhan 430074, China;
4. Centre for severe weather and climate and hydro-geological hazards, Wuhan 430074, China
5. School of Geography and the Environment, University of Oxford, Oxford OX1 3QY, UK;
6. Collaborative Innovation Center for Western Ecological Safety, Lanzhou University, Lanzhou 730000, China;
7. State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, CAS, Xi'an 710061, China;
8. Hubei Key Laboratory of Critical Zone Evolution, School of Geography and Information Engineering, China University of Geosciences, Wuhan 430074, China.

*Corresponding authors: Xihui Gu (guxh@cug.edu.cn) and Xuesong Yan (yanxs@cug.edu.cn)

Abstract: The influence of moisture recycling and transport on major drought events is poorly understood, but essential to enhance our knowledge of the atmospheric water cycle. Here, we investigate this for two record-breaking droughts over the Mid-to-Lower Reaches of the Yangtze River (MLRYR), the winter-spring (WS) drought of 2011 and summer-autumn (SA) drought of 2019. Using a land-atmosphere water balance framework, we find the precipitation recycling ratio (the percentage of precipitation in a region derived from the same region's evaporation) increased during both droughts, especially for the SA drought (from 14.5% to 22.9%). The WS drought was characterized by a 27.8% reduction in external advected moisture, originating principally from the northeast China and Bohai Sea (reduced by 22.3%) and from the northwest Pacific and South China Sea (25.7%). The SA drought was driven by a 43.8% reduction in external advected moisture, originating mainly from a southwesterly path, i.e. the Bay of Bengal and the South China Sea (reduced by 26.8%). From a regional viewpoint, moisture transportation from the Pacific Ocean (and South China Sea) decreased during the WS (SA) droughts, mainly resulting in moisture deficit over the MLRYR. Analyses reveal that this reduction was driven by strong negative convergence, which was unfavorable for precipitation formation and enhanced air flow out of the MLRYR. The weakened moisture transport was principally driven by seasonal mean flow rather than transient eddies. Changes in wind (i.e. dynamic processes), rather than specific humidity (i.e. thermodynamic processes) were dominant in regulating the seasonal mean moisture transport. Our study helps understand the atmospheric water cycle anomalies driving extreme drought events, and advances knowledge on moisture transportation and its controlling processes.

Keywords: Record-breaking droughts; Moisture recycling; Moisture transport; Dynamic and thermodynamic processes; MLRYR

Highlights:

- The atmospheric water cycle behind two droughts is quantified based on the land-atmosphere water balance;
- Moisture sources, pathways and transport are tracked for both droughts by using the HYSPLIT model;
- The controls of moisture transportation during the two droughts are identified and quantified.

1. Introduction

The Mid-to-Lower Reaches of the Yangtze River (MLRYR; see Fig. 1a and b) are one of the most developed and densely populated regions in China. Droughts in the MLRYR cause serious social and economic losses (Gu et al., 2019a, 2019b, 2019c; Li et al., 2020; Zhang et al., 2017, 2019). In the last decade, this region suffered two record-breaking drought events (Jin et al., 2013; Ma et al., 2020; Sun and Yang, 2012; Wang and Yuan, 2021; Xu et al., 2020): one in the winter-spring season (i.e. January-May) of the year 2011 (WS drought for short) and the other in the summer-autumn (i.e. July-November) season of the year 2019 (SA drought for short). The WS drought destroyed crops over more than 98.9 million hectares and led to water shortages for more than 4.9 million people and 3.4 million livestock (Sun and Yang, 2012). The SA drought affected more than 2.4 million hectares of crops, with direct economic losses exceeding 15.1 billion Chinese yuan (Wang and Yuan, 2021).

Given the severe socio-economic impacts of these two droughts, previous studies have paid much attention to their generation mechanisms, such as large-scale circulation patterns (Sun and Yang, 2012), sea surface temperature (SST) anomalies (Jin et al., 2013; Xu et al., 2020), and anthropogenic climate change (Ma et al., 2020;

Wang and Yuan, 2021). Precipitation in the winter-spring/summer-autumn season over the MLRYR is significantly impacted by the East Asian winter/summer monsoon (EAWM/EASM; Chen et al., 2015; Ding and Chan, 2005; Huang et al., 2012; Zhou, 2011; Zhou and Wu, 2010). A La Nina winter usually witnesses a strong EAWM, resulting in decreased winter-spring precipitation over eastern China (Yang et al., 2002; Zhang and Sumi, 2002). Sun and Yang (2012) indicated that the La Nina event in 2010-2011 played an important role in the decrease of wet-warm moisture translation from the tropical oceans to southern China, resulting in the WA drought. Jin et al. (2013) further pointed out that the quasi-stationary Rossby wave–related teleconnection combined with persistent anomalous thermal forcing over the Maritime Continent led to a divergence of water vapor from the MLRYR into tropical oceans during the WA drought. For the SA drought, the decreased moisture transport from the South China Sea was associated with a strong El Nino event in the central Pacific (Ma et al., 2020), and the large-scale circulation anomalies associated with this El Nino event explained 60% of its intensity (Xu et al., 2020). The other 40 percent could be explained by the positive Indian Ocean Dipole event via a teleconnection linkage (Xu et al., 2020).

Although the above studies characterized water vapor flux anomalies during the two droughts, there is still limited understanding of their moisture supply, i.e. remote moisture fluxes and local evaporation. Quantifying moisture transport and precipitation recycling (i.e. the percentage of precipitation in a region derived from the same region's evaporation; Zhao and Zhou, 2021) is essential for understanding the atmospheric water cycle and forecasting the severity of extreme events such as droughts (Findell and Eltahir, 2003; Roy et al., 2019). Both hydrological and meteorological approaches can be used to track the moisture supply quantitatively (Brubaker et al., 1993; Eltahir and Bras, 1996; Guo et al., 2018). From a hydrological viewpoint, the water cycle processes over a region involve external moisture advection, local evaporation, precipitation, moisture outflow, and land water availability (i.e. runoff and terrestrial water storage fluctuations) (Eltahir and Bras, 1996; Guo et al., 2018; Li et al., 2019; Zhao and Zhou, 2021). Hydrological assessments of moisture supply tend to focus on the sources governing a region's precipitation (i.e. advected moisture and local evaporation). For example, Guo et al. (2018) employed the Bulk model (Brubaker et al., 1993; Curio et al., 2015) to separate the contributions of advected moisture and local evaporation to mean precipitation and its variability over southeast China, and found that they were dominated by the moisture flux. Curio et al. (2015) indicated that precipitation from local evaporation accounted for around 60% of local total precipitation over the Tibetan Plateau.

In contrast, meteorological assessments of moisture supply tend to focus more on moisture pathways and transport processes. Several moisture tracking models have been developed to depict moisture trajectories in time, such as FLEXPART (Sun and Wang, 2014), Hybrid-Single Particle Lagrangian Integrated Trajectory (HYSPLIT; Chu et al., 2017), the Water Accounting Model (Van der Ent et al., 2013), and the Dynamical Recycling model (Cheng and Lu, 2020). Each of these models has its strengths and weaknesses. For example, the HYSPLIT model is based on the Lagrangian approach and can analyze multiple moisture trajectories in space and time (Stein et al., 2015), while the Water Accounting Model is based on the Eulerian model and can track the evaporative source backward for all precipitation (Zhang, 2020). Despite these differences, all these moisture tracking models have an ability to track moisture sources and pathways. Cheng and Lu (2020) found that terrestrial evaporation plays an equal or even competitive role to warm-season precipitation in some EASM land regions by using the Dynamical Recycling model to investigate moisture sources. Hao et al. (2020) used the HYSPLIT model to track the precipitation sources during the rainy season in Southwest China, and found that moisture from the Bay of Bengal (South China Sea) contributes the most to precipitation in Yunnan (Guangxi). Besides tracking the moisture transport, some studies further decomposed it into dynamic and thermodynamic processes (i.e. wind and specific humidity changes, respectively) (Li et al., 2013; Roxy et al., 2017; C Zhang et al., 2017). Zhang et al. (2017) found that decreasing July-September precipitation in Southwest China can be attributed to weakening moisture transport from the extended west region, which is dominated by dynamic processes.

These hydrological and meteorological methods are usually used to quantify the influence of atmospheric moisture supply on the variability of precipitation over a region (Cheng and Lu, 2020; Chu et al., 2017; Gao et al., 2014; C. Zhang et al., 2019; Chi Zhang et al., 2017; Zhao and Zhou, 2021). Although some studies extended these methods to quantify moisture origins and transport processes for extreme climatic events (Roxy et al., 2017; Sun and Wang, 2013; Zhang et al., 2021; Zhao et al., 2016), almost all these studies focused on heavy precipitation events, such as the 2020 Yangtze River record-breaking precipitation (Zhang et al., 2021), widespread snowfall in northeastern China (Sun and Wang, 2013), or regional extreme precipitation in central India (Roxy et al., 2017). Only few studies have linked moisture recycling and transport to droughts: Roy et al. (2019) used the Dynamical Recycling model to investigate the role of moisture transport in two drought events in the United States. Zhang (2020) employed the Water Accounting Model to identify the moisture source anomalies dominating two extreme droughts in Southwest China.

Here, we employ both the hydrological and meteorological approaches to investigate the role of moisture recycling, sources, and transport in two record-breaking droughts over the MLRYR. We aim to fill knowledge gaps concerning the moisture supply of the two droughts by addressing the following questions:

- What were the roles of remotely transported and locally evaporated moisture anomalies during the two droughts?
- Which moisture sources and transport processes contributed to the two droughts?
- Were the moisture transport anomalies dominated by dynamic (i.e. wind) or thermodynamic (specific humidity) processes?

2. Study region and data

The MLRYR mainly convers the provinces of Hubei, Hunan, Jiangxi, Anhui, Jiangsu, Zhejiang, and Shanghai city. The gross domestic product and population in these six provinces and one city in the year 2020 accounted for 31.2% and 24.3% of the total in China, respectively. Rain-fed agriculture in the MLRYR is essential for food security, with several plains producing the majority of commodity grain, such as the Jianghan plain. Streamflow in the MLRYR is extracted for local water needs, but 8.9 billion m^3 is also diverted to the Henan and Hebei provinces and to Tianjin and Beijing cities through the middle route of the South-to-North Water Diversion Project in 2020 (Ministry of Water Resources of the People's Republic of China, http://www.mwr.gov.cn/xw/sjzs/202111/t20211108_1550510.html). Annual mean air temperature over the MLRYR is around 14℃~18℃, and precipitation fluctuates substantially, with annual totals of 1000~1500 mm. The uneven spatio-temporal distribution and temporal variability of precipitation lead to a high risk of drought in the MLRYR. During the past six decades, extreme droughts have occurred during the summer-autumn season in the years 1966, 1967, 1978, 2001, 2003 and 2019 and during the winter-spring season in the years 1973, 1979, and 2011 (Qian et al., 2011). The 2011 WS drought and the 2019 SA drought were the most severe and intense of these events.

Gridded daily precipitation observations with a 0.5° spatial resolution during the period of 1961-2021 were obtained from the China Meteorological Data Service Centre. This gridded dataset is produced by using a thin-plate spline method to interpolate precipitation values at 2472 stations, and its quality has been evaluated by previous studies (Zhao et al., 2019). Monthly terrestrial water storage anomalies (TWS; units: cm) with a 0.5° resolution during the period of 1979-2019 are reconstructed based on satellite observations by using machine learning methods (Li et al., 2021). The quality of this dataset has been evaluated and is considered to be more reliable than other products (Li et al., 2021).

Hourly meridional and zonal winds (units: m/s), specific humidity (units: kg/kg), surface pressure (units: Pa), total precipitation (m), evaporation (m), vertically integrated moisture divergence (units: kg/m^2), vertical integral of northward water vapor flux (units: kg/(m·s)), and vertical integral of eastward water vapor flux (units: kg/(m·s)) were obtained from the ERA5 reanalysis data. These variables have a spatial resolution of 0.25° and cover the period 1961-2019. We aggregated the hourly values into daily ones.

Six-hourly surface pressure (units: Pa), 2-m air temperature (units: K), 10-m wind field (units: m/s), and precipitation (units: $kg/m^2/s$) data, as well as six-hourly geopotential height (units: m), air temperature (units: K), meridional and zonal winds (units: m/s), vertical velocity (units: Pa/s), and specific humidity (units: kg/kg) at 17 levels from the surface to top of the atmosphere (i.e. 1000 hPa-10 hPa), during the period of 1961-2019 are sourced from the National Centers for Environmental

Prediction- National Center for Atmospheric Research (NCEP-NCAR). The National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory (ARL) has processed them as the HYSPLIT model inputs to track moisture sources and pathways.

3. Model and methods

3.1 Land-atmosphere water balance

On a region over land, the water balance equation is:

$$P - E = R + CMS \quad (1)$$

where P is precipitation (units: mm), E is evaporation (units: mm), R is runoff (units: mm), and CMS is the change of land moisture storage (units: mm). Brubaker et al. (1993) proposed a conceptual model of the atmospheric vapor fluxes over a land region. In this conceptual model, precipitation originates from external advected moisture (F_{in}) and local evaporation (E). The external moisture and local evaporation are assumed to be well-mixed in the atmosphere (Burde and Zangvil, 2001), and partly fall as precipitation (P), while the remainder is transported out the region (F_{out}). This means precipitation consists of an advective component (P_a; the remaining advected moisture flows out of this region, i.e. F_{out-a}) and an evaporative component (P_e; the remaining evaporation flows out of this region, i.e. F_{out-e}). Based on this atmospheric moisture budget (see Fig. 3), any changes in vertically integrated vapor moisture for a unit area are equal to (Guo et al., 2018; Zhao and Zhou, 2021):

$$\frac{\partial F}{\partial t} = -\left(\frac{\partial F_u}{\partial x} + \frac{\partial F_v}{\partial y}\right) + E - P \quad (2)$$

where F is the vertically integrated vapor moisture (units: mm), and $\left(\frac{\partial F_u}{\partial x} + \frac{\partial F_v}{\partial y}\right)$ is the horizontal moisture flux divergence (units: mm). The change in vertically integrated vapor moisture is assumed to be negligible due to its small magnitude relative to the moisture flux (Burde and Zangvil, 2001). Then, precipitation (P) and precipitation from the external advected moisture (P_a) are equal to (Guo et al., 2018; Zhao and Zhou, 2021):

$$\begin{cases} P = -\left(\frac{\partial F_u}{\partial x} + \frac{\partial F_v}{\partial y}\right) + E \\ P_a = -\left(\frac{\partial F_u^a}{\partial x} + \frac{\partial F_v^a}{\partial y}\right) \end{cases} \quad (3)$$

In Equation 3, P, E, and P_a are assumed to be constant across the region (Burde and Zangvil, 2001). Based on this assumption and Gauss's divergence theorem, Equation 3 is applied over a region with area of A (units: m^2) (Guo et al., 2018; Zhao and Zhou, 2021):

$$\begin{cases} -\left(\frac{\partial F_u}{\partial x} + \frac{\partial F_v}{\partial y}\right) | A = F_{in} - F_{out} = (P - E)A \\ -\left(\frac{\partial F_u^a}{\partial x} + \frac{\partial F_v^a}{\partial y}\right) | A = F_{in} - F_{out-a} = P_a A \end{cases} \quad (4)$$

Due to the assumed well-mixed external moisture and local evaporation, the ratio of evaporative and advective water vapor is equal in both precipitation and moisture flux. Therefore, the contribution of the advective and evaporative water vapor to precipitation is estimated as (Guo et al., 2018; Zhao and Zhou, 2021):

$$\begin{cases} \frac{P_a}{P} = \frac{2F_{in}}{2F_{in}+EA} \\ \rho = 1 - \frac{P_a}{P} = \frac{EA}{2F_{in}+EA} \end{cases} \quad (5)$$

where $\frac{P_a}{P}$ and ρ are the contributions of the advected moisture and local evaporation, respectively. ρ is also taken as the precipitation recycling ratio. Further details on the land-atmosphere water balance and associated equations can be found in Brubaker et al. (1993) and Burde and Zangvil (2001).

The moisture transport process in the Brubaker model is dominated by parallel flow, which is affected by terrain conditions. The MLRYR region is a plain area with elevations in most of areas below 50 m; hence, impacts of terrain conditions on moisture process are relatively small. The Brubaker model assumes that moisture from external transport and local evaporation are well mixed in the atmosphere, and this assumption requires a sufficiently long period of time for the moisture to be well mixed. The two droughts in our study lasted longer than 4 months, meeting the mixing conditions of moisture.

3.2 Moisture tracking model: HYSPLIT model

The Lagrangian-based HYSPLIT model, developed by NOAA's ARL (The Air Resources Laboratory of the National Oceanic and Atmospheric Administration) and one of the most commonly used atmospheric transport and dispersion models (Stein et al., 2015), is used to track moisture sources and pathways for precipitation over the MLRYR. After more than 30 years of development and applications, HYSPLIT can achieve multiple objectives, such as computing air parcel trajectories, determining the origin of air masses, and establishing source-receptor relationships.

In the Lagrangian method, moisture changes in an air parcel within a time interval are the difference between evaporation into and precipitation out of this air parcel (Zhang et al., 2021; Zhao and Zhou, 2021):

$$E - P = m\frac{\Delta q}{\Delta t} \tag{6}$$

where m is the air mass (units: kg/m^2), q is the specific humidity (units: kg/kg), and Δt is the time interval (i.e. 6 hours in this study). We use the HYSPLIT model to backward track all the air parcel trajectories that precipitated over the MLRYR. These back-trajectories are tracked for 10 days which is the time water vapor is generally retained in the atmosphere (Zhang et al., 2021). We employ the Curve Clustering Toolbox (Gaffney et al., 2007) to cluster the identified trajectories into several groups and then detect the main moisture pathways from their sources to the target region (Chen and Luo, 2018; Li et al., 2016).

Trajectories with $\Delta q > 0$ indicate moisture-uptake and are taken as moisture origin; otherwise, moisture in the locations is lost. The contribution from these moisture origins is the ratio of the net moisture uptake from these sources and moisture loss during transport processes to the total water content released from all parcels in the target areas. Thus, we attribute precipitation in the MLRYR to the evaporation locations along these trajectories as well as to the regions from which the moisture originates, based on the moisture source attribution method (see specific calculation processes in Sodemann, 2008). It should be noted that the HYSPLIT model only tracks the transport of moisture through the atmosphere, which can not track precipitation falling to the ground (the WAM-2layers can achieve this purpose; Van der Ent et al., 2013).

3.3 Moisture transport decomposing

Understanding moisture flux is essential for understanding moisture recycling in the land-atmosphere water balance as well as moisture tracking. Moisture flows over a region in two ways: through advection and convergence of water vapor transport (Banacos and Schultz, 2005; Roxy et al., 2017):

$$\begin{cases} Q = \frac{1}{g}\int_{p_{t0}}^{p_{t1}} q\boldsymbol{V}\mathrm{d}p_t \\ \nabla \cdot Q = \underbrace{-u\frac{\mathrm{d}q}{\mathrm{d}x} - v\frac{\mathrm{d}q}{\mathrm{d}y}}_{Advection} \underbrace{-q(\frac{\mathrm{d}u}{\mathrm{d}x} + \frac{\mathrm{d}v}{\mathrm{d}y})}_{Convergence} \end{cases} \tag{7}$$

where Q is vertically integrated moisture transport (units: $\mathrm{kg/(m \cdot s)}$), $\nabla \cdot$ is the divergence operator, g is the gravitational acceleration (units: $\mathrm{m/s^2}$), p_{t0} / p_{t1} is pressure (i.e. p_t) at the top/bottom of the troposphere (units: Pa), q is the specific humidity (units: kg/kg), and $\boldsymbol{V}$ is the mean wind field (meridional wind v and zonal wind u; units: m/s). The $-u\frac{\mathrm{d}q}{\mathrm{d}x} - v\frac{\mathrm{d}q}{\mathrm{d}y}$ indicates the horizontal advection of specific humidity, while $-q(\frac{\mathrm{d}u}{\mathrm{d}x} + \frac{\mathrm{d}v}{\mathrm{d}y})$ is the moisture convergence, which depends on specific humidity and horizontal mass convergence.

In Equation 7, Q consists of two components, i.e. stationary and transient (Li et al., 2013; C Zhang et al., 2017):

$$\bar{Q} = \underbrace{\frac{1}{g}\int_{p_{t0}}^{p_{t1}} \bar{q}\overline{\boldsymbol{V}}\mathrm{d}p_t}_{Stationary} + \underbrace{\frac{1}{g}\int_{p_{t0}}^{p_{t1}} \overline{q' \boldsymbol{V}'}\mathrm{d}p_t}_{Transient} \tag{8}$$

where $\bar{Q}$ is the monthly mean value of Q, $\bar{q}$ is the monthly mean specific humidity, $\overline{\boldsymbol{V}}$ is the monthly mean wind field, and $\overline{q' \boldsymbol{V}'}$ are the corresponding anomalies of daily values to the monthly mean. In Equation 8, the stationary (transient) term indicates moisture transport caused by seasonal mean circulation (transient eddies). Since $\bar{q} = \bar{q}_c + \bar{q}_a$ and $\bar{\boldsymbol{V}} = \bar{\boldsymbol{V}}_c + \bar{\boldsymbol{V}}_a$ (where $\bar{q}_c$ and $\bar{\boldsymbol{V}}_c$ are the climatological mean of specific humidity and wind field, respectively, and $\bar{q}_a$ and $\bar{\boldsymbol{V}}_a$ are corresponding deviations relative to the climatological mean), the stationary component is then decomposed as (Li et al., 2013; Seager et al., 2010):

$$\left[\int_{p_{t0}}^{p_{t1}} \nabla \cdot (\bar{q}\bar{\boldsymbol{V}})\mathrm{d}p_t\right] = \left[\int_{p_{t0}}^{p_{t1}} \nabla \cdot (\bar{q}_c + \bar{q}_a)(\bar{\boldsymbol{V}}_c + \bar{\boldsymbol{V}}_a)\mathrm{d}p_t\right] = \left[\int_{p_{t0}}^{p_{t1}} \nabla \cdot (\bar{q}_c\bar{\boldsymbol{V}}_c)\mathrm{d}p_t\right] + \left[\int_{p_{t0}}^{p_{t1}} \nabla \cdot (\bar{q}_c\bar{\boldsymbol{V}}_a)\mathrm{d}p_t\right] + \left[\int_{p_{t0}}^{p_{t1}} \nabla \cdot (\bar{q}_a\bar{\boldsymbol{V}}_c)\mathrm{d}p_t\right] + \left[\int_{p_{t0}}^{p_{t1}} \nabla \cdot (\bar{q}_a\bar{\boldsymbol{V}}_a)\mathrm{d}p_t\right] \quad (9)$$

Among the four decomposed components in Equation 9, $\left[\int_{p_{t0}}^{p_{t1}} \nabla \cdot (\bar{q}_c\bar{\boldsymbol{V}}_c)\mathrm{d}p_t\right]$ is constant during the study period and $\left[\int_{p_{t0}}^{p_{t1}} \nabla \cdot (\bar{q}_a\bar{\boldsymbol{V}}_a)\mathrm{d}p_t\right]$ can be neglected due to the small deviations of both $\bar{q}_a$ and $\bar{\boldsymbol{V}}_a$ relative to their climatological mean. Therefore, the variation of the stationary component is determined as (Li et al., 2013; Zhang et al., 2017):

$$\boldsymbol{\delta}\left[\int_{p_{t0}}^{p_{t1}} \nabla \cdot (\bar{q}\bar{\boldsymbol{V}})\mathrm{d}p_t\right] \approx \underbrace{\left[\int_{p_{t0}}^{p_{t1}} \nabla \cdot (\bar{q}_c\bar{\boldsymbol{V}}_a)\mathrm{d}p_t\right]}_{Dynamic} + \underbrace{\left[\int_{p_{t0}}^{p_{t1}} \nabla \cdot (\bar{q}_a\bar{\boldsymbol{V}}_c)\mathrm{d}p_t\right]}_{Thermodynamic} \quad (10)$$

where δ denotes the variation of the stationary component. In Equation 10, the dynamic (thermodynamic) component only depends on the change in wind field (specific humidity).

4. Results and discussion

4.1 Features and atmospheric water cycle of the two droughts

The MLRYR witnessed two record-breaking droughts: a WS drought in Jan. 11-May 19, 2011, and a SA one in Jul. 21-Nov. 26, 2019. Using the gridded precipitation, we identified the areas with negative precipitation anomalies during the two droughts relative to the climatological WS/SA period (1981-2010) (Fig. 1a and b). Extreme precipitation anomalies (less than -50 mm) are found in the area enclosed by the dashed blue lines in Fig. 1a and b (i.e. 25.25°N to 32.75°N and 110.25°E to 120.25°E; hereafter, referred to as MLRYR with an area of 855,227 km^2). Spatially, the precipitation anomalies are distributed unevenly, with the maximum deficit (i.e. -471.2/-451.2 mm for the WS/SA drought) in the central part of the MLRYR for both droughts. The slightly higher precipitation deficit of the WS drought implies a larger severity, which is reflected in the precipitation anomalies over the entire MLRYR (Fig. 1c and d). Specifically, the precipitation total during the WS drought was 240.2 mm lower than the climatological mean for the WS season, and this precipitation deficit is almost twice as large as the second highest WS drought (i.e. 140.2 mm in the year 1971); for the SA drought, the precipitation anomaly is 213.2 mm, and 33.1 percent higher than the second highest SA drought (i.e. 160.1 mm in the year 1992).

The temporal evolution of the two droughts are also different (Fig. 1e and f). The WS drought started in Jan. 2011 over the MLRYR, and intensified progressively until May 2011 (Fig. 1e). Several precipitation events in June (see positive precipitation anomalies in Fig. 1e) terminated the WS drought. Inversely, in the case of the SA drought, multiple precipitation events occurred in the first half of Jul. 2019, then the SA drought struck suddenly, and persisted and weakened gradually (Fig. 1f). It should be noted that air temperature during the SA drought was 1.8°C higher than the climatological mean of SA season and also ranked the highest over the past six decades (Ma et al., 2020). The abnormal warming-induced evaporation rapidly enhanced the severity of the SA flash drought over the MLRYR; its onset was found to have been accelerated by 24 ± 16% through anthropogenic climate change (Wang and Yuan, 2021). Overall, the WS and SA droughts occurred in different seasons and had different temporal evolution processes that WS drought gradually evolved from the light drought to the severe drought and SA drought showed the sudden change from flooding to the severe drought and gradual mitigation.

The anomalies of vapor flux during the two droughts show strong dry northerly flows over the MLRYR (see arrows in Fig. 2a and b). Climatologically, the warm-wet moisture from the northwest Pacific and Indian Ocean and the cold-dry moisture from the Siberian regions was transported (and merged) over the MLRYR (Jin et al., 2013; Ma et al., 2020; Sun and Yang, 2012). The strong dry northerly air fluxes over the MLRYR indicate that the vapor moisture transported from the ocean was weakened during the two droughts (Fig. 2a and b). Sun and Yang (2012) found that the northerly flow (humidity) was 2-3 m/s higher (at least 0.9 g/kg lower) than the climatological mean. During the WS drought, two anomalous cyclones were located over the South China Sea and Bay of Bengal, such that vapor moisture flows formed a strong divergence over the MLRYR and were then transported into the South China Sea and Bay of Bengal, i.e. the two moisture convergence regions (Fig. 2a and c). During the SA drought, an anomalous cyclone occurred in the northwest Pacific, with two strong anticyclones in the east of Japan and Bay of Bengal (Fig. 2b; also see Ma et al., 2020). Due to these circulation patterns, northeasterly wind anomalies and southwestward moisture transport were prevalent (Fig. 2b), resulting in a strong moisture divergence over the MLRYR (Fig. 2d), detrimental to the formation of precipitation.

The climatology and anomalies of the atmospheric water cycle during the two droughts are further estimated based on the ERA5 reanalysis data (Fig. 3). It can be seen from Fig. 3a that during the Jan. 11-May 19, the climatic total precipitation was 48.0×10^6 kg/s and the precipitation recycling ratio was 4.8%, suggesting that the precipitation was evidently dominated by the external advected moisture (i.e. 190.3×10^6 kg/s). During the WS drought in 2011, the external advected moisture over the MLRYR was 137.4×10^6 kg/s, 27.8% lower than the climatological mean. More importantly, the percentage of precipitation from external advected moisture (i.e. P_a/F_{in}) decreased from 24.0% to 15.6%. Due to the terrestrial water storage deficit, evaluated by the standardized drought severity index ($DSI_{year,month} = \frac{TWSA_{year,month} - \overline{TWSA_{month}}}{\sigma_{month}}$, where TWSA is terrestrial water storage anomalies, and negative DSI represent drought and positive DSI represent humidness; see colored areas in Fig. 2a; Zhao et al., 2017; Hu et al., 2021), the evaporation increased slightly from 19.2×10^6 kg/s (climatological mean) to 19.4×10^6 kg/s of which only 1.5×10^6 kg/s was recycled as precipitation. These processes indicate that 84.4% of external advected moisture and 92.2% of local evaporation were transported out of the MLRYR, hence the severity of the WS drought.

For the SA drought (Fig. 3b), the total precipitation was only 52.5% of the climatological mean (21.6 vs. 41.6×10^6 kg/s), while the evaporation was 33.5% higher than the total precipitation (at 29.2×10^6 kg/s). Although the terrestrial water storage deficit also limited evaporation induced by the high temperature, the actual evaporation was high due to the availability of runoff and CMS was -7.3×10^6 kg/s during the SA drought. The contribution of evaporation to precipitation also increased from 14.5% (climatological mean) to 22.9% (the SA drought), implying that the SA drought was not driven by precipitation recycling but rather by a decrease in external moisture. Specifically, the external moisture flowing over the MLRYR was only of 43.8% relative to the climatology (49.1 vs. 87.5×10^6 kg/s) during the SA drought. These results indicate that the remarkable reduction in external moisture was responsible for the SA drought.

4.2 Anomalies in moisture sources and transport

The atmospheric moisture budget during the two droughts indicates that moisture transport played a key role in their generations. Hence, we quantify the anomalies in moisture sources and transport by using the HYSPLIT model (Figs. 4-6). During the WS periods of 1961-2019 (Jan. 11-May 19), we tracked 281020 moisture trajectories over the MLRYR and classified them into five groups: three continent-originating and two ocean-originating paths (Fig. 4a). Climatologically, we find that the three continent-originating paths contribute the most to the total number of trajectories and total moisture (i.e. 60% and 52%, respectively). Specifically, the northwesterly path (Group 1) originating from Eurasia provides 21% of the trajectories and 25% of the moisture, while the westerly path (Group 2) originating from northern Africa and passing through the Middle East produces 22% of the trajectories but only 10% of the moisture (Fig. 4a and b). Because of the blocking effect of the Tibetan Plateau, most of the moisture carried by the air particles in the westerly path is lost. The northeasterly path (Group 5) originates from northeast China and the Bohai Sea, with 17% of the trajectories and 16% of the moisture. The two ocean-associated paths are from the Arabian Sea and Bay of Bengal (Group 3) and another from the South China Sea and the Northwest Pacific (Group 4). The moisture from the South China Sea and Northwest Pacific in particular plays a dominant role for WS precipitation, with 20% of the trajectories and 32% of the moisture.

In comparison with the climatology, an enhanced frequency of trajectories and moisture were found in the two continent-originating paths (i.e. northwesterly and westerly; see Group 1 and Group 2 in Fig. 4c and d). Due to an anomalous anti-cyclonic circulation over Siberia (Sun and Yang, 2012), more dry northerly air flowed over the MLRYR. Specifically, the trajectory frequency of Groups 1 and 2 increased from 943 and 973 (climatology) to 1442 and 1478 (the WS drought), i.e. by 52.9% and 51.9%, respectively; however, the moisture carried by Group 1 and Group 2 only increased by 11.9% and 20.1% (Fig. 4e and f). A decrease in the number of trajectories and moisture anomalies occurred over the Pacific (Fig. 4c and d), which can be explained by an abnormal cyclone over the northwestern Pacific and a weaker eastward western Pacific subtropical high (Sun and Yang, 2012). The authors also reported an anticyclone over the western Tibetan Plateau which would weaken the westerly moisture transport from the South China Sea. Based on our results, the trajectory frequency from the southerly (Group 4) and northeasterly (Group 5) paths was reduced by 18.5% and 11.1%, respectively, with a corresponding reduction for moisture of 25.7% and 22.3%. Thus, the notable reduction in moisture from the Pacific played a dominant role in generating the WS drought.

For the SA drought, similarly, we tracked 287736 trajectories during Jul. 21-Nov. 26 over 1961-2019 (Fig. 5). These trajectories were classified into four groups: Group 1, a northerly path originating from Siberia and China’s coastal areas; Group 2, a northwesterly path originating from Europe and passing through Central Asia; Group 3, a southwesterly path originating from the Bay of Bengal and passing through the South China Sea; and Group 4, a southeasterly path originating from the northwestern Pacific. The two ocean paths comprise the largest number of tracks (52% of all the trajectories), but the two land paths contributed 57% of the moisture (Fig. 5a and b). It should be noted that Group 1 (Group 3) provided 22% (30%) of all the trajectories and 34% (25%) of the moisture. These two groups played a dominant role in the MLRYR SA precipitation.

During the SA drought, we also observed enhanced (weakened) air particle transportation from the land (ocean) (Fig. 5c and d). Although the number of trajectories from the two continental paths increased by 21.2% and 25.2% (Fig. 5e and f), the moisture only increased by 11.8% and 9.0%. The number of trajectories from both oceanic paths decreased (by 25.2% for Group 3 and 11.9% for Group 4), while moisture decreased most notably in Group 3 (i.e. 26.8%). An anomalous cyclone over the northwest Pacific and an anomalous anti-cyclone (see Fig. 2b) over the Bay of Bengal are detrimental to moisture transportation to the MLRYR. The resulting reduction of moisture from Group 3 was thus responsible for the generation of the SA drought.

Due to the impacts of evaporation and precipitation along the trajectories, the specific humidity carried by air parcels may increase or decrease repeatedly before they arrive in the target region. Therefore, we further quantified the moisture transported from six relevant regions (Fig. 6): the MLRYR, Pacific ocean (PO), South China Sea (SCS), Bay of Bengal (BOB), India ocean (IO), and Eurasia (EU). This division is consistent with previous studies (Chen and Luo, 2018; Li et al., 2016), and the moisture from the MLRYR is also an important source for the local moisture supply. The contribution of local moisture increased slightly, from 18.1% to 20.6% for the WS drought and from 16.6% to 20.5% for the SA drought. Beside the MLRYR, the Pacific Ocean, South China Sea, and Eurasia are three other important moisture sources for the MLRYR. We find the WS drought was dominated by the decrease of moisture from the Pacific Ocean (a relative decrease of 32.8%), while the SA drought was driven by the decrease of moisture from the Pacific Ocean and South China Sea jointly (a relative decrease of 12.2% and 17.2%, respectively).

4.3 Controls of moisture transport

After elucidating the moisture sources and pathways behind the two droughts, the next logical question is understanding what controls this moisture transport. Therefore, the role of moisture transport in the two droughts is further investigated by analyzing the moisture divergence and associated components (Figs. 7-9). During the two droughts, we find strong moisture divergences over the MLRYR (Fig. 2c and d) which can be further decomposed into moisture advection and convergence (Fig. 7). During the two droughts, both the advection and convergence exhibit negative anomalies, leading to strong moisture divergence over the MLRYR. The horizontal advected moisture over the MLRYR is slightly lower during the two droughts than during the climatology. Specifically, the accumulated moisture divergence anomalies during the two droughts are -3.5×10^{-3}g/m$^2\cdot$s and -0.4×10^{-3}g/m$^2\cdot$s (Fig. 2c and d), and 12.6% and 1.6% of this moisture is advected, respectively. The moisture transportation during the two droughts is dominated by convergent transport, which is -24.4×10^{-3}g/m$^2\cdot$s and -25.8×10^{-3}g/m$^2\cdot$s, and accounts for 87.4% and 98.4% of the total moisture transport for the WS and SA droughts, respectively. This strong negative convergent transport reveals a downward motion of air flow over the MLRYR (Jin et al., 2013), which is not conducive to the formation of precipitation. Further, this strong wind field divergence is likely to have transported both the local and external moisture out of the MLRYR.

The reduction of vertically integrated moisture transport over the MLRYR during the two droughts was driven by both stationary and transient components (i.e. seasonal mean flow and transient eddies; Fig. 8). The MLRYR was impacted mainly by the stationary moisture transport than by transient component for both droughts. Specifically, the stationary component was $-30.7\times10^{-3}g/m^2\cdot s$ ($-27.3\times10^{-3}g/m^2\cdot s$) and 7.4 (16.2) times higher than the transient component for the WS (SA) drought. This result shows that the contribution of moisture transport to the two droughts in the MLRYR occurred mainly through a notable reduction in seasonal mean flow rather than transient eddies. In other work, transient eddies systems were also found to play a small role in precipitation variability during the summer over the southeastern United States (Li et al., 2013). Further, seasonal mean flow was found to play a dominant role in explaining the decrease in warm-season precipitation over southwest China (Zhang et al. 2017).

The above results suggest that convergent transport and stationary moisture transport controlled the moisture flux anomalies during the two droughts. However, the role of specific humidity and wind is still unknown, because they jointly affect the convergent transport and the stationary component. We therefore decomposed the stationary moisture transport into thermodynamic and dynamic components to separate the effects of specific humidity and wind (Fig. 9). The thermodynamic component was $-0.3\times10^{-3}g/m^2\cdot s$ and $-1.8\times10^{-3}g/m^2\cdot s$ during the two droughts, which explains only 0.9% and 5.7% of the stationary moisture transport. The dynamic component was -33.9×10^{-3}g/m^2·s and -29.1×10^{-3}g/m^2·s, namely 117 and 16.6 times than the thermodynamic component, indicating that the moisture transport anomalies during the two droughts were controlled by dynamic processes. In other words, changes in atmospheric circulation (wind) played a dominant role in regulating the precipitation anomalies during the two droughts over the MLRYR.

5. Conclusions

In this study, we focused on the two record-breaking droughts in the MLRYR (i.e the WS and SA droughts). We used the land-atmosphere water balance framework to investigate the role of local and external moisture during these two droughts. Additionally, the HYSPLIT model was employed to track moisture sources and pathways, and we quantified the processes controlling moisture transport during the two droughts.

Both droughts were substantially affected by a notable reduction in external transport moisture (i.e. -52.9×10^{-6} kg/s for the WS drought and -38.4×10^{-6} kg/s for the SA drought) over the MLRYR. The external and local moisture contributions were well-mixed in the atmosphere before most of the moisture (84.4% and 61.9% for the WS and SA drought, respectively) flowed out of the MLRYR, due to a strong moisture flux divergence over the MLRYR. However, the specific atmospheric water cycle processes driving the two droughts differed. For the WS drought, the external moisture transport was reduced by 27.8% relative to the WS climatology, and the percentage of this moisture falling as precipitation decreased from 24.0% to 15.6%. In contrast, the SA drought was dominated by a precipitous decrease in external moisture transport (by 43.8%), with an increase in the precipitation recycling ratio from 14.5% to 22.9%.

Continental moisture pathways contributed to approximately half (52%) of the winter-spring moisture over the MLRYR. The northeasterly path originating from the northeast China and Bohai Sea and southeasterly path originating from the northwest Pacific and South China Sea, contributed 16% and 32% of the moisture. The reduction of moisture from the two paths (by 22.3% and 25.7% relative to climatology, respectively) played a major role in the WS drought. In contrast, the oceanic pathways contributed 57% of the summer-autumn moisture, and the reduction of moisture (26.8%) from the southwesterly path (originating from the Bay of Bengal and the South China Sea) played an important role in the SA drought. From a regional viewpoint, the notable reduction in moisture from the Pacific (and South China Sea) was the major reason for the WS (SA) drought.

The strong moisture flux divergence during both droughts over the MLRYR was dominated by convergent transport. This anomalous convergent transport not only caused the downward motion of air flow but also enhanced air flow out of the MLRYR. The reduced moisture transport was mainly caused by the negative anomalies of the stationary moisture transport, i.e. changes in the seasonal mean flow which is controlled by dynamic processes (i.e. changes in wind) rather than by thermodynamic processes (changes in specific humidity).

Data Availability Statement:

The gridded precipitation observations were obtained from the China Meteorological Data Service Centre and are available at http://www.nmic.cn/en. The terrestrial water storage anomalies were produced by Li et al. (2021) and available at https://doi.org/10.5061/dryad.z612jm6bt. The ERA5 reanalysis data are provided by the European Centre for Medium-Range Weather Forecasts and available at https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5. The data used for the HYSPLIT model are provided by the National Oceanic and Atmospheric Administration Air Resources Laboratory and available at ftp://ftp.arl.noaa.gov/pub/archives/reanalysis.

Acknowledgements:

The following projects support this study: the Strategic Priority Research Program Grant of the Chinese Academy of Sciences (Grant XDA19070402), National Natural Science Foundation of China (Grants 41901041 and U1911205), the Fundamental Research Funds for the Central Universities (lzujbky-2021-kb12), and the fund for State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment (Grant No. SKLLQG2108). X. Gu is also supported by the China

Scholarship Council, and LJS is supported by a UKRI fellowship (MR/V022008/1).

References

Banacos, P.C., Schultz, D.M., 2005. The Use of Moisture Flux Convergence in Forecasting Convective Initiation: Historical and Operational Perspectives. Weather Forecast. 20, 351–366. https://doi.org/10.1175/WAF858.1

Brubaker, K.L., Entekhabi, D., Eagleson, P.S., 1993. Estimation of Continental Precipitation Recycling. J. Clim. 6, 1077–1089. https://doi.org/10.1175/1520-0442(1993)006<1077:EOCPR>2.0.CO;2

Burde, G.I., Zangvil, A., 2001. The Estimation of Regional Precipitation Recycling. Part I: Review of Recycling Models. J. Clim. 14, 2497–2508. https://doi.org/10.1175/1520-0442(2001)014<2497:TEORPR>2.0.CO;2

Chen, F., Xu, Q., Chen, J., Birks, H.J.B., Liu, J., Zhang, S., Jin, L., An, C., Telford, R.J., Cao, X., Wang, Z., Zhang, X., Selvaraj, K., Lu, H., Li, Y., Zheng, Z., Wang, H., Zhou, A., Dong, G., Zhang, J., Huang, X., Bloemendal, J., Rao, Z., 2015. East Asian summer monsoon precipitation variability since the last deglaciation. Sci. Rep. 5, 11186. https://doi.org/10.1038/srep11186

Chen, Y., Luo, Y., 2018. Analysis of Paths and Sources of Moisture for the South China Rainfall during the Presummer Rainy Season of 1979–2014. J. Meteorol. Res. 32, 744–757. https://doi.org/10.1007/s13351-018-8069-7

Cheng, T.F., Lu, M., 2020. Moisture Source–Receptor Network of the East Asian Summer Monsoon Land Regions and the Associated Atmospheric Steerings. J. Clim. 33, 9213–9231. https://doi.org/10.1175/JCLI-D-19-0868.1

Chu, Q., Wang, Q., Feng, G., 2017. Determination of the major moisture sources of cumulative effect of torrential rain events during the preflood season over South China using a Lagrangian particle model. J. Geophys. Res. Atmos. 122, 8369–8382. https://doi.org/https://doi.org/10.1002/2016JD026426

Curio, J., Maussion, F., Scherer, D., 2015. A 12-year high-resolution climatology of atmospheric water transport over the Tibetan Plateau. Earth Syst. Dynam. 6, 109–124. https://doi.org/10.5194/esd-6-109-2015

Ding, Y., Chan, J.C.L., 2005. The East Asian summer monsoon: An overview. Meteor. Atmos. Phys. 89, 117–142.

Eltahir, E.A.B., Bras, R.L., 1996. Precipitation recycling. Rev. Geophys. 34, 367–378. https://doi.org/https://doi.org/10.1029/96RG01927

Findell, K.L., Eltahir, E.A.B., 2003. Atmospheric Controls on Soil Moisture–Boundary Layer Interactions. Part I: Framework Development. J. Hydrometeorol. 4, 552–569. https://doi.org/10.1175/1525-7541(2003)004<0552:ACOSML>2.0.CO;2

Gaffney, S.J., Robertson, A.W., Smyth, P., Camargo, S.J., Ghil, M., 2007. Probabilistic clustering of extratropical cyclones using regression mixture models. Clim. Dyn. 29, 423–440. https://doi.org/10.1007/s00382-007-0235-z

Gao, Y., Cuo, L., Zhang, Y., 2014. Changes in Moisture Flux over the Tibetan Plateau during 1979–2011 and Possible Mechanisms. J. Clim. 27, 1876–1893. https://doi.org/10.1175/JCLI-D-13-00321.1

Gu, X., Li, J., Chen, Y.D., Kong, D., Liu, J., 2019a. Consistency and Discrepancy of Global Surface Soil Moisture Changes From Multiple Model-Based Data Sets Against Satellite Observations. J. Geophys. Res. Atmos. 124, 1474–1495. https://doi.org/https://doi.org/10.1029/2018JD029304

Gu, X., Zhang, Q., Li, J., Singh, V.P., Liu, J., Sun, P., Cheng, C., 2019b. Attribution of Global Soil Moisture Drying to Human Activities: A Quantitative Viewpoint. Geophys. Res. Lett. 46, 2573–2582. https://doi.org/https://doi.org/10.1029/2018GL080768

Gu, X., Zhang, Q., Li, J., Singh, V.P., Liu, J., Sun, P., He, C., Wu, J., 2019c. Intensification and Expansion of Soil Moisture Drying in Warm Season Over Eurasia Under Global Warming. J. Geophys. Res. Atmos. 124, 3765–3782. https://doi.org/https://doi.org/10.1029/2018JD029776

Guo, L., Klingaman, N.P., Demory, M.-E., Vidale, P.L., Turner, A.G., Stephan, C.C., 2018. The contributions of local and remote atmospheric moisture fluxes to East Asian precipitation and its variability. Clim. Dyn. 51, 4139–4156. https://doi.org/10.1007/s00382-017-4064-4

Hu, Z., Zhang, Z., Sang, Y.-F., Qian, J., Feng, W., Chen, X., Zhou, Q., 2021. Temporal and spatial variations in the terrestrial water storage across Central Asia based on multiple satellite datasets and global hydrological models. J. Hydrol. 596, 126013. https://doi.org/https://doi.org/10.1016/j.jhydrol.2021.126013

Huang, R., Chen, J., Wang, L., Lin, Z., 2012. Characteristics, processes, and causes of the spatio-temporal variabilities of the East Asian monsoon system. Adv. Atmos. Sci. 29, 910–942. https://doi.org/10.1007/s00376-012-2015-x

Jin, D., Guan, Z., Tang, W., 2013. The Extreme Drought Event during Winter–Spring of 2011 in East China: Combined Influences of Teleconnection in Midhigh Latitudes and Thermal Forcing in Maritime Continent Region. J. Clim. 26, 8210–8222. https://doi.org/10.1175/JCLI-D-12-00652.1

Li, F., Kusche, J., Chao, N., Wang, Z., Löcher, A., 2021. Long-Term (1979-Present) Total Water Storage Anomalies Over the Global Land Derived by Reconstructing GRACE Data. Geophys. Res. Lett. 48, e2021GL093492. https://doi.org/https://doi.org/10.1029/2021GL093492

Li, L., Li, W., Barros, A.P., 2013. Atmospheric moisture budget and its regulation of the summer precipitation variability over the Southeastern United States. Clim. Dyn. 41, 613–631. https://doi.org/10.1007/s00382-013-1697-9

Li, R., Chen, N., Zhang, X., Zeng, L., Wang, X., Tang, S., Li, D., Niyogi, D., 2020. Quantitative analysis of agricultural drought propagation process in the Yangtze River Basin by using cross wavelet analysis and spatial autocorrelation. Agric. For. Meteorol. 280, 107809. https://doi.org/https://doi.org/10.1016/j.agrformet.2019.107809

Li, X., Zhou, W., Chen, Y.D., 2016. Detecting the origins of moisture over southeast China: Seasonal variation and heavy rainfall. Adv. Atmos. Sci. 33, 319–329. https://doi.org/10.1007/s00376-015-4197-5

Li, Y., Su, F., Chen, D., Tang, Q., 2019. Atmospheric Water Transport to the Endorheic Tibetan Plateau and Its Effect on the Hydrological Status in the Region. J. Geophys. Res. Atmos. 124, 12864–12881. https://doi.org/https://doi.org/10.1029/2019JD031297

Ma, S., Zhu, C., Liu, J., 2020. Combined Impacts of Warm Central Equatorial Pacific Sea Surface Temperatures and Anthropogenic Warming on the 2019 Severe Drought in East China. Adv. Atmos. Sci. 37, 1149–1163. https://doi.org/10.1007/s00376-020-0077-8

Qian, W., Shan, X., Zhu, Y., 2011. Ranking regional drought events in China for 1960–2009. Adv. Atmos. Sci. 28, 310–321. https://doi.org/10.1007/s00376-009-9239-4

Roxy, M.K., Ghosh, S., Pathak, A., Athulya, R., Mujumdar, M., Murtugudde, R., Terray, P., Rajeevan, M., 2017. A threefold rise in widespread extreme rain events over central India. Nat. Commun. 8, 708. https://doi.org/10.1038/s41467-017-00744-9

Roy, T., Martinez, J.A., Herrera-Estrada, J.E., Zhang, Y., Dominguez, F., Berg, A., Ek, M., Wood, E.F., 2019. Role of Moisture Transport and Recycling in Characterizing Droughts: Perspectives from Two Recent U.S. Droughts and the CFSv2 System. J. Hydrometeorol. 20, 139–154. https://doi.org/10.1175/JHM-D-18-0159.1

Seager, R., Naik, N., Vecchi, G.A., 2010. Thermodynamic and Dynamic Mechanisms for Large-Scale Changes in the Hydrological Cycle in Response to Global Warming. J. Clim. 23, 4651–4668. https://doi.org/10.1175/2010JCLI3655.1

Stein, A.F., Draxler, R.R., Rolph, G.D., Stunder, B.J.B., Cohen, M.D., Ngan, F., 2015. NOAA’s HYSPLIT Atmospheric Transport and Dispersion Modeling System.

Bull. Am. Meteorol. Soc. 96, 2059–2077. https://doi.org/10.1175/BAMS-D-14-00110.1

Sun, B., Wang, H., 2014. Moisture Sources of Semiarid Grassland in China Using the Lagrangian Particle Model FLEXPART. J. Clim. 27, 2457–2474. https://doi.org/10.1175/JCLI-D-13-00517.1

Sun, B., Wang, H., 2013. Water Vapor Transport Paths and Accumulation during Widespread Snowfall Events in Northeastern China. J. Clim. 26, 4550–4566. https://doi.org/10.1175/JCLI-D-12-00300.1

Sun, C., Yang, S., 2012. Persistent severe drought in southern China during winter–spring 2011: Large-scale circulation patterns and possible impacting factors. J. Geophys. Res. Atmos. 117. https://doi.org/https://doi.org/10.1029/2012JD017500

van der Ent, R.J., Tuinenburg, O.A., Knoche, H.-R., Kunstmann, H., Savenije, H.H.G., 2013. Should we use a simple or complex model for moisture recycling and atmospheric moisture tracking? Hydrol. Earth Syst. Sci. 17, 4869–4884. https://doi.org/10.5194/hess-17-4869-2013

Wang, Y., Yuan, X., 2021. Anthropogenic Speeding Up of South China Flash Droughts as Exemplified by the 2019 Summer-Autumn Transition Season. Geophys. Res. Lett. 48, e2020GL091901. https://doi.org/https://doi.org/10.1029/2020GL091901

Xu, K., Miao, H.-Y., Liu, B., Tam, C.-Y., Wang, W., 2020. Aggravation of Record-Breaking Drought over the Mid-to-Lower Reaches of the Yangtze River in the Post-monsoon Season of 2019 by Anomalous Indo-Pacific Oceanic Conditions. Geophys. Res. Lett. 47, e2020GL090847. https://doi.org/https://doi.org/10.1029/2020GL090847

Yang, S., Lau, K.-M., Kim, K.-M., 2002. Variations of the East Asian Jet Stream and Asian–Pacific–American Winter Climate Anomalies. J. Clim. 15, 306–325. https://doi.org/10.1175/1520-0442(2002)015<0306:VOTEAJ>2.0.CO;2

Zhang, C., 2020. Moisture sources for precipitation in Southwest China in summer and the changes during the extreme droughts of 2006 and 2011. J. Hydrol. 591, 125333. https://doi.org/https://doi.org/10.1016/j.jhydrol.2020.125333

Zhang, Chi, Tang, Q., Chen, D., 2017. Recent Changes in the Moisture Source of Precipitation over the Tibetan Plateau. J. Clim. 30, 1807–1819. https://doi.org/10.1175/JCLI-D-15-0842.1

Zhang, C, Tang, Q., Chen, D., Li, L., Liu, X., Cui, H., 2017. Tracing changes in atmospheric moisture supply to the drying Southwest China. Atmos. Chem. Phys. 17, 10383–10393. https://doi.org/10.5194/acp-17-10383-2017

Zhang, C., Tang, Q., Chen, D., van der Ent, R.J., Liu, X., Li, W., Haile, G.G., 2019. Moisture Source Changes Contributed to Different Precipitation Changes over the Northern and Southern Tibetan Plateau. J. Hydrometeorol. 20, 217–229. https://doi.org/10.1175/JHM-D-18-0094.1

Zhang, L., Zhao, D., Zhou, T., Peng, D., Xiao, C., 2021. Moisture Origins and Transport Processes for the 2020 Yangtze River Valley Record-Breaking Mei-yu Rainfall. Adv. Atmos. Sci. 38, 2125–2136. https://doi.org/10.1007/s00376-021-1097-8

ZHANG, R., SUMI, A., 2002. Moisture Circulation over East Asia during El Niño Episode in Northern Winter, Spring and Autumn. J. Meteorol. Soc. Japan. Ser. II 80, 213–227. https://doi.org/10.2151/jmsj.80.213

Zhang, X., Chen, N., Li, J., Chen, Z., Niyogi, D., 2017. Multi-sensor integrated framework and index for agricultural drought monitoring. Remote Sens. Environ. 188, 141–163. https://doi.org/https://doi.org/10.1016/j.rse.2016.10.045

Zhang, X., Chen, N., Sheng, H., Ip, C., Yang, L., Chen, Y., Sang, Z., Tadesse, T., Lim, T.P.Y., Rajabifard, A., Bueti, C., Zeng, L., Wardlow, B., Wang, S., Tang, S., Xiong, Z., Li, D., Niyogi, D., 2019. Urban drought challenge to 2030 sustainable development goals. Sci. Total Environ. 693, 133536. https://doi.org/https://doi.org/10.1016/j.scitotenv.2019.07.342

Zhao, M., A, G., Velicogna, I., Kimball, J.S., 2017. Satellite Observations of Regional Drought Severity in the Continental United States Using GRACE-Based Terrestrial Water Storage Changes. J. Clim. 30, 6297–6308. https://doi.org/10.1175/JCLI-D-16-0458.1

Zhao, W., Chen, S., Chen, W., Yao, S., Nath, D., Yu, B., 2019. Interannual variations of the rainy season withdrawal of the monsoon transitional zone in China. Clim. Dyn. 53, 2031–2046. https://doi.org/10.1007/s00382-019-04762-9

Zhao, Y., Xu, X., Zhao, T., Xu, H., Mao, F., Sun, H., Wang, Y., 2016. Extreme precipitation events in East China and associated moisture transport pathways. Sci. China Earth Sci. 59, 1854–1872. https://doi.org/10.1007/s11430-016-5315-7

Zhao, Y., Zhou, T., 2021. Interannual Variability of Precipitation Recycle Ratio Over the Tibetan Plateau. J. Geophys. Res. Atmos. 126, e2020JD033733. https://doi.org/https://doi.org/10.1029/2020JD033733

Zhou, L.-T., 2011. Impact of East Asian winter monsoon on rainfall over southeastern China and its dynamical process. Int. J. Climatol. 31, 677–686. https://doi.org/https://doi.org/10.1002/joc.2101

Zhou, L.-T., Wu, R., 2010. Respective impacts of the East Asian winter monsoon and ENSO on winter rainfall in China. J. Geophys. Res. Atmos. 115. https://doi.org/https://doi.org/10.1029/2009JD012502