AMSR-2 Soil Moisture Retrieval over the Mongolian Plateau and Its Response to Meteorological Factors: A Postprint

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Abstract

Soil moisture is a crucial parameter in land surface hydrological process research and represents the integrated outcome of multiple environmental factors. Scientifically determining the response characteristics of soil moisture to environmental factors is of great significance for drought monitoring and early warning, adjusting agricultural production structures, and improving the regional ecological environment in the Mongolian Plateau. This study developed a soil moisture retrieval equation tailored for the Mongolian Plateau based on AMSR-2 observed brightness temperature and SPOT-NDVI data, utilizing a microwave radiative transfer model and a rough surface emissivity Qp model, and applied the model to retrieve soil moisture during the 2013 vegetation growing season on the Mongolian Plateau. Building upon this, combined with TRMM 3B43 precipitation data and meteorological station temperature data, the response characteristics of soil moisture to meteorological factors and vegetation were investigated. The results demonstrate that: 1) The developed surface soil moisture retrieval model for the Mongolian Plateau exhibits high accuracy, with a coefficient of determination of 0.6806 between retrieved and measured soil moisture values and a root mean square error (RMSE) of 0.0316 $cm^3 \cdot cm^{-3}$, which is significantly superior to the AMSR-2 soil moisture product data provided by JAXA (RMSE = 0.0441 $cm^3 \cdot cm^{-3}$). 2) Linear fitting of TRMM 3B43 precipitation data against measured precipitation yields a coefficient of determination of 0.8598 and a slope of K = 0.9415, being slightly lower than station-measured values numerically, indicating that TRMM 3B43 data possesses high accuracy and excellent applicability in the Mongolian Plateau. 3) During the vegetation growing season on the Mongolian Plateau, soil moisture, vegetation index, and precipitation all display a spatial pattern of gradual decrease from north to south and from northeast to southwest. In arid regions, soil moisture is most sensitive to temperature variations, exhibiting a significant positive correlation, followed by precipitation and vegetation; in semi-arid regions, vegetation constitutes the key factor influencing soil moisture, while the effects of temperature and precipitation on soil moisture demonstrate seasonal variations; in semi-humid regions, the relative influence of the three factors on soil moisture follows the order vegetation > precipitation > temperature. In conclusion, leveraging the response characteristics of soil moisture to meteorological factors and vegetation enables the implementation of appropriate measures to reduce disaster risk on the Mongolian Plateau and provides a scientific basis for regional ecological environment construction.

Full Text

Preamble

Analysis of soil moisture retrieval and response to meteorological factors using AMSR-2*

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Abstract

Soil moisture is an important component of the hydrologic cycle in terrestrial ecosystems and it is critical for predicting and understanding various hydrological processes, including changes in weather conditions, precipitation patterns, runoff generation and irrigation scheduling. Soil moisture is a function of the total effect of environmental factors. The Mongolia Plateau is an ideal area for studying the interaction between soil moisture and environmental factors, because of its arid and semi-arid location and its high ecological fragility and sensitivity to global climate change. Therefore, it was necessary to study the response of soil moisture to environmental factors, which was favorable to monitor and predict droughts, adjust agricultural production structures and improve regional eco-environment in the Mongolia Plateau. A soil moisture retrieval model for the Mongolia Plateau was built using microwave radiance transfer function and Qp model based on AMSR-2 brightness temperature and SPOT normalized difference vegetation index (NDVI) data. Soil moisture was retrieved, and the retrieval precision was verified during vegetation growth period from April to October 2013 in the Mongolia Plateau. Combination with TRMM 3B43 precipitation and air temperature data acquired by meteorological stations, the study explored response characteristics between soil moisture, meteorological factors and vegetation. The results showed that 1) the coefficient of determination (r) between retrieved and ground-based soil moisture was 0.680 6, with a root-mean square error (RMSE) of 0.031 6 cm$^{3}\cdot$cm^{-3}. The retrieval result was much better than soil moisture product data of JAXA (RMSE = 0.044 1 cm$^{3}\cdot$cm^{-3}). 2) The developed model had a high accuracy and was applicable in surface soil moisture estimation. The regression coefficient of the linear fit of the TRMM 3B43 precipitation measure (rainfall) was 0.859 8 and with a slope line of 0.941 5, which suggested that TRMM 3B43 data were applicable in the Mongolia Plateau. 3) Total precipitation, mean NDVI and soil moisture during the growing season decreased gradually from north to south and from northeast to southwest. In the arid region of the study area, soil moisture was significantly and positively correlated with temperature, followed by precipitation and vegetation. In the semi-arid region of the study area, vegetation was the key factor driving soil moisture, and the effects of temperature and precipitation on soil moisture showed seasonal variations. The response of soil moisture to the three factors was in the order of vegetation > precipitation > temperature in the semi-humid region of the study area. In conclusion, the response of soil moisture to both environmental factors and vegetation could provide scientific basis for constructing healthy regional eco-environments with reducing disasters risk.

Keywords Soil moisture; Meteorological factor; Vegetation; AMSR-2; Mongolia Plateau

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1.1 Study Area Overview

The Mongolia Plateau is an inland plateau in Asia, located between 36°34 – 53°06 N and 86°33 –126°38 E, covering an area of 2.75$×10^{6}$ km^{2}. Surrounded by mountains on all sides, it extends from the western foothills of the Greater Khingan Mountains in the east to the Sayan and Altai Mountains in the west, bounded by the Sayan, Yablonoi, and Khentii Mountains in the north, and demarcated by the Yinshan Mountains in the south. The plateau encompasses the entire territory of Mongolia, southern Siberia in Russia, and parts of Inner Mongolia and Xinjiang Uygur Autonomous Region in China. This study focuses on the main body of the Mongolia Plateau, comprising Mongolia and China' s Inner Mongolia Autonomous Region [Figure 1: see original paper]. The study area is dominated by mountainous terrain and high plains, with an average elevation of 1,580 m and a gradual descent from west to east. The Mongolia Plateau features a typical temperate continental climate with long, cold winters and hot, dry summers. Precipitation primarily originates from the Arctic

Ocean in the north and the Pacific Ocean in the south, decreasing gradually from north to south and from southeast to northwest. Influenced by precipitation, temperature, and soil characteristics, vegetation cover types transition from forest to forest-steppe, typical steppe, desert steppe, Gobi desert, and back to typical steppe from north to south, creating a diverse yet fragile ecological environment.

1.2.1 Data Sources

The Global Change Observation Mission for Water-1 (GCOM-W1) satellite carrying the AMSR-2 sensor was successfully launched by the Japan Aerospace Exploration Agency (JAXA) on May 1, 2012. AMSR-2 is the successor to the Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E), with its primary mission to monitor Earth' s water and energy cycles. The sensor has an antenna scanning angle of 55° and includes 7 frequencies with 14 channels: 6.9 GHz, 7.3 GHz, 10.65 GHz, 18.7 GHz, 23.8 GHz, 36.5 GHz, and 89 GHz, with brightness temperature data at a spatial resolution of 0.1°. Compared with AMSR-E, AMSR-2 newly added two 7.3 GHz channels to reduce C-band radio frequency interference and obtain more reliable soil moisture data [20]. This study obtained AMSR-2 L1R brightness temperature data for the upper, middle, and lower decades of each month during the 2013 vegetation growth period (April–October) in the Mongolia Plateau from JAXA' s GCOM-W1 Data Service Center (http://gcom-w1.jaxa.jp/product-download.html) in HDF5 format with WGS-84 geographic coordinates.

Precipitation data were derived from the Tropical Rainfall Measuring Mission (TRMM) satellite, jointly developed by the Japan National Development Agency and NASA, launched in November 1997. The satellite carries two microwave sensors—a passive microwave radiometer and precipitation radar—to monitor precipitation conditions in tropical and subtropical regions [21]. To extend the satellite' s service life, its orbital altitude was increased from 350 km to 400 km, expanding its scanning range from 35°N–35°S to 50°N–50°S, which covers most of the Mongolia Plateau. This study used TRMM 3B43 precipitation data (http://disc.sci.gsfc.nasa.gov/) from April to October 2013. This dataset is produced from the TRMM 3B42 global 3-hour precipitation product, with units of $\mathrm{mm \cdot h^{-1}}$, requiring conversion to monthly precipitation data using the formula: DN$\times 24 \times$days per month, at a spatial resolution of 0.25°.

SPOT-NDVI data were obtained from the VEGETATION Image Center of the Flemish Institute for Technological Research (VITO) in Belgium, with a spatial resolution of 0.008929° and a temporal resolution of 10 days, also for the 2013 vegetation growth period in the Mongolia Plateau. To match the AMSR-2 microwave data, both TRMM precipitation and NDVI datasets were resampled to 0.1° resolution.

Ground-based measurement data included two sources: 1) soil moisture data from 8 observation stations at the Xilinhot National Meteorological Observatory in China, primarily for validating the accuracy of soil moisture retrieval results; and 2) monthly average precipitation and temperature data from 107 meteorological stations in Mongolia and Inner Mongolia, China. The precipitation data were mainly used to verify the applicability of TRMM 3B43 precipitation data in the Mongolia Plateau, providing a basis for accurately analyzing the response characteristics of soil moisture to meteorological factors and for future application of TRMM data in monitoring precipitation changes in the region.

1.2.2 Soil Moisture Retrieval

Under low-frequency microwave bands (less than 37 GHz) and ignoring atmospheric effects, the brightness temperature observed by microwave radiometers for vegetated surfaces generally considers only the two-layer zero-order radiation transfer model for vegetation surfaces [22], expressed as:

$$T_{bp} = T_s \cdot e_{sp} \cdot \tau_c$$

where T_{bp} is the brightness temperature observed by the microwave radiometer (K), e_{sp} is the surface emissivity, T_s is the surface temperature, ω is the vegetation single scattering albedo, and τ_c is the vegetation optical thickness in the observation direction. In low-frequency situations, the vegetation single scattering albedo can be neglected and approximated as 0.

Surface temperature (T_s) can be calculated from the 36.5 GHz vertical polarization channel [23], with calculation formulas for ascending and descending orbit data as follows:

$$T_{s,A} = T_{v,A,36.5GHz}$$

$$T_{s,D} = T_{v,D,36.5GHz}$$

where $T_{s,A}$ and $T_{s,D}$ are the surface temperatures corresponding to ascending and descending orbits respectively, and $T_{v,A,36.5GHz}$ and $T_{v,D,36.5GHz}$ are the vertical polarization brightness temperatures (K) for ascending/descending orbits at 36.5 GHz.

Vegetation optical thickness (τ_c) reflects the attenuation of surface emissivity by the vegetation layer and has an approximately linear relationship with vegetation water content (VWC), calculated as follows:

$$\tau_c = b \cdot \mathrm{VWC}/\cos(\theta)$$

where VWC is vegetation water content ($\mathrm{kg} \cdot \mathrm{m}^{-2}$), b is related to vegetation canopy structure and frequency, θ is the sensor observation angle, and NDVI is the normalized difference vegetation index.

The VWC is calculated as:

$$\mathrm{VWC} = 1.9134 \times \mathrm{NDVI} - 0.3215 \quad (0.17 < \mathrm{NDVI} \leq 0.5)$$

$$\mathrm{VWC} = 0 \quad (\mathrm{NDVI} \leq 0.17)$$

After calibrating vegetation optical thickness through the above formulas and substituting into the radiative transfer equation, surface emissivity e_{sp} can be isolated. However, in many cases, the soil surface is rough relative to the microwave wavelength. Therefore, in soil moisture retrieval, the influence of surface roughness on soil emissivity must be eliminated. Chen et al. [24] developed the Advanced Integrated Equation Model (AIEM) based on the Integral Equation Model (IEM) for random surface scattering. This model can reproduce the radiation conditions of real surfaces across a wide range of surface roughness with high simulation accuracy, but it is too complex for retrieval applications. Shi et al. [19] proposed a dual-channel retrieval algorithm based on the Qp model in 2005, which showed good consistency with AIEM simulation results. Therefore, this study used AMSR-2 6.9 GHz frequency data at an incidence angle of 55° to isolate surface emissivity using the microwave radiation transfer equation, and the dual-channel retrieval algorithm to eliminate roughness effects on surface emissivity, establishing the relationship between soil moisture and rough surface emissivity:

$$\mathrm{SMC} = A + B \cdot e_v + C \cdot e_h$$

where SMC is soil volumetric water content ($\mathrm{cm}^3 \cdot \mathrm{cm}^{-3}$), e_v and e_h are surface emissivity for V/H polarization, and A, B, C are coefficients to be determined. Finally, combining the Dobson model [25], which relates dielectric constant to soil moisture and dielectric constant to Fresnel transmissivity, the coefficients A, B, and C were calculated.

In the Dobson model, soil texture data for the study area were obtained from the global Harmonized World Soil Database (HWSD), including surface soil sand content, clay content, and soil bulk density ($\mathrm{g} \cdot \mathrm{cm}^{-2}$) information. By calibrating the coefficients A, B, and C, a soil moisture retrieval equation suitable for the Mongolia Plateau was obtained:

$$\mathrm{SMC} = 4.0475 + 0.5779 \cdot \frac{e_v}{e_h}$$

where SMC is soil volumetric water content ($\mathrm{cm}^3 \cdot \mathrm{cm}^{-3}$), and e_v and e_h are surface emissivity for V/H polarization.

1.2.3 Retrieval Accuracy Evaluation

The standard for testing soil moisture retrieval accuracy is validation using measured data. Accuracy was assessed by introducing the Root-Mean Square Error (RMSE) between measured and retrieved values, calculated as follows:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (R_i - M_i)^2}{n}}$$

where RMSE is root-mean-square error, i is observation point index, n is number of observation points, R_i and M_i represent retrieved and measured values respectively.

2.1 Soil Moisture and TRMM Precipitation Data Accuracy Verification

Using the retrieval equation, 63 scenes of soil moisture data were retrieved for the upper, middle, and lower decades of each month during the vegetation growth period (April-October) in the Mongolia Plateau. To address the gap issue between AMSR-2 ascending and descending orbit soil moisture data, a same-day averaging method was applied to obtain complete monthly coverage of the plateau (21 scenes). The 8 validation observation points were located within a single pixel of the AMSR-2 soil moisture image at coordinates 44°12 16.07 N, 116°17 43.93 E. Research indicates that the effective detection depth of microwave soil moisture is generally 2–5 cm, with an effective depth of approximately 1 cm at 10.65 GHz frequency. Since the shallowest depth of soil moisture observation probes at the experimental stations was 2 cm below the surface, this study selected measured data at the 2 cm depth for validation. After eliminating anomalous observations, the average of the 8 observation points was taken as the pixel' s daily soil moisture value, with validation results shown in Figure 2a [Figure 2: see original paper].

Figure 2a demonstrates that the retrieved soil moisture correlates well with measured soil moisture at 2 cm depth, with a Pearson correlation coefficient of 0.825, significant at the 0.01 level, and an RMSE of 0.0316 $cm^3 \cdot cm^{-3}$. The RMSE between JAXA' s AMSR-2 soil moisture product data and measured values was 0.0441 $cm^3 \cdot cm^{-3}$, indicating that the soil moisture results retrieved using the model developed in this study are significantly better than the JAXA product. By extracting TRMM 3B43 precipitation grid data corresponding to 107 meteorological observation points in the study area and fitting them with measured monthly average precipitation data (Figure 2b), the coefficient of determination (R^2) was 0.8598, with a linear fit slope $K = 0.9415$, slightly lower than station measurements. This indicates that TRMM 3B43 data have high accuracy at the monthly timescale and good applicability in the Mongolia Plateau region, providing a reliable data source for analyzing soil moisture response to meteorological factors and for future precipitation monitoring applications.

2.2 Spatial Distribution of Soil Moisture, Precipitation and Vegetation Index in the Mongolia Plateau

Figures 3a–c [Figure 3: see original paper] show the distribution of average soil moisture, average vegetation index, and annual precipitation during the 2013 vegetation growth period in the Mongolia Plateau. All three parameters exhibit similar spatial patterns, gradually decreasing from north to south and from northeast to southwest. Average soil moisture across the Mongolia Plateau ranges from 0.047 to 0.234 $cm^3 \cdot cm^{-3}$ [Figure 3a: see original paper], with significant regional variation. Higher soil moisture areas are mainly distributed in the intermountain basins east of the Sayan and Khentii Mountains in Mongolia and the deciduous coniferous-broadleaf forest region of the Greater Khingan

Mountains in Inner Mongolia, extending southward to the northern edge of the Horqin Sandy Land. Based on iso-moisture lines, these regions have soil moisture values greater than 0.12 $cm^3 \cdot cm^{-3}$. Transitional zones with soil moisture values of 0.08–0.12 $cm^3 \cdot cm^{-3}$ primarily cover typical steppe and some desert steppe areas of the Mongolia Plateau. Notably, in the Badain Jaran-Tengger Desert region of Alxa League, Inner Mongolia, soil moisture values around 0.1 $cm^3 \cdot cm^{-3}$ are significantly higher than surrounding areas, likely due to the presence of numerous lakes. In contrast, soil moisture content in the interior plateau region is less than 0.08 $cm^3 \cdot cm^{-3}$, with minimum values below 0.06 $cm^3 \cdot cm^{-3}$ occurring in the Gobi desert area north of the Altai and Gobi-Altai Mountains in Mongolia.

Annual precipitation in the Mongolia Plateau in 2013 ranged from 23.84 to 748.48 mm [Figure 3b: see original paper], decreasing rapidly from 700 mm in the Greater Khingan Mountains region of northeastern Inner Mongolia toward the northwest, with minimum values below 100 mm occurring in the southern foothills of the Altai and Gobi-Altai Mountains and the hinterland of the Badain Jaran Desert in western Alxa League, Inner Mongolia. Based on precipitation isoline distribution, the study area was divided into three climatic regions: semi-humid areas with 400-800 mm annual precipitation, located mainly in the forest-forest steppe zones east of the Sayan-Khentii Mountains, northern Dornod Province in Mongolia, and the Tumet Plain and Xilingol Grassland in Inner Mongolia; arid areas with less than 200 mm annual precipitation, located mainly in the southern foothills of the Hangai Mountains, central and eastern Gobi provinces in Mongolia, and the Gobi desert-desert steppe region west of the Ordos Plateau-Sonid Left Banner in Inner Mongolia; and semi-arid areas with 200–400 mm annual precipitation, covering typical steppe and some desert steppe regions.

The average NDVI during the 2013 vegetation growth period ranged from 0.03 to 0.61 [Figure 3c: see original paper], showing a distribution pattern similar to soil moisture and total precipitation, gradually decreasing from north to south and from northeast to southwest.

2.3 Response Characteristics of Soil Moisture to Meteorological Factors and NDVI

To investigate the response characteristics of soil moisture to meteorological factors and NDVI, the study area was divided into climatic sub-regions based on precipitation. Soil moisture, precipitation, temperature, and NDVI values for all grids in each sub-region were extracted and imported into SPSS software to calculate Pearson correlation coefficients, with results shown in Table 1 .

In arid regions with precipitation less than 200 mm, both precipitation-soil moisture and temperature-soil moisture relationships showed significant positive correlations. Beginning in April, as temperatures gradually increased, soil moisture content rose with temperature, reaching a maximum Pearson correlation coefficient of 0.440 in May. The simultaneous PT-SM correlation coefficient indicated that precipitation had a smaller impact on soil moisture than temperature. From June to August, the influence of temperature on soil moisture gradually decreased while the role of precipitation became more prominent, with the PT-SM correlation coefficient reaching its maximum value of 0.492 in August. From September to October, as temperatures decreased and moisture from the Pacific and Arctic Oceans gradually retreated from the plateau, soil began to freeze and soil moisture gradually declined, with temperature once again becoming the dominant factor affecting soil moisture. Vegetation showed a significant positive correlation with soil moisture (SM-VI), but its influence was smaller than that of temperature or precipitation during the same period.

In semi-arid regions with 200–400 mm precipitation, the effects of temperature and precipitation on soil moisture showed seasonal variations. From April to June, during the full vegetation green-up period, water demand increased while precipitation was low and rising temperatures increased evaporation, leading to rapid soil moisture loss and significant negative correlations between temperature/precipitation and soil moisture. From July to August, the arrival of the rainy season replenished soil moisture, and precipitation showed a significant positive correlation with soil moisture, reaching a maximum value of 0.426 in August, while the relationship between temperature and soil moisture reached its maximum negative correlation of -0.49, indicating that temperature had a more significant impact than precipitation. Notably, vegetation’ s influence on soil moisture became prominent beginning in June, showing a significant positive correlation that first increased then decreased, with the correlation coefficient increasing from 0.558 in June to a maximum of 0.772 in July before gradually decreasing. Based on the correlation coefficients between temperature, precipitation, vegetation and soil moisture, vegetation was identified as the key factor affecting soil moisture in semi-arid regions, followed by temperature and then precipitation.

In semi-humid regions with 400–800 mm precipitation, temperature showed a significant negative correlation with soil moisture, while precipitation showed a significant positive correlation, with correlation coefficients indicating that precipitation had a more significant impact on soil moisture than temperature. Meanwhile, the correlation between vegetation index and soil moisture was more pronounced than in semi-arid and arid regions, reaching 0.831 in June. This is because abundant precipitation in this region provides timely replenishment of water consumed by vegetation, maintaining a virtuous cycle of soil moisture conditions, consistent with conclusions drawn by Li Xiaoying et al. [26] regarding the relationship between soil moisture and vegetation index in the Loess Plateau. Additionally, in semi-humid regions with better vegetation growth, the water conservation function of vegetation may also explain why vegetation shows a more significant correlation with soil moisture than temperature and precipitation.

Conclusions

This study constructed a soil moisture retrieval equation suitable for the Mongolia Plateau based on AMSR-2 observed brightness temperature and SPOT-NDVI data using microwave radiative transfer models and the Qp model. The model was applied to retrieve soil moisture during the 2013 vegetation growth period in the Mongolia Plateau, and combined with TRMM 3B43 precipitation and station temperature data to explore the response characteristics of soil moisture to meteorological factors and vegetation. The results indicate: 1) The constructed model effectively retrieved soil moisture in the Mongolia Plateau, with a correlation coefficient of 0.825 between retrieved and measured values and an RMSE of 0.0316 $\mathrm{cm}^3 \cdot \mathrm{cm}^{-3}$, significantly outperforming JAXA' s AMSR-2 soil moisture product data (RMSE = 0.0441 $\mathrm{cm}^3 \cdot \mathrm{cm}^{-3}$). Linear fitting of TRMM 3B43 monthly precipitation data with measured precipitation from 107 meteorological stations in the Mongolia Plateau yielded a coefficient of determination $\mathrm{R}^2 = 0.8598$ and a slope K = 0.9415, indicating high data accuracy and good applicability in the Mongolia Plateau, though slightly lower than station measurements. 2) During the vegetation growth period, soil moisture, average vegetation index, and precipitation in the Mongolia Plateau showed similar spatial distribution patterns, all decreasing gradually from north to south and from northeast to southwest. 3) The response characteristics of soil moisture to precipitation, temperature, and vegetation differed significantly among climatic sub-regions. In arid regions, both precipitation and temperature showed significant positive correlations with soil moisture, but soil moisture was more sensitive to temperature. In semi-arid regions, vegetation was the key factor affecting soil moisture, with their correlation showing an initial increase followed by a decrease, while temperature and precipitation effects showed seasonal variations. In semi-humid regions, temperature showed a significant negative correlation with soil moisture while precipitation showed a significant positive correlation, and the vegetation-soil moisture correlation was more pronounced than in other regions, with correlation coefficients indicating vegetation as the primary factor affecting soil moisture distribution, followed by precipitation and then temperature.

Soil moisture is an important parameter in terrestrial hydrological processes and the result of combined effects of multiple environmental factors. Scientifically determining the response characteristics of soil moisture to environmental factors is crucial for drought monitoring and early warning, agricultural production structure adjustment, and regional ecological environment improvement in the Mongolia Plateau. This study extracted surface soil moisture during the 2013 vegetation growth period in the Mongolia Plateau using microwave remote sensing and discussed the response characteristics of temperature, precipitation, and vegetation to soil moisture at regional scale using multi-source remote sensing data including TRMM and SPOT-NDVI. Compared with previous small-scale studies examining the impact of single factors on soil moisture, this research offers new insights. However, at such a large scale, the effects of soil properties and topographic factors on soil moisture cannot be ignored. Future research will continue to explore the response characteristics of soil moisture to multiple factors, aiming to develop predictive relationships for soil moisture trends in the Mongolia Plateau to provide better scientific guidance for regional ecological environment construction and various early warning and monitoring applications.

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