

## Impact of May Soil Moisture Anomalies on June Precipitation in Central Asia (Postprint)

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### Abstract

Using ERA5 monthly mean reanalysis data from the European Centre for Medium-Range Weather Forecasts and monthly precipitation data from the Global Precipitation Climatology Centre (GPCC) for the period 1980–2019, we analyze the influence of May soil moisture anomalies in Central Asia on local precipitation changes in the subsequent June. The results indicate: (1) Monthly soil moisture in spring over Central Asia generally exhibits a spatial distribution characterized by high values in the north and central regions and low values in the southwest and southeast; the region of large interannual variability of soil moisture during March–April is primarily located in southwestern Central Asia; soil moisture in northern Central Asia shows a significant increasing trend in March and a significant decreasing trend during April–May; soil moisture in southwestern Central Asia exhibits a significant decreasing trend in March. (2) May soil moisture anomalies in central Central Asia are significantly positively correlated with local precipitation variations in June, passing the 95% confidence level test. Positive soil moisture anomalies in May can persist into June, leading to increased local evaporation and more atmospheric precipitable water in June; simultaneously, surface upward latent heat flux increases while sensible heat flux decreases, and the Bowen ratio decreases, which in turn leads to a lowered atmospheric boundary layer, increased low-level atmospheric moist entropy, and enhanced convective instability energy, favoring the occurrence of precipitation events. (3) The preceding winter Niño3.4 index is significantly positively correlated with both May soil moisture and June precipitation anomalies in central Central Asia in the following year; May soil moisture serves as an important medium through which the El Niño–Southern Oscillation (ENSO) influences June precipitation anomalies in central Central Asia in the following year, but soil moisture can also influence June precipitation independently of ENSO.

## Full Text

# Influences of Soil Moisture Anomalies in May on June Precipitation in Central Asia

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## Abstract

Using ERA5 monthly reanalysis data from the European Centre for Medium-Range Weather Forecasts and monthly precipitation records from the Global Precipitation Climatology Centre spanning 1980–2019, this study examines the influence of May soil moisture anomalies on subsequent June precipitation variability in Central Asia. The findings unveil the following key insights: (1) The spatial distribution of springtime soil moisture exhibited elevated levels in Central Asia's northern and central regions and lower levels in the southwest and southeast. Maximum standard deviations occurred in southwest Central Asia during March and April. In the north of Central Asia, soil moisture experiences a noteworthy increasing trend in March but displays a declining trend from April to May. Conversely, southwest Central Asia witnessed substantial decreases in March. (2) June precipitation in Central Asia positively correlates with local soil moisture in May. Persistent wet soil moisture anomalies from May to June contribute to increased atmospheric precipitable water, modifying regional evaporation patterns in June. Heightened evaporation leads to increased latent heat flux and reduced sensible heat flux. A small Bowen ratio indicates a relatively shallow boundary layer that promotes low-layer moist entropy and a heightened potential for convective activity. Consequently, June rainfall over the central regions of Central Asia increased. (3) A notable positive correlation exists between soil moisture in May and precipitation in June over middle Central Asia and the preceding winter Niño3.4 index. The influence of the preceding El Niño-Southern Oscillation (ENSO) on June precipitation in middle Central Asia is mediated by May soil moisture. Nonetheless, soil moisture anomalies can independently impact the variability of June precipitation, separate from the influence of ENSO.

**Keywords:** Central Asia; soil moisture; precipitation; evaporation; ENSO

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## 1.1 Study Area Overview

Central Asia encompasses Kazakhstan, Kyrgyzstan, Tajikistan, Uzbekistan, Turkmenistan, and parts of northwestern China. This vast region features diverse landforms, with mountainous terrain and basins dominating the landscape and exhibiting an overall east-high, west-low topographic distribution [Figure

1: see original paper]. The figure was produced using the standard map downloaded from the National Administration of Surveying, Mapping and Geoinformation (approval number: GS(2020)4393), with no modifications to the base map boundaries.

## 1.2 Data Sources

Previous studies have evaluated multiple soil moisture products for their applicability in Central Asia, concluding that ERA5 soil moisture data from the European Centre for Medium-Range Weather Forecasts most closely matches actual observations and can effectively characterize soil moisture variability in the region. Consequently, this study utilizes ERA5 monthly averaged surface (0–7 cm) soil volumetric water content data from 1980–2019 for soil moisture analysis. Additionally, ERA5 monthly atmospheric reanalysis data from the same period are employed, including surface air temperature, evaporation, water vapor content, precipitable water, sensible heat flux, latent heat flux, boundary layer height, and convective available potential energy. While soil moisture, evaporation, surface temperature, sensible heat flux, and latent heat flux have a horizontal resolution of  $0.1^\circ \times 0.1^\circ$ , *all other variables are at  $0.25^\circ \times 0.25^\circ$  resolution. Monthly precipitation data from 1980–2019 are obtained* from the Climate Prediction Center (CPC).

## 1.3 Research Methods

Pearson correlation coefficients are used to identify the relationship between spring soil moisture and subsequent precipitation in Central Asia. Composite analysis, regression, and T-tests are employed to analyze the physical processes through which soil moisture influences precipitation variability. Partial correlation analysis is subsequently applied to reveal the independent effect of soil moisture on precipitation. Partial correlation analysis examines the relationship between two variables while excluding the influence of other variables in a multi-factor system, yielding what is termed a partial correlation coefficient. For variables  $x_1$ ,  $x_2$ , and  $x_3$ , the partial correlation coefficient between  $x_1$  and  $x_2$  after removing the effect of  $x_3$  (denoted as  $r_{12(3)}$ ) can be expressed as:

$$r_{12(3)} = \frac{r_{12} - r_{13}r_{23}}{\sqrt{(1 - r_{13}^2)(1 - r_{23}^2)}}$$

where  $r_{12}$  represents the correlation coefficient between  $x_1$  and  $x_2$ ,  $r_{13}$  between  $x_1$  and  $x_3$ , and  $r_{23}$  between  $x_2$  and  $x_3$ .

## 2.1 Monthly Variation Characteristics of Spring Soil Moisture in Central Asia

During March–May, soil moisture in Central Asia generally exhibits higher values in the northern and central regions and lower values in the southwestern and

southeastern areas [Figure 2: see original paper]. The minimum soil moisture occurs in northwestern China, falling below  $0.1 \text{ m}^3/\text{m}^3$ , while the maximum is found in northern Kazakhstan, likely related to land cover types—northern Kazakhstan features extensive croplands, whereas Turkmenistan, Uzbekistan, and northwestern China are predominantly covered by deserts and grasslands. The standard deviation of soil moisture is greatest in southwestern Central Asia in March and April, decreases slightly in May, and increases in northern Central Asia, making the central region a zone of high soil moisture variability [Figure 2: see original paper].

The spatial distribution of soil moisture trends from March to May shows that northern Kazakhstan experiences a significant increasing trend in March, while southwestern Central Asia, including southern Kazakhstan and Uzbekistan, shows a significant drying trend [Figure 3: see original paper]. Northwestern China and Tajikistan-Kyrgyzstan exhibit drying and wetting trends, respectively, though these fail to reach statistical significance. By April, the trend pattern remains similar but with reduced magnitude in southern Kazakhstan and southwestern Central Asia. In May, soil moisture decreases further across the region, with Kyrgyzstan and Tajikistan emerging as high-value centers [Figure 3: see original paper]. Overall, spring soil moisture climatology and interannual variability in Central Asia display pronounced spatial and intra-seasonal differences, with northern and central areas serving as high-value zones and southwestern and southeastern areas as low-value zones. Soil moisture in northern Central Asia decreases month-by-month from March to May, while the interannual variability is most pronounced in southwestern Central Asia in March and April, with May showing higher variability than April.

## 2.2 Monthly Lead-Lag Correlation Between Spring Soil Moisture and Summer Precipitation

The relationship between soil moisture and precipitation is complex and bidirectional—precipitation can moisten soil, while wet soil can enhance precipitation through modified evaporation. Since this study focuses on soil moisture's influence on precipitation, we emphasize the effect of antecedent soil moisture on subsequent precipitation. Analysis of local correlations between summer precipitation (June–August) and preceding monthly soil moisture reveals that June precipitation shows significant positive correlations with May soil moisture in central Central Asia [Figure 4: see original paper]. Based on these results, we select a key region ( $39\text{--}49^\circ\text{N}$ ,  $62\text{--}73^\circ\text{E}$ ) for subsequent focused analysis [Figure 4: see original paper].

Standardized area-averaged time series of soil moisture and precipitation for this key region are defined as the soil moisture index and precipitation index, respectively, representing interannual variations in soil moisture anomalies and precipitation amounts. Both indices exhibit pronounced interannual variability with consistent patterns [Figure 5: see original paper]. The correlation coefficient between the May soil moisture index and June precipitation index reaches

0.56, passing the 95% confidence level, confirming that these indices effectively capture the soil moisture-precipitation relationship. Using  $\pm 1$  standard deviation as the criterion, we identify 7 years with anomalously high May soil moisture and 8 years with anomalously low values. Composite analysis of June precipitation anomalies for these selected years shows that when soil moisture is high, precipitation in the key region increases significantly [Figure 5: see original paper]. Repeating this analysis with alternative soil moisture products—including ESA CCI\_{SM}, FLDAS, and GLDAS—yields consistent results (figures omitted). These findings robustly demonstrate the close relationship between May soil moisture and subsequent June precipitation in central Central Asia.

### 2.3 Physical Processes of How Soil Moisture Anomalies Influence Precipitation Changes

How do May soil moisture anomalies affect June precipitation? Given soil moisture's persistence, we examine whether May anomalies can sustain through June to alter atmospheric conditions and induce precipitation anomalies. Composite differences between high and low May soil moisture years reveal that significant positive soil moisture anomalies persist into June across Central Asia [Figure 6: see original paper]. The correlation coefficient between May and June soil moisture indices in the key region reaches 0.85, indicating that central Central Asian soil moisture anomalies can indeed persist from May to June.

Soil moisture anomalies influence precipitation by modifying evaporation. Composite differences show that in years with wet May soil moisture, June evaporation increases locally in central Central Asia [Figure 7: see original paper]. Enhanced evaporation provides a crucial moisture source for precipitation, as evidenced by increased atmospheric water vapor content and precipitable water [Figure 7: see original paper]. Regression analysis using the May soil moisture index confirms these patterns, showing positive anomalies in June evaporation, water vapor content, and precipitable water when May soil moisture is high [Figure 7: see original paper].

Soil moisture anomalies also affect precipitation by altering land-atmosphere energy budgets. Composite analysis of June anomalies reveals that wet May soil moisture leads to increased latent heat flux from the surface to the atmosphere due to enhanced evaporation [Figure 8: see original paper]. The evaporative cooling process reduces surface temperature and decreases upward sensible heat flux, resulting in a reduced Bowen ratio (the ratio of sensible to latent heat flux). A small Bowen ratio promotes a shallower boundary layer [Figure 8: see original paper], increased low-level moist entropy, and greater convective available potential energy, thereby favoring convective activity and local precipitation [Figure 8: see original paper]. Regression results using the May soil moisture index corroborate these composite findings [Figure 8: see original paper].

In summary, when May soil moisture is anomalously wet in central Central Asia, the persistence of these anomalies into June enhances local evaporation, which

increases atmospheric moisture content and precipitable water. Simultaneously, increased evaporation raises latent heat flux while reducing sensible heat flux and the Bowen ratio. The reduced Bowen ratio leads to a thinner boundary layer, increased low-level moist entropy, and greater convective instability, creating favorable conditions for precipitation. Through these combined moisture and dynamic effects, June precipitation increases locally.

### **3.1 Connection Between ENSO and Soil Moisture/Precipitation Changes in Central Asia**

The Niño 3.4 index exhibits weak correlations with concurrent Central Asian soil moisture and precipitation but shows significant correlations with the following year's conditions. Specifically, the preceding winter Niño 3.4 index correlates positively with May soil moisture in central-eastern Central Asia, while correlations are weaker in western, northern, and southeastern regions [Figure 9: see original paper]. The winter Niño 3.4 index also shows significant positive correlations with June precipitation in southern Central Asia [Figure 9: see original paper]. These results indicate that ENSO events influence both subsequent May soil moisture and June precipitation in Central Asia, though the affected regions differ. Notably, both May soil moisture and June precipitation in our selected key region show significant positive correlations with the preceding winter Niño 3.4 index [Figure 9: see original paper]. The correlation coefficients between the winter Niño 3.4 index and the May soil moisture index and June precipitation index are 0.38 and 0.42, respectively, both passing significance tests. Thus, preceding winter ENSO events can influence both soil moisture and precipitation in the key region.

### **3.2 Relationship Between ENSO, Central Asian Soil Moisture, and Their Impacts on Central Asian Precipitation**

To examine whether soil moisture anomalies can influence June precipitation independently of ENSO, we conduct partial correlation analysis. After removing the influence of May soil moisture, the correlation coefficient between the preceding winter Niño 3.4 index and June precipitation drops to 0.21, failing significance testing. This indicates that May soil moisture serves as an important mediator of ENSO's influence on June precipitation in central Central Asia. However, soil moisture can also exert an independent effect. When the influence of ENSO is excluded, the partial correlation coefficient between May soil moisture and June precipitation remains significantly positive at 0.48. These results demonstrate that while ENSO influences June precipitation through its effect on soil moisture, May soil moisture anomalies can independently impact June precipitation variability in central Central Asia.

## **4 Conclusions**

Based on ERA5 reanalysis data and GPCP precipitation data from 1980–2019, this study investigates the influence of spring soil moisture anomalies on subse-

quent precipitation in Central Asia, revealing several key findings:

Spring soil moisture in Central Asia from March to May exhibits higher values in the north and center, with lower values in the southwest and southeast. Northwestern China represents the region with minimum soil moisture. The seasonal variation is relatively small in Tajikistan and Kyrgyzstan, while other regions show month-by-month decreases from March to May. Interannual variability is most pronounced in southwestern Central Asia during March and April, whereas northwestern China shows the weakest interannual variation. Trend analysis reveals significant spatial and intra-seasonal differences: northern Central Asia shows a significant increasing trend in March but decreasing trends from April to May, while southwestern Central Asia experiences significant drying in March. The drying trend in northwestern China is weaker and not statistically significant.

June precipitation in Central Asia correlates positively with local May soil moisture, particularly in central Central Asia where the relationship is locally significant. When May soil moisture is anomalously wet, these anomalies persist into June, increasing atmospheric precipitable water. Enhanced evaporation raises latent heat flux while reducing sensible heat flux, leading to a decreased Bowen ratio. The small Bowen ratio contributes to a shallower boundary layer, increased low-level moist entropy, and greater convective instability, collectively favoring precipitation formation and resulting in increased June rainfall.

The preceding winter Niño 3.4 index correlates significantly with both May soil moisture and June precipitation in central Central Asia, indicating that ENSO can influence both variables. However, partial correlation analysis reveals that May soil moisture anomalies serve as an important mediator of ENSO's impact on June precipitation while also exerting an independent influence on precipitation variability.

While this study establishes the observed relationships and physical mechanisms, further validation through numerical modeling experiments is needed. Additionally, this analysis focuses solely on local correlations between soil moisture and precipitation; the potential influence of non-local soil moisture anomalies on Central Asian summer precipitation and the remote effects of Central Asian soil moisture anomalies on precipitation elsewhere remain important topics for future investigation. Previous studies have also identified other factors influencing Central Asian summer precipitation, including tropical Indian Ocean SST anomalies, the South Asian High, the East Atlantic-West Russia teleconnection pattern, and the North African subtropical high. The relative importance and synergistic relationships among these various factors warrant further research.

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