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Soil moisture and vegetation memories in a cold, arid climate

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ABSTRACT

Continental climate is established as a result of a complex interplay between the atmosphere and various land-surface systems such as the biosphere, soil, hydrosphere, and cryosphere. These systems function as climate memory, allowing the maintenance of interannual atmospheric anomalies. In this paper, we present new observational evidence of an interseasonal moisture memory mechanism mediated by the land surface that is manifested in the coupled cold and arid climate of Mongolia. Interannual anomalies of soil moisture and vegetation due to rainfall during a given summer are maintained through the freezing winter months to the spring, acting as an initial condition for subsequent summer land-surface and rainfall conditions. Both the soil moisture and vegetation memories were prominent over the eastern part of the Mongolian steppe zone (103–112°E and 46–50°N). That is, the cold-season climate with low evapotranspiration and strong soil freezing acts to prolong the decay time scale of autumn soil moisture anomalies to 8.2 months that is among the longest in the world. The vegetation also has a memory of the similar time scale, likely because the large rootstock of the perennial plants dominant in the Mongolian steppe may remain alive, retain belowground biomass anomalies during the winter, and have an impact on the initial vegetation growth during the spring.

1. Introduction

Across the world's widest continent, Eurasia, especially at middle-to-high latitudes, soil moisture acts as an efficient memory storage device for interannual precipitation anomalies due to its low potential evapotranspiration (Delworth and Manabe, 1988; Vinnikov and Yeserkepova, 1991). The interseasonally persistent hydrological effects of melted snow, simulated in general circulation models (e.g., Barnett et al., 1989; Yasunari et al., 1991), have also been considered as a potential memory mechanism and explain the apparent correlation between Eurasian snow cover and subsequent Indian summer monsoon rainfall (e.g., Hahn and Shukla, 1976). On the other hand, subsequent observational studies have shown that the hydrological effect of melted snow is limited in region and season (Shinoda, 2001; Shinoda et al., 2001; Ueda et al., 2003; Iijima et al., 2008). Mongolia is located over mid-latitude highlands in the far eastern continent and has a cold, arid climate with soil freezing and small snowpack in the winter (Morinaga et al., 2003; Shinoda and Morinaga, 2005). These climate conditions are considered to have a specific impact on the soil moisture memory that is highlighted in the present study.

A large drying trend has been observed in a soil moisture index over land areas in the Northern Hemisphere since the middle 1950s, especially over northern Africa, Canada, Alaska, and Eurasia, including Mongolia (Dai et al., 2004). In particular, below-normal precipitation in the Northern Hemisphere during 1999–2002 appears to have led to extensive decreases in vegetation activity over Eurasia and North America as revealed by the satellite-estimated Normalized Difference Vegetation Index (NDVI) (Lotsch et al., 2005). These facts strongly suggest that soil moisture acts as a bridge between deficits in precipitation (meteorological drought) and failures of plant growth (agricultural or vegetation drought). In fact, this phenomenon has recently been explored for Mongolia that is highlighted here (e.g., Shinoda et al., 2007; Nandintsetseg et al., 2010).

Historical records of soil moisture content measured in situ are available for few regions in the world and often represent very short periods (Robock et al., 2000); however, a unique long-term, quality-controlled dataset has recently been established for Mongolia (Nandintsetseg and Shinoda, 2011a). Given this background, we focused on this area to explore the processes of how the interseasonal moisture memory operates in the soil–vegetation system in such drying cold, arid climate.

2. Data and methods

2.1. Observed soil moisture

The soil moisture (W) dataset used in this paper was obtained from that produced by Nandintsetseg and Shinoda (2011a), so-called the Mongolian Soil Moisture Climatology Dataset and the original

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data were derived from the Institute of Meteorology and Hydrology of Mongolia (IMH). The dataset has 26 stations in grass-covered fields over Mongolia for the entire period of 1986–2005, while the periods of available soil moisture data differed from station to station. To study natural conditions of soil moisture on a consistent basis, only data collected at grass-covered field sites were included in the dataset. In general, the dominant soil texture in the top 50-cm layer at the selected stations was sandy. Out of the 26 stations, we used 24 stations having missing observations for less than 30% of all the observations. As explained below, the missing ones were replaced with modeled estimates.

At all stations, soil moisture observations were conducted on the 8th, 18th, and 28th of each month during the warm season (April–October) using the gravimetric method. Soil moisture was not measured in winter (November–March) as the soil was frozen. Soil moisture was measured in 11 vertical layers; 5-cm layers from 0-cm to 10-cm depth and 10-cm layers from 10-cm to 100-cm depth. Most of the stations had no observations beneath 50-cm depth, and thus only data for the 0–50 cm soil layer were analyzed. This soil layer includes the major rooting zone of the grasses that dominate most of the Mongolian steppe (e.g., Shinoda et al., 2010a). The data are expressed as plant-available soil moisture (mm) in the upper 0–50 cm soil layer and were calculated as the actual total soil moisture minus the moisture content at the wilting point. The plant-available soil moisture is closely related to plant physiology and has commonly been used in the former Soviet Union and neighboring countries. We also used data of soil hydraulic properties such as wilting point (W_{wp}) and field capacity (W_{fc}) from the IMH. In addition, precipitation (P), air temperature (T), and snow depth (SD) data for the 24 stations from IMH were used to investigate the soil moisture dynamics. In the following analysis, the monthly anomalies were defined as the deviations from the corresponding monthly values averaged over the period from 1986 to 2005.

At the Underkhaan station in eastern Mongolia, special observations of soil moisture as well as soil temperature (T_g) were also carried out at the depths of 20, 50, 100, and 150 cm on an hourly interval from September 2002 to June 2006 by the time-domain reflectometry (TDR) method. This provided a source for a detailed analysis of the soil moisture memory.

2.2. Modeled soil moisture

To fill in gaps of the soil moisture observations during the winter, we used daily model-estimated soil moisture (W_m) data (Nandintsetseg and Shinoda, 2011a). This model is a version of the one-layer water balance model developed by Yamaguchi and Shinoda (2002) for low-latitude arid regions and it was modified to represent the extratropical characteristics of winter soil freezing and spring snowmelt in Mongolia (Nandintsetseg and Shinoda, 2011a). This kind of water balance model has been widely used for operational monitoring or climate change studies of soil moisture in many regions of the world (e.g., Huang et al., 1996; Shinoda and Yamaguchi, 2003; Dai et al., 2004). In accordance with the observed data (W_o), this model calculates absolute plant-available W_m in the upper 50-cm soil layer based on P and T data with a limited number of measured soil parameters (e.g., soil wilting point and field capacity). Missing observations were replaced with the modeled estimates. This model also calculates evapotranspiration (ET) based on T data, as shown in Figs. 4 and 8.

2.3. NDVI data

We used a 21-year (1982–2002) monthly $1° \times 1°$ grid of NDVI data from the semimonthly 8-km-resolution Global Inventory Modeling and Mapping Studies (GIMMS) dataset produced by Tucker et al. (2005). The GIMMS NDVI data sets were generated from the National Oceanic and Atmospheric Administration/Advanced Very High Resolution Radiometer (NOAA/AVHRR), which includes corrections for NDVI variations arising from calibration, view geometry, volcanic aerosols, and other factors unrelated to vegetation change (Pinzon, 2002; Tucker et al., 2005). For the period 2003–2005, we derived monthly $1° \times 1°$ grids of NDVI data from the semimonthly 8-km-resolution GIMMS data; namely, the monthly data were calculated by taking the mean of the two semimonthly data.

2.4. Autocorrelation and singular value decomposition analyses

We made an autocorrelation analysis of a geophysical field (such as the W and NDVI) to measure the persistence of the memory of interannual anomalies. Moreover, we conducted a singular value decomposition (SVD) analysis to identify well-coupled modes of spatiotemporal variability between two geophysical fields, as seen in Shinoda and Gamo (2000). In this analysis, the two fields are decomposed into two sets of orthogonal spatial patterns (e.g., one for the P and the other for the W) and their time coefficients. For presentation of the spatial patterns, the map of correlation of each field with the time coefficients of the other field (hereafter referred to as the 'heterogeneous' correlation map) was used in the following analysis. The detailed conceptual framework and climatic application of this technique can be found in Bretherton et al. (1992) and Wallace et al. (1992), respectively. All variables employed in the SVD analysis (P, W, and NDVI) have data for the 24 stations in Mongolia. For all time series data, the climatological seasonal cycles were removed from each of the 24 stations, and normalized anomalies were computed for each month during the growing season (May to September) of 1986 to 2005. Prior to the main SVD analysis, we chose a pair of the time-lagged periods between which the two fields exhibit persistent correlations in the following method; that is, a preliminary SVD analysis was applied to the two sets of data for each field from May to September (namely, data for the 24 stations by 5 months). According to this analysis, we chose the combinations between P for June–September ($P_{6–9}$) and W for August–September ($W_{8–9}$), and between P for June–August ($P_{6–8}$) and NDVI for September ($NDVI_9$). Accordingly, the preliminary analysis used 5 monthly data at each station for each year, while the main analysis used one multi-monthly (or monthly) data at each station for each year.

3. Results and discussion

3.1. Climatological patterns

Fig. 1 illustrates the climatological patterns of important agrometeorological elements in Mongolia. In general, the annual P ranges from over 400 mm in the northern mountains to below 100 mm in the south, and is concentrated in the summer months from June to September (Fig. 1b) (Nandintsetseg and Shinoda, 2011a). Thus, the winter P comprises only a small portion of the annual total. The monthly T falls below 0 °C from November to March. Thus, the SD during January, when the yearly maximum SD value is observed over most of Mongolia, ranges from over 100 mm in the northern mountains to below 10 mm in the south (Morinaga et al., 2003). In general, there is a latitudinal gradient in W, with the southwestern soils being drier than northeastern soils (Nandintsetseg and Shinoda, 2011a). During the late summer-autumn (Fig. 1c and d) and spring (data not shown), W in the top 50-cm-deep layer and the NDVI both exhibit southwestward decreasing patterns, similar to that observed for summer P. The absolute level of W is comparable between the two seasons, but that of the NVDI is reduced substantially in the spring, due to the decay of vegetation during the winter.

3.2. SVD and autocorrelation patterns

In this section, an SVD analysis is applied to two pairs of variables; (1) the $P_{6–9}$ and $W_{8–9}$ and (2) the $P_{6–8}$ and $NDVI_9$ in order to