Effects of Spring Soil Moisture over the Eurasian Continent on Summer Precipitation in Central Asia

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Abstract

Soil moisture is a key factor in land-surface processes and can continuously influence precipitation variability in subsequent seasons through its pronounced "memory effect" ; however, studies on the influence of spring soil moisture over Eurasia on summer precipitation in Central Asia remain very limited. Based on reanalysis data including CRU monthly precipitation, CPC monthly soil moisture, and ERA5 monthly mean circulation fields for 1961–2020, this study analyzes the relationship between spring soil moisture over Eurasia and summer precipitation in Central Asia and the associated influencing processes. The results show that spring soil moisture over Eurasia generally exhibits a spatial pattern characterized by higher values in the west and north and lower values in the southeast, with the East European Plain as the main wet center, and it has shown a significant wetting trend over the past 60a. Singular Value Decomposition (SVD) analysis reveals a significant positive correlation between spring soil moisture anomalies over Eurasia and summer precipitation in southern Central Asia. When soil moisture over the East European Plain is anomalously high, precipitation in southern Central Asia increases significantly, and this correlation is independent of the ENSO signal. Positive spring soil moisture anomalies can modulate the position of the Central Asian subtropical westerly jet, enhance upper-level divergence and mid- to lower-level convergence, and promote moisture transport and convergence, thereby forming a circulation configuration favorable for the occurrence of summer precipitation in southern Central Asia. These findings reveal the nonlocal influence of spring soil moisture over Eurasia on summer precipitation in Central Asia and provide a scientific basis for predicting summer precipitation in Central Asia.

Full Text

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Effects of Spring Soil Moisture over the Eurasian Continent on Summer Precipitation in Central Asia

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Abstract: Soil moisture is a key factor in land-surface processes. Through its significant "memory effect," it can exert a sustained influence on precipitation changes in subsequent seasons. However, research on the influence of spring soil moisture over the Eurasian continent on summer precipitation in Central Asia remains quite limited. Based on CRU monthly precipitation, CPC monthly soil moisture, and ERA5 monthly mean circulation-field reanalysis data for 1961–2020, this study analyzes the relationship between spring soil moisture over the Eurasian continent and summer precipitation in Central Asia, as well as the processes through which this influence occurs. The results show that spring soil moisture over the Eurasian continent is generally characterized by higher values in the west and north and lower values in the southeast, with the East European Plain serving as the main high-moisture center, and that it has exhibited a significant wetting trend over the past 60 years. Singular Value Decomposition (SVD) analysis indicates a significant positive correlation between spring soil-moisture anomalies over the Eurasian continent and summer precipitation in southern Central Asia: when soil moisture over the East European Plain is anomalously high, precipitation in southern Central Asia increases significantly, and this relationship is independent of the ENSO signal. Positive spring soil-moisture anomalies can modulate the position of the Central Asian subtropical westerly jet, enhance upper-level divergence and convergence in the middle and lower troposphere, and promote water-vapor transport and convergence, thereby forming a circulation configuration favorable for summer precipitation in southern Central Asia. The findings reveal the nonlocal influence of spring soil moisture over the Eurasian continent on summer precipitation in Central Asia and provide a scientific basis for summer precipitation prediction in Central Asia.

Keywords: Eurasian continent; soil moisture; Central Asia; summer precipitation; atmospheric circulation

Soil moisture is a key variable in hydrology and meteorology. It directly affects water and energy balance, plant growth, and runoff generation, and is a key factor influencing water, energy, and carbon cycles[1–5]. As an important variable in the land-surface climate system, it plays an important role in land–atmosphere exchange processes. Soil moisture has a significant "memory effect," meaning that soil moisture can retain signals of preceding climate anomalies and feed them back to atmospheric circulation and precipitation processes after a lag[6–12]. Over the past several decades, the influence of soil moisture on global precipitation has received extensive attention[5,13–17]. Spring soil-moisture anomalies in the Northern Hemisphere can influence precipitation patterns in subsequent seasons through feedbacks involving atmospheric circulation, significantly altering precipitation distributions. Moist soils usually enhance evaporation and modify the partitioning of surface sensible and latent heat fluxes, thereby affecting local circulation and ultimately leading to changes in precipitation[18–19]. Among these effects, the positive feedback mechanism between soil moisture and local precipitation is especially pronounced in arid–semiarid transition zones or subhumid forest–grassland transition zones; in regions with higher soil moisture, convective activity and precipitation are usually enhanced[20–21].

The coupling effect between soil moisture and the atmosphere amplifies climate change, especially in the high-latitude regions of the Eurasian continent[22]. Studies have shown that soil moisture plays a dominant role in vegetation growth in the arid regions of Eurasia and directly affects ecosystems and agricultural production[23]; in the northern part of the East European Plain, soil moisture has relatively high stability, providing favorable conditions for agricultural production[24]. In addition, changes in soil moisture over the Eurasian continent have important impacts on global water, energy, and carbon cycles[25]. Recent studies have further pointed out that soil moisture over the Eurasian continent has a significant modulating effect on Asian summer precipitation: late-spring soil-moisture anomalies over northern Eurasia can significantly affect East Asian summer circulation and precipitation[26–27]; Eurasian soil-water anomalies affect surface thermal processes, excite an eastward-propagating Rossby wave train, and, together with sea-surface temperature anomalies in the central-eastern Pacific, lead to precipitation anomalies in western North China[28]. Meanwhile, spring soil moisture in central Siberia can also significantly affect summer drought and precipitation anomalies in Northeast Asia by modulating the structure of downstream atmospheric circulation[29]. In addition, southern Central Asia has been identified as a global soil moisture–precipitation (SSM-P)

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coupling[1], indicating that this region has a strong climatic response to soil-moisture anomalies. During strong El Niño events, from the winter when the event reaches its peak to the following spring when it weakens, precipitation in Central Asia is significantly above normal. Such precipitation anomalies increase soil moisture and produce a “memory effect,” which can continue to

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influence subsequent seasons and thereby enhance precipitation in the following summer[2].

Central Asia is a typical arid region. Its precipitation is an important supplement to surface water resources, is a bottleneck factor constraining economic development in Central Asia, and is also of great significance for the ecological environment and water-resource security. Under the influence of the westerly circulation system and complex terrain, precipitation in Central Asia exhibits pronounced spatial heterogeneity[3]. In addition, summer precipitation in Central Asia shows marked dynamic variability on both interannual and interdecadal scales, and its spatiotemporal distribution and interannual fluctuations are highly unstable. On the interannual scale, precipitation changes in Central Asia are closely related to anomalies in the westerly circulation, especially under the modulation of shifts in the subtropical jet position, blocking-high activities, and the evolution of mid- and high-latitude weather systems. On the interdecadal scale, under the background of global warming, adjustments in regional dry–wet patterns and changes in the frequency of extreme precipitation events make summer precipitation in Central Asia exhibit more complex characteristics[4]. From the perspective of formation mechanisms, precipitation in Central Asia is jointly affected by circulation systems at multiple scales. It is regulated not only by planetary-scale waves and large-scale mid- and high-latitude circulation, but is also closely related to regional-scale water-vapor transport processes and the dynamical forcing of complex terrain[5]. Studies have shown that the water-vapor sources of Central Asian precipitation have multiple pathways, mainly including water vapor transported from the North Atlantic by the westerlies, continental water vapor from Eurasia, and locally evaporated and recycled water vapor; the relative contributions of different sources differ significantly on seasonal and interdecadal scales[6]. The combined action of the above multiple processes gives the mechanism of summer precipitation change in Central Asia marked complexity and also increases the difficulty of identifying and predicting its variability.

In recent years, against the background of climate change, anomalous precipitation events in Central Asia have occurred frequently. Studies have examined the influence of soil moisture on summer precipitation in Central Asia, but have mainly emphasized its local effects[7]. Soil moisture can not only affect local precipitation, but can also regulate atmospheric circulation through a pronounced "memory effect" and thereby exert remote influences. However, current research on the influence of soil moisture over the European continent on summer precipitation in Central Asia remains insufficient, and the physical processes by which European soil moisture affects Central Asian summer precipitation are still un-

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clear. To address these questions, this study uses global gridded monthly precipitation and soil-moisture datasets for 1961–2020. It first identifies key regions of spring soil-moisture anomalies over the European continent, then analyzes the relationship between spring soil moisture in the key regions and summer precipitation in Central Asia, and finally reveals the main physical processes by which spring soil moisture over the European continent affects summer precipitation in Central Asia. The results deepen understanding of the mechanisms underlying anomalous changes in summer precipitation over Central Asia.

1 Data and Methods

1.1 Data Sources

The precipitation data are from the CRU TS v 4.0 monthly gridded dataset released by the Climatic Research Unit (CRU) of the University of East Anglia, United Kingdom. The spatial resolution is 0.5° × 0.5°. This dataset has been widely used in studies of climate change globally and in Central Asia[8].

The soil-moisture data are from the global monthly mean soil-moisture gridded dataset provided by the Climate Prediction Center (CPC) of the National Oceanic and Atmospheric Administration (NOAA), namely CPC Soil Moisture V 2[9], with a spatial resolution of 0.5° × 0.5°. The CPC monthly mean soil-moisture dataset has been validated and widely applied in many studies; its spatial distribution characteristics show good agreement with observations[10], and it exhibits good stability across different climatic regions and time scales[11].

The atmospheric-circulation reanalysis data use the ERA5 reanalysis product of the European Centre for Medium-Range Weather Forecasts (ECMWF)[12]. The dataset contains 11 pressure levels (1000, 925, 850, 800, 700, 600, 500, 400, 300, 250 hPa, and 200 hPa). This study uses monthly pressure-level data, including zonal wind, meridional wind, specific humidity, and vertical velocity, with a horizontal spatial resolution of 0.25° × 0.25°.

1.2 Research Methods

The study period is 1961–2020. Unless otherwise stated, spring refers to March–May and summer refers to July–August. To reveal the covariation relationship between spring soil moisture over the European continent and summer precipitation in Central Asia, the singular value decomposition (Singular Value Decomposition, SVD) method is used to conduct a joint analysis of the two variable fields[13]. SVD can extract coupled modes with the maximum covari-

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[11] 45–47
[12] 48
[13] 49–51

ance between two climate fields, and is widely applied in studies of air–sea and land–atmosphere interactions[14], being especially suitable for identifying teleconnection structures. By decomposing the covariance matrix of two spatial fields —spring soil moisture and summer precipitation—mutually orthogonal pairs of spatial modes and the corresponding time coefficients are extracted to identify the principal coupling relationship between the two. The first mode represents the coupling pattern with the maximum covariance and reflects the dominant covariation relationship between soil moisture and precipitation. To test the statistical significance of the relationship between soil moisture and precipitation, the spatial distribution results of the SVD modes and the correlation coefficients of the time series are subjected to a two-sided t test for significance analysis. Regions reaching the 95% or higher significance level are indicated by stippling. The key regions of soil moisture and precipitation are mainly determined according to the high-value centers and significant regions in the spatial distribution of the first SVD mode.

and its area of concentration were delineated.

When calculating water vapor flux, considering that water vapor above the 300 hPa level is almost negligible, the water vapor flux from the surface to the 300 hPa level was calculated. The calculation equation is as follows[^54]:

$$Q = \frac{1}{g}\int_{P_2}^{P_1} qV dP$$

where: Q is the water vapor flux $(\mathrm{kg} \cdot \mathrm{m}^{-1} \cdot \mathrm{s}^{-1})$; g, q, and V are the gravitational acceleration $(\mathrm{m} \cdot \mathrm{s}^{-2})$, specific humidity $(\mathrm{kg} \cdot \mathrm{kg}^{-1})$, and horizontal wind vector $(\mathrm{m} \cdot \mathrm{s}^{-1})$, respectively; and P_1 and P_2 are 300 hPa and surface air pressure (Pa), respectively. The regional mean sea surface temperature anomaly (SSTA) over 5°S–5°N, 170°–120°W is defined as the Niño 3.4 index, which is commonly used to describe the intensity and phase of ENSO[^55].

2 Results and Analysis

2.1 Climatic Characteristics of Spring Soil Moisture over Eurasia

Based on CPC soil moisture data, the spatiotemporal distribution characteristics of spring soil moisture over Eurasia during 1961–2020 were analyzed. Overall, spring soil moisture exhibits a spatial distribution pattern characterized by higher values in the west and north and lower values in the southeast (Fig. 1a–Fig. 1c). Among these regions, the East European Plain west of the Ural Mountains and east of the Baltic Sea is a prominent high-value center of spring soil moisture, with mean values exceeding 320 mm. The relatively high spring soil moisture over the East European Plain is mainly due to extensive snowmelt recharge caused by the rapid melting of winter snow in spring. At the same

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time, the region has low and flat terrain, a dense river network, and frequent spring floods, leading to surface water retention and rising groundwater levels, thereby significantly increasing soil water content[^40]. In terms of seasonal evolution, the spatial extent of the high-value soil moisture area in April–May is slightly smaller than that in March, but the mean soil moisture in the key region of the East European Plain remains at a relatively high level. In addition, the spatial distribution differences and intraseasonal variations in the monthly spring soil moisture climatology over Central Asia are relatively small. The East European Plain and the West Siberian Plain persistently appear as high-value soil moisture areas, whereas Central Asia and its eastern regions are low-value areas; within the key region, soil moisture decreases slightly from March to May, but overall remains in a relatively moist state.

From the distribution of linear trends in monthly spring soil moisture over Eurasia during 1961–2020 (Fig. 2a–Fig. 2c), it can be seen that soil moisture in each spring month shows an increasing trend. Spatially, the increasing trend in soil moisture is most significant from the East European Plain to the West Siberian Plateau, and this enhanced signal is relatively stable in each spring month. In addition, soil moisture in the Central Siberian Plateau also shows a significant increasing trend. By contrast, the increasing trend in soil moisture over Central Asia is weaker; in particular, the wetting trend in western Central Asia is not significant, and slight decreases occur in some areas. This regional difference may be related to arid terrain, scarce precipitation, and enhanced potential evapotranspiration[^56–^58].

Panel labels: (a) March; (b) April; (c) May. Color scale: soil moisture/mm.

Note: The black rectangular area is the key soil moisture region. The same applies below.

Fig. 1 Climatological distribution of soil moisture over Eurasia for different months from 1961 to 2020

Overall, spring soil moisture over Eurasia has shown a clear increasing trend over the past 60 years, with wetting centers mainly distributed over the East European Plain and surrounding areas. Trend test results indicate that the increasing trend of soil moisture in the key region passed the 95% significance level test, indicating a significant increasing trend in soil moisture in this region. The increase in spring soil moisture over Eurasia is mainly concentrated in the mid- and high-latitude regions, especially over the East European Plain and West Siberia, whereas changes in Central Asia and its western arid regions are not significant. This indicates that, over the past 60 years, soil moisture in the mid- and high-latitude regions of Eurasia has generally tended toward wetting, while the response of arid regions to climate warming shows stronger regional differences.

The interannual variability of spring soil moisture over Eurasia also exhibits similar spatial distribution characteristics (Fig. 3a–Fig. 3c). The interannual fluctuations of spring soil moisture are relatively small, and the standard deviation shows a pattern of being higher in the west and lower in the east, consistent with the climatological distribution (Fig. 1a–Fig. 1c). Among these areas, the East European Plain and its surrounding regions have the highest standard deviation values, indicating relatively large amplitudes of soil moisture variation in this region, whereas the eastern regions vary relatively steadily, reflecting the relatively high humidity level of the key region and its moisture conditions.

Fig. 2 Linear trend distribution of soil moisture over Eurasia for different months from 1961 to 2020

Panels: (a) March; (b) April; (c) May.
Color scale: Trend / $(\mathrm{mm} \cdot \mathrm{a}^{-1})$.

Note: Dotted areas indicate regions passing the 95% significance test. The same applies below.

Fig. 3 Distribution of standard deviation of soil moisture over Eurasia for different months from 1961 to 2020

Panels: (a) March; (b) April; (c) May.
Color scale: Standard deviation / mm.

It is relatively sensitive to interannual climatic variability, and on the seasonal scale may exert an important influence on subsequent atmospheric-circulation evolution and precipitation processes.

2.2 Relationship between spring soil moisture over the Eurasian continent and summer precipitation in Central Asia

By focusing on the first SVD mode, whose variance contribution rate is 49.1%, the principal covariation characteristics between spring soil moisture over Eurasia and summer precipitation in Central Asia can be well represented. Spring soil moisture shows a significant positive-correlation center over the East European Plain and its surrounding areas, indicating that positive spring soil-moisture anomalies in this region exhibit clear covariation with the summer precipitation field (Fig. 4a). Meanwhile, precipitation in southern Central Asia displays a significant positive-anomaly distribution, with its core region located south of the Caspian Sea and south of Lake Balkhash; the spatial correspondence between the two passes the 95% significance test (Fig. 4b). High spring soil-moisture anomalies over the East European Plain may influence variations in summer precipitation over Central Asia. Fig. 4c presents the standardized time series of the first mode. The results show that the correlation coefficient between the two is 0.56 and passes the 99% significance test ($P < 0.01$), indicating a significant positive correlation between spring soil-moisture anomalies and summer precipitation in southern Central Asia.

Based on the above results, precipitation in the key region of summer precipitation over southern Central Asia (39°–45°N, 57°–78°E) is selected and subjected to normalized regional averaging, and is defined as the precipitation index Pre_{ja}. Soil moisture in the key region of spring soil moisture over the Eurasian continent (50°–58°N, 28°–50°E) is subjected to normalized regional averaging and defined as the soil-moisture index; among these, the spring soil-moisture index is denoted SM_{mam}, and the summer soil-moisture index is denoted SM_{ja}.

The El Niño–Southern Oscillation (ENSO) is one of the most important external forcing factors affecting the climate of the Eurasian continent. Studies have shown that ENSO events, by modulating tropical Pacific convective activity and the structure of atmospheric circulation, can influence the distribution of precipitation and temperature changes over Eurasia on subseasonal to seasonal scales [59–60]. In particular, under the background of strong El Niño events in winter and spring, summer precipitation in some parts of Central Asia exhibits certain response characteristics. Therefore, when examining the relationship between spring soil moisture and summer precipitation in Central Asia, it is necessary to distinguish and remove the influence of ENSO. Accordingly, this study selects the Niño 3.4 index as the representative indicator of ENSO events.

(a) Spring soil moisture **(b) Summer precipitation**

Color bar: correlation coefficient (−1.0 to 1.0)

(c) Time series of the first mode

Legend: soil moisture index; precipitation index
Vertical axis: standardized value
Horizontal axis: year
$R = 0.56$ ($P < 0.01$)

Note: The blue rectangle denotes the key precipitation region.

Fig. 4 Results of the SVD analysis between spring soil moisture over Eurasia and summer precipitation over Central Asia from 1961 to 2020

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From the regression distributions of the spring Niño 3.4 index during 1961–2020 with concurrent precipitation (Fig. 5a) and soil moisture (Fig. 5b), it can be seen that, except in southern Central Asia and the western part of the East European Plain, the regression coefficients are generally low east of the East European Plain and north of Central Asia, and do not pass the significance test. This indicates that the influence of spring Niño 3.4 on spring precipitation in the mid- and high latitudes of Eurasia is limited, and that the Niño 3.4 signal is unlikely to directly affect spring precipitation variability in this region. The regression coefficients between spring Niño 3.4 and concurrent soil moisture are even lower, and the significant areas are further reduced (Fig. 5b). In particular, the correlation with soil moisture in the western part of the East European Plain is markedly weakened, revealing that ENSO has only a weak influence on spring soil moisture in the mid- and high latitudes of Eurasia. Therefore, the spring

Niño 3.4 index has no significant effect on spring precipitation or soil moisture in the key region. After excluding the influence of Niño 3.4, the independent effect of spring soil moisture on summer precipitation in Central Asia can be more accurately assessed (Fig. 6).

Figure 6 presents the regression analysis results for spring soil moisture and summer precipitation in Central Asia before and after removing the influence of ENSO. It is found that, after removing the spring soil moisture signal in the key region, the correlation coefficient between the spring Niño 3.4 index and summer precipitation in Central Asia is weak and does not pass the significance test,

(a) Regression of the spring Niño 3.4 index onto spring precipitation (b) Regression of the spring Niño 3.4 index onto spring soil moisture

Color bar: correlation coefficient (-0.3 to 0.3)

Fig. 5 Regression distributions of the spring Niño 3.4 index onto spring precipitation and soil moisture, respectively, from 1961 to 2020

Fig. 5 Regression distribution of the spring Niño 3.4 index onto spring precipitation and soil moisture respectively from 1961 to 2020

(a) Partial regression of the spring Niño 3.4 index with summer precipitation
(b) Partial regression of the spring soil moisture index with summer precipitation

Color scale: correlation coefficient, $-10, -8, -6, -4, -2, 0, 2, 4, 6, 8, 10$

Fig. 6 Partial regression distribution of the spring Niño 3.4 index and the spring soil moisture index onto summer precipitation, respectively, from 1961 to 2020

This indicates that ENSO has a limited influence on summer precipitation in Central Asia (Fig. 6a). By contrast, after removing the interference of the spring Niño 3.4 index, soil moisture in the spring key region shows a significant positive correlation with summer precipitation in Central Asia, and the areas with large correlation values are mainly distributed in southern Central Asia, passing the 95% significance test (Fig. 6b). Therefore, the spring Niño 3.4 signal is not the dominant factor affecting summer precipitation in Central Asia; rather, spring soil moisture over the Eurasian continent may independently influence summer precipitation changes in southern Central Asia, further confirming that land-surface processes have an independent and critical regulatory role in the Eurasian climate system.

To verify the persistence of spring soil moisture, Fig. 7 presents the standardized time series of the spring and summer soil moisture indices from 1961 to 2020 and the correlation coefficient between them. The interannual variation trends of spring and summer soil moisture are found to be basically consistent, with a correlation coefficient of 0.44, passing the 99% significance test ($P < 0.01$).

This indicates that spring soil moisture can continue to affect conditions into summer and has a significant "memory effect." Further analysis shows that the correlation coefficient between Pre_{ja} and SM_{mam} is 0.45 ($P < 0.01$), indicating that the increase in summer precipitation in Central Asia is closely related to the enhancement of spring soil moisture.

2.3 Nonlocal Influence of Eurasian Spring Soil Moisture on Summer Precipitation in Central Asia

To further reveal the dynamical mechanism by which spring soil moisture affects summer precipitation, the nonlocal response process of spring soil moisture anomalies was analyzed from the perspectives of atmospheric circulation and water vapor transport. Figures 8a–8c show the regression characteristics of the Central Asian summer precipitation index with atmospheric circulation. In years with excessive precipitation, there is a corresponding meridional dipole anomaly at 200 hPa, positive in the south and negative in the north; the subtropical westerly jet shifts slightly southward and strengthens, Central Asia lies in the left-exit region of the jet, and upper-level divergence is significantly enhanced (Fig. 8a). The 500 hPa wind field exhibits a mid-level cyclonic convergence anomaly, with enhanced upward motion, forming a vertically coupled structure with upper-level divergence (Fig. 8b). From the perspective of whole-layer water vapor flux (Fig. 8c), the inflow of water vapor from central-western Siberia and the westerly belt is enhanced, providing sufficient moisture conditions for precipitation development, with obvious water vapor convergence in southern Central Asia. The circulation configuration of summer precipitation in Central Asia presents a typical vertically coupled feature of "upper-level divergence—mid-level convergence—low-level water vapor convergence."

By analyzing the regression relationship between the spring soil moisture index and summer atmospheric circulation (Figs. 8d–8f), it is found that the significant circulation anomalies are mainly

Figure 7 plot text: Standardized time series of soil moisture indices in different seasons; standardized value; year; spring soil moisture index; summer soil moisture index; $R = 0.44\,(P < 0.01)$.

Fig. 7 Interannual variation of the spring and summer soil moisture indices from 1961 to 2020

Summer precipitation index

(a) 200 hPa zonal wind
Zonal wind speed / $(\mathrm{m \cdot s^{-1}})$: −5, −4, −3, −2, −1, 0, 1, 2, 3, 4, 5

(b) 500 hPa wind field
Wind speed / $(2\ \mathrm{m \cdot s^{-1}})$

(c) Water vapor flux and its divergence
Water vapor flux divergence / $[10^{-5}\ \mathrm{kg \cdot m^{-2} \cdot s^{-1}}]$: 0, 4, 8, 12, 16, 20, 24

10 kg · (m · s)$^{-1}$ water vapor flux

Spring soil moisture index

(d) 200 hPa zonal wind
Zonal wind speed / (m · s^{-1}): −5, −4, −3, −2, −1, 0, 1, 2, 3, 4, 5

(e) 500 hPa wind field
Wind speed / (2 m · s^{-1})

(f) Water vapor flux and its divergence
Water vapor flux divergence / [10^{-5} kg · m^{-2} · s^{-1}]: 0, 4, 8, 12, 16, 20, 24
10 kg · (m · s)$^{-1}$ water vapor flux

Note: Blue arrows indicate significance at the 90% level. The same applies below.

Fig. 8 Regressed atmospheric circulation and water vapor fields against the 1961–2020 summer precipitation index and spring soil moisture index

Located in Central Asia, this indicates that spring soil moisture anomalies over the East European Plain do not directly affect precipitation in the form of a local response. Rather, as an antecedent land-surface forcing signal, they modulate large-scale circulation and water vapor transport, forming a circulation configuration downstream over Central Asia that is favorable for above-normal precipitation. When spring moisture is anomalously high, the 200 hPa jet extends southward and strengthens, and upper-level divergence intensifies; at 500 hPa, significant cyclonic convergence appears in the same location, strengthening mid-level ascending motion. Water vapor transport from northern Central Asia is stronger; this water vapor originates from the Central West Siberian Plateau. Meanwhile, significant water vapor convergence forms in southeastern Central Asia, indicating that spring soil moisture anomalies, by influencing the upper-level jet and the mid-level water vapor convergence structure, provide more sufficient water vapor conditions for precipitation, regulate summer circulation, and promote the development of regional precipitation.

Regressing the 200 hPa divergent wind and velocity potential onto the spring soil moisture index shows (Fig. 9a) that significant upper-level [[unclear: sentence continues on next page]]

(a) 200 hPa divergent wind and velocity potential
Velocity potential /[10^{-6} m^2 · s^{-1}]; 1 m · s^{-1} divergent wind

(b) 500 hPa vertical velocity
Vertical velocity /[10^2 Pa · s^{-1}]

Fig. 9 Regressed fields of divergent wind, velocity potential, and vertical velocity against the 1961–2020 spring soil moisture index

divergence center, the upper-level divergence source strengthens, providing forced ascent for lower-level convection. At the same time, the 500 hPa vertical velocity shows a significant negative anomaly ($\omega < 0$) over central-southern Central Asia, indicating strengthened mid-level ascent (Fig. 9b). The upper-level divergence and mid-level ascent centers exhibit an inclined structure of "eastern divergence–western ascent," reflecting a typical meridional phase-difference configuration that is conducive to maintaining tropospheric vertical circulation and continuously supplying energy for precipitation. This structure is consistent with the synoptic configuration of divergence–ascent in the left-exit region of the jet stream, indicating that spring soil moisture modulates the upper-level jet and upper-level thermal structure, excites local vertical circulation, and thereby affects summer precipitation over Central Asia on a nonlocal scale.

This result reveals a nonlocal mechanism by which soil-moisture anomalies drive precipitation changes in the mid- and high-latitude climate system through thermodynamic–dynamic coupling processes (Fig. 10). Specifically, spring soil-moisture anomalies lead to weakened surface sensible heat and enhanced latent heat, thereby altering the thermal structure of the upper troposphere and modulating the position and intensity of the subtropical jet. The coordinated strengthening of upper-level divergence and mid-level convergence promotes moisture convergence and ascending motion, ultimately forming a dynamic environment favorable for the development of summer precipitation over Central Asia.

Labels in Fig. 10: upper-level divergence; subtropical jet; southward shift and strengthening; moisture inflow and convergence; latent heating; soil moisture; lower- to mid-level convergence.

Fig. 10 Influence mechanism of spring soil moisture over Eurasia on summer precipitation over Central Asia

3 Discussion

Positive spring soil-moisture anomalies are an important precursor signal for summer precipitation over southern Central Asia. Soil-moisture anomalies regulate surface energy and water exchange processes, affect the partitioning of surface sensible and latent heat fluxes, and further alter the boundary-layer thermal structure and the temperature gradient in the upper troposphere, thereby modulating the position and intensity of the subtropical jet [61–63]. Against this background, upper-level divergence and mid-level ascending motion in the left-exit region of the jet are strengthened, accompanied by enhanced moisture transport and convergence, which ultimately favors an increase in summer precipitation over southern Central Asia on a nonlocal scale (Fig. 10). This mechanism provides new evidence for understanding the active role of mid- and high-latitude land-surface processes in seasonal climate modulation. Unlike previous studies that mainly emphasized oceanic forcing, such as ENSO and the Indian Ocean Dipole [64–65], this study shows that soil-moisture anomalies exert relatively independent and persistent influences and can play an important role in precipitation over downstream arid regions by modulating large-scale circulation. In addition, under the background of global warming, the arid and semi-arid regions of Central Asia have shown significant warming characteristics in recent decades [66], accompanied by systematic adjustments in hydrothermal conditions. Existing studies have shown that the increase in wet-season precipitation in Central Asia is closely related to tropospheric circulation anomalies in the mid- and high latitudes; these anomalies can enhance the net moisture input toward Central Asia, thereby strengthening moisture transport from central-western Eurasia, Central Asia itself, and the North Atlantic [67]. Against this background, the related arid regions of eastern Central Asia, including northwestern China, also exhibit a certain wetting tendency, and the relationship between changes in soil moisture and precipitation patterns has become closer [68–70]. Climate warming may alter the regional water cycle by affecting surface evapotranspiration and land–atmosphere energy and moisture exchange, thereby influencing agricultural production and ecosystems. As the climate continues to warm in the future, the modulation of regional precipitation by land-surface processes may become more prominent, and its climatic effects as well as ecohydrological impacts deserve further attention [71].

The "land-surface memory" effect of antecedent soil moisture anomalies provides a potential predictability signal for seasonal-scale precipitation prediction in Central Asia. Based on the nonlocal linkage revealed in this study between spring Eurasian soil moisture and summer precipitation in Central Asia, future seasonal prediction should place greater emphasis on the role of land-surface initial conditions. The quality of initial soil moisture fields can be improved through land-surface data assimilation or improved land-surface initialization, thereby representing land–atmosphere coupling processes more realistically. Previous studies have shown that improved land-surface initialization helps enhance prediction skill on subseasonal-to-seasonal timescales, and that such improvements are more evident in regions with stronger land–atmosphere coupling [72]. On the other hand, the predictability of precipitation in Central Asia is generally limited and exhibits obvious seasonal and regional differences. Therefore, sensitivity assessments or contribution decompositions of soil-moisture impacts can be conducted, and multimodel ensemble methods can be combined to reduce uncertainty arising from biases in individual models [73]. On this basis, statistical correction methods such as machine learning can also be introduced to calibrate precipitation forecasts, so as to improve ensemble distributions and reliability and provide more stable operational support for seasonal precipitation prediction in Central Asia [74]. Although this paper verifies this land–atmosphere coupling chain using multiple reanalysis datasets, certain limitations remain. First, although the CPC soil moisture dataset has been validated many times, its spatial resolution is relatively low and may underestimate the heterogeneity of local processes. Second, the contributions of soil moisture anomalies to the energy budget and evapotranspiration processes have not been quantified in depth. Changes in soil moisture can significantly alter the spatiotemporal pattern of evapotranspiration, thereby affecting the water cycle and precipitation evolution [75]. Evaporation over the Eurasian continent contributes 90% of the interannual variability of summer precipitation in Central Asia [76]. Soil moisture in Eastern Europe can also significantly influence downstream circulation structures and thermal conditions by regulating the surface thermal gradient and Rossby wave-train activity, further demonstrating that soil moisture anomalies can affect regional climate change through thermal processes [77]. Therefore, future work may combine land–atmosphere coupling models or energy-closure analyses to quantitatively evaluate the role of changes in evapotranspiration and heat fluxes in the formation of circulation anomalies. Finally, linear methods are insufficient for fully revealing complex nonlinear feedback mechanisms and multiscale interactions. Subsequent studies may combine high-resolution simulations and machine-learning methods to systematically identify the key pathways and influence chains of land–atmosphere coupling across multiple spatiotemporal scales.

4 Conclusion

Based on reanalysis and observational data for 1961–2020, this study systematically analyzed the spatiotemporal distribution characteristics of spring soil moisture over the Eurasian continent and its nonlocal influence on summer precipitation in southern Central Asia, and revealed the potential dynamical mechanisms. The main conclusions are as follows:

(1) During 1961–2020, spring soil moisture over the Eurasian continent generally exhibited a spatial pattern of "high in the west and north, low in the southeast," with the East European Plain being the main high-moisture center. Soil moisture in this region has increased significantly over the past 60 a and shows pronounced interannual fluctuations, reflecting the sustained accumulation of soil water and climatic response characteristics in the mid- to high-latitude regions of Eurasia.

(2) Spring soil moisture anomalies over the Eurasian continent are significantly positively correlated with summer precipitation in southern Central Asia. This relationship remains robust after excluding the ENSO signal, indicating that spring soil moisture anomalies can significantly influence summer precipitation in Central Asia independently of tropical air–sea forcing.

(3) When summer precipitation anomalies in Central Asia are positive, the upper-tropospheric subtropical jet shifts southward and strengthens; Central Asia lies in the divergence zone on the left side of the jet exit region, and cyclonic circulation in the middle troposphere is accompanied by ascending motion. Low-level water vapor mainly originates from central-western Siberia and westerly transport, converging in southern Central Asia. The coordinated circulation anomalies in the upper, middle, and lower troposphere form a vertical coupling structure favorable for increased precipitation.

(4) Positive spring soil moisture anomalies over the Eurasian continent al-

ter the surface energy distribution through land–atmosphere interactions, thereby affecting the thermal structure of the upper troposphere and modulating the location and intensity of the subtropical jet. They strengthen upper-level divergence over the left exit region of the jet and mid-level ascent, while also promoting water vapor transport and convergence, ultimately favoring enhanced summer precipitation in southern Central Asia at the nonlocal scale.

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Impact of Eurasian spring soil moisture on Central Asian summer precipitation

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Abstract: Soil moisture is a key factor in land surface processes and persistently influences subsequent seasonal precipitation through its memory effect. However, research on the impact of Eurasian spring soil moisture on Central Asian summer precipitation remains limited. Using CRU precipitation, CPC soil moisture, and ERA5 circulation data (1961–2020), this study analyzes their relationship and mechanisms. Results show that Eurasian spring soil moisture is higher in the west and north and lower in the southeast, with the East European Plain as the main wet center that has undergone a significant wetting trend over the past 60 years. Singular Value Decomposition reveals a significant positive correlation between spring soil moisture anomalies and summer precipitation over southern Central Asia. When spring soil moisture is higher over the East European Plain, summer precipitation increases significantly over southern Central Asia, independent of ENSO. Positive anomalies modulate the subtropical westerly jet position, enhance upper-level divergence and mid-to-lower-level convergence, and promote water vapor transport, thereby creating a circulation pattern favorable for increased summer precipitation over southern Central Asia. These findings reveal the non-local influence of Eurasian spring soil moisture on Central Asian summer precipitation and provide a scientific basis for predicting summer precipitation in the region.

Keywords: Eurasian continent; soil moisture; Central Asia; summer precipitation; atmospheric circulation

Note: Figure translations are in progress. See original paper for figures.