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Impacts of vegetation and cold season processes on soil moisture and climate relationships over Eurasia

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[1] A number of modeling studies have addressed soil moisture persistence and its effects on the atmosphere. Such analyses are particularly valuable for seasonal to interannual prediction. In this study, we perform an observation-based study to further investigate the impacts of vegetation and cold season processes on soil moisture persistence and climate feedbacks. The joint analysis of independent meteorological, soil moisture and land cover measurements, without the use of a model, in the former Soviet Union provides a unique look at soil moisture–climate relationships at seasonal to interannual timescales. Averaged data over the growing season show a strong consistency between soil moisture and precipitation over grassland dominant regions, suggesting that precipitation anomalies are a dominant control of soil moisture at interannual timescales. Investigation of soil moisture persistence at the seasonal timescale shows a strong correlation between soil moisture in spring and the subsequent precipitation in summer over forest dominant regions and between cold season precipitation accumulation in winter and soil moisture in the following spring. Our findings can be explained by the theory proposed by Koster and Suarez (2001) and are consistent with the results from other modeling studies. Although it is hard to obtain the statistical meaningful conclusions because of the short data records, our results show the potential role of vegetation and cold season processes in land-atmosphere interactions. Further modeling studies and analyses using long in situ data records are necessary to fully verify our results.

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1. Introduction

[2] Land surface processes influence weather and climate by regulating the partitioning of surface water and energy exchanges. Soil moisture controls the relative magnitudes of the sensible and latent heat fluxes from the surface into the overlying atmospheric boundary layer, which can influence the atmospheric circulation. Soil has the ability to store precipitated water from periods of excess for later evaporation during periods of shortage and to "remember" the wet or dry weather conditions longer than atmospheric processes [*Shukla and Mintz*, 1982; *Koster and Suarez*, 2001]. Soil moisture stores exhibit persistence on the different timescales and varies with soil depth, geographical location, vegetation type, and climate [e.g., *Liu and Avissar*, 1999; *Wu and Dickinson*, 2004]. A 2–3 month soil moisture persistence exists in soil moisture measurements collected in Eurasia and Illinois, United States [*Vinnikov and Yeserkepova*, 1991; *Vinnikov et al.*, 1996; *Entin et al.*, 2000]. *Vinnikov and Yeserkepova* [1991] also found that the spatial variability of soil memory is also determined by prevailing atmosphere and surface conditions. Soil moisture memory ranges from less than a month at the surface to 4 1/2 months of memory at 1m depth in both mid- and high-latitude regions, with the opposite relationship in tropical regions due to the difference of solar radiation and the ratio of evaporation to precipitation [*Wu and Dickinson*, 2004].

[3] The persistence of soil moisture anomalies at seasonal to interannual timescales has a strong impact on the behavior of the atmosphere, according to atmospheric general circulation model studies [*Delworth and Manabe*, 1988; *Koster and Suarez*, 1995]. Understanding the control and the influence of soil moisture on regional climate may have implications for improving seasonal to interannual climate predictions, particularly for summer forecasts for transition zones between dry and humid regions [*Koster and Suarez*, 2001, 2003]. Soil moisture information may also be important not only for short-term weather forecasts, but also for predicting climate change, drought and flood disasters [e.g., *Yeh et al.*, 1984; *Pan et al.*, 1995].

[4] General circulation models (GCM) have been used to quantify the effects of soil moisture on future climate at both regional scales [*Pan et al.*, 1995; *Huang et al.*, 1996], and continental scales [*Yeh et al.*, 1984; *Mintz*, 1984;

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Koster and Suarez, 2001]. These models are particularly valuable tools to better understand the land-atmosphere feedbacks. However, different models with different parameterization schemes, produce different results. For example, some studies show the positive feedback of spring soil moisture and surface evaporation on summer precipitation [*Shukla and Mintz*, 1982; *Fennessy and Shukla*, 1999]. However, some studies show a negative feedback [*Giorgi and Marinucci*, 1996]. The Global Soil Moisture Data Bank [*Robock et al.*, 2000], an archive of historical soil moisture observations, allows these model results to be evaluated using direct observations of soil moisture and climate. The intensive soil moisture measurements collected at hundreds of Eurasian catchments, approximately every 10 days provide a baseline for evaluation of model performance, and potentially the improvement of model parameterizations [*Robock et al.*, 1995, 1998; *Schlosser et al.*, 1997; *Luo et al.*, 2003].

[5] Another approach to explore these land-atmosphere feedback processes is to analyze statistically the soil moisture variability from a multiyear integrated GCM model simulation [*Delworth and Manabe*, 1988; *Koster and Suarez*, 2001]. *Delworth and Manabe* [1988] first found that the soil acts as an integrator of the white noise spectrum (high frequency) of rainfall plus snowmelt input. The result is a red response spectrum (low frequency) of soil moisture, with temporal variability on both the intraseasonal and interannual scales. *Koster and Suarez* [2001] developed a more complex statistical model and demonstrated that soil moisture variability is not only controlled by atmospheric conditions (precipitation and radiation), but also by land surface processes (evaporation and runoff) and the feedback of soil moisture to consequent atmospheric conditions. However, these studies either neglect the roles of vegetation and cold season processes, which occur in the real climate system, or do not examine their roles explicitly.

[6] Cold land processes such as snow accumulation and melting processes play important roles in land–atmosphere interactions. Water is stored in snow during winter and released to the soil in spring after melting. In effect, snow stores water and builds up the soil moisture memory storage in spring. Soil memory behaves differently in regions with and without snow accumulation [*Wu and Dickinson*, 2004].

[7] Terrestrial vegetation influences climate and generally promotes the land/atmosphere water exchange via evapotranspiration and thus reduces surface temperature, but can also act to restrict surface transpiration when the vegetation is stressed [*Pielke et al.*, 1998]. Many studies demonstrated the role of vegetation in regional climate [*Dickinson and Henderson-Sellers*, 1988; *Xue et al.*, 2004; *Heck et al.*, 1999, 2001]. However, few studies have explored the role of vegetation on soil moisture memory and soil moisture–precipitation feedbacks.

[8] The purpose of this study is to analyze soil moisture and climate (precipitation and air temperature) feedbacks over Eurasia, particularly focusing on analyzing the roles of vegetation and cold season precipitation accumulation in soil moisture memory and soil moisture and precipitation feedbacks using independent meteorological, soil moisture and land cover measurements collected in the former Soviet Union. This study is based strictly on observational data; no model data are employed.

2. Data Sets

[9] We used the following data sets for our analysis.

[10] 1. Observed plant available soil moisture data for the top meter of soil as available from the Global Soil Moisture Data Bank [*Robock et al.*, 2000]. The data set for the former Soviet Union contains 130 stations, as shown in Figure 1. The data spans 1978 to 1985 with temporal resolution of 10 to 11 days.

[11] 2. Monthly half-degree gridded surface air temperature and precipitation data were generated for the period 1901–1995 by interpolating directly from station observations [*New et al.*, 2000].

[12] 3. Satellite based land cover data at a spatial resolution of 1 km^2 and with 14 land cover types [*Hansen et al.*, 2000]. This data set is used to identify the dominant vegetation type around in situ stations at a spatial resolution of 0.5×0.5 degree, for consistency with the climate data. Forests are defined from the satellite classifications of broadleaf forest, needleleaf forest, mixed forest, woodland, and half the area of wooded grassland. Comparison of total forest area estimates from forest inventories provides some confidence in the remote sensing data [*Dong et al.*, 2003]. Soil moisture measurement stations are classified into different categories on the basis of surrounding dominant vegetation cover types and soil moisture measurement availability (see Figure 1).

[13] Climate systems show substantial regional and land cover variations [*IPCC*, 2001]. Although the in situ soil moisture observations were collected mostly from grassland and cropland, most stations are surrounded by forest and other land covers. At large spatial scales, the effect of the land surface on the atmosphere is primarily through transpiration determined by dominant land cover and the effect of the atmosphere on the land surface (e.g., soil moisture) is primarily determined by precipitation, thus the effect from a small patchy grassland area within the large-scale dominant forest regions can be neglected. For example, *Vinnikov et al.* [1996] and *Schlosser et al.* [1997] found that the soil moisture data collected in forest covered plots in Valdai, Russia show little difference from the data collected over grass-covered plots in the surrounding area. Therefore this study emphasizes the impact of the dominant land cover on soil moisture and climate interactions. Figure 2 (top and middle) shows the fractions of each half-degree pixel area under forest or grass/crop land covers in Eurasia. Over the study area (20°E–150°E and 20°N–80°N), forests covers about 32% of the land, and grass and crop occupy 30% of the land area (Table 1). Figure 2 also shows the precipitation in summer averaged over 1978 to 1985. Larger summer precipitation is observed over Russian boreal forest regions and the monsoon climate regions in eastern China. The consistency of vegetation and precipitation patterns in Russia in Figure 2 clearly shows vegetation and climate are interrelated. Forests enhance the water exchanges between the surface and the atmosphere through their access to deeper water stores and control of evapotranspiration, and larger amounts of precipitation is observed in forested regions than in grasslands over continental interior.

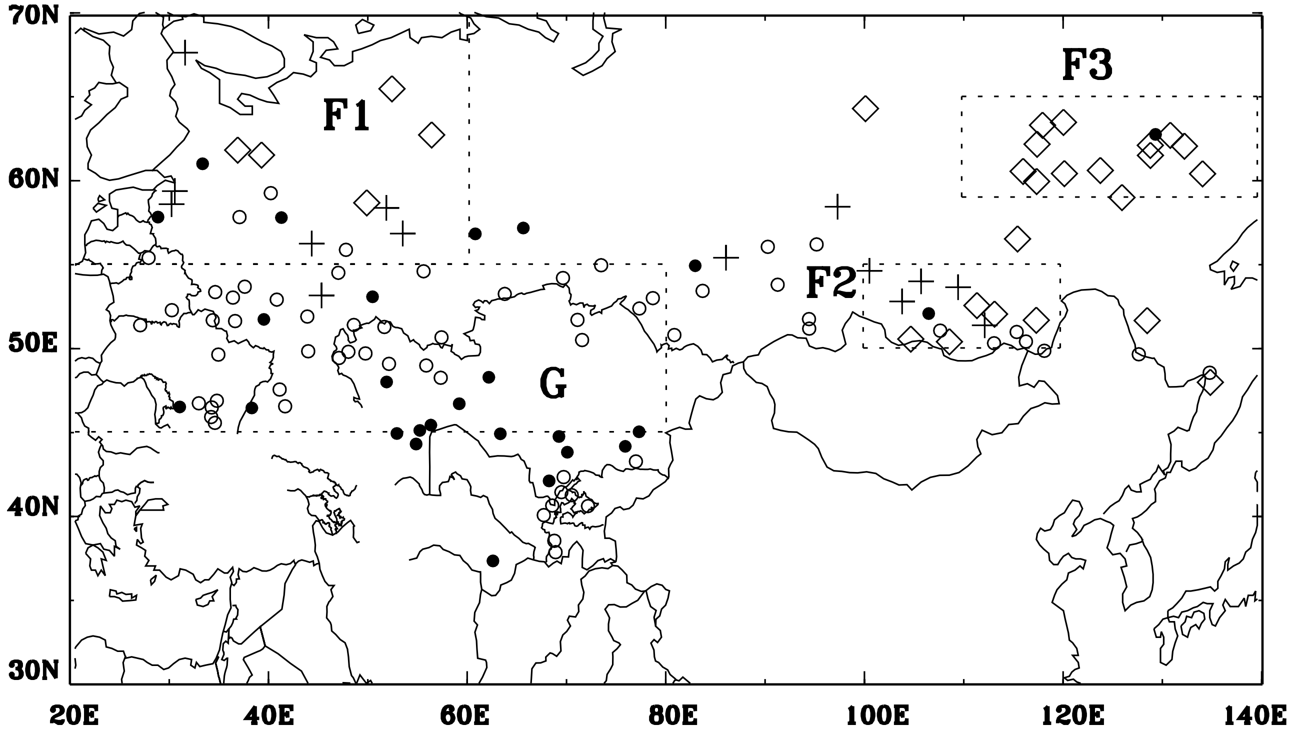

Figure 1. Map of soil moisture profile monitoring stations: (pluses) soil moisture available in spring with the defined forest fraction above 50%, (diamonds) no soil moisture data available in spring, with the defined forest fraction above 50%, (open circles) the defined grassland fraction above 50%, and (solid circles) both forest fraction and grassland fraction are less than 50%.

[14] The former Soviet Union was chosen as the study site because its precipitation is less dominated by oceanic water vapor transport, as compared to a monsoonal climate regime. *Delworth and Manabe* [1989] and *Betts* [2004] suggested that land surface evaporation largely determines precipitation over the continental interior. For such conditions, local moisture recycling will play an important role in summer precipitation, and soil moisture persistence will be stronger and longer over these regions [*Betts*, 2004].

3. Interannual Variations of Soil Moisture and Climate: Role of Vegetation

3.1. Soil Moisture and Climate Feedbacks

[15] Most of Russia is covered by boreal forests, including about 771.2 million ha of forest in 1988 and 769.8 million ha in 1998 [*Alexeyev and Birdsey*, 1998]. Therefore we presume the land cover changes are not significant during our study period. Forests have a lower albedo than other ecosystems and, through their extensive root systems, have more access to soil water than other types of vegetation. Large growing season evapotranspiration increases the local precipitation and cools the temperature [*Pielke et al.*, 1998]. Therefore the stations were regrouped according to land cover types (forest and grassland/cropland) to investigate the effects of vegetation on soil moisture variations. Among the in situ stations, the dominant vegetation type is forest in most eastern stations and in some western stations (Figure 3). Forests occupy 69% of the half-degree pixel area around the in situ stations for the eastern stations and 31% for the western stations.

[16] Figure 4 shows the change of soil moisture, precipitation and temperature with vegetation cover, which is calculated as the specified vegetation fraction equal to or greater than the indicated thresholds within each half-degree pixel and the corresponding difference of soil moisture, precipitation and temperature over forest and grassland. This technique of compositing half-degree pixel relationships omits any nonlocal effects such as evapotranspiration from adjacent pixels. That is, the higher the threshold, the more representative the vegetation type is in the study region. Soil moisture measurements at forest dominant sites, averaged over growing season for 8 years, is persistently larger than soil moisture measured at grassland dominant sites, presumably because of the continuously large precipitation and relatively low air temperature at forest dominant sites (see Figure 4). The difference of soil moisture, precipitation and temperature between forest and grassland shows a slight increase trend with the increase of the imposed thresholds. This emphasizes that forest with lower surface albedo and larger evapotranspiration, enhances the water exchanges between land surface and atmosphere and increases local precipitation and cools air temperature, as mentioned before. It is not surprise that the precipitation decreases as forest fraction increases, for the precipitation patterns show high spatial variability. Moreover, the atmospheric general circulation is the most dominant factor to control precipitation pattern, and the forest land cover is the secondary to enhance the precipitation. With the increase of the forest fraction threshold, the sample size decreases, and Figure 4, bottom, shows the sample size over subsamples with the fraction of forest or grassland greater than a

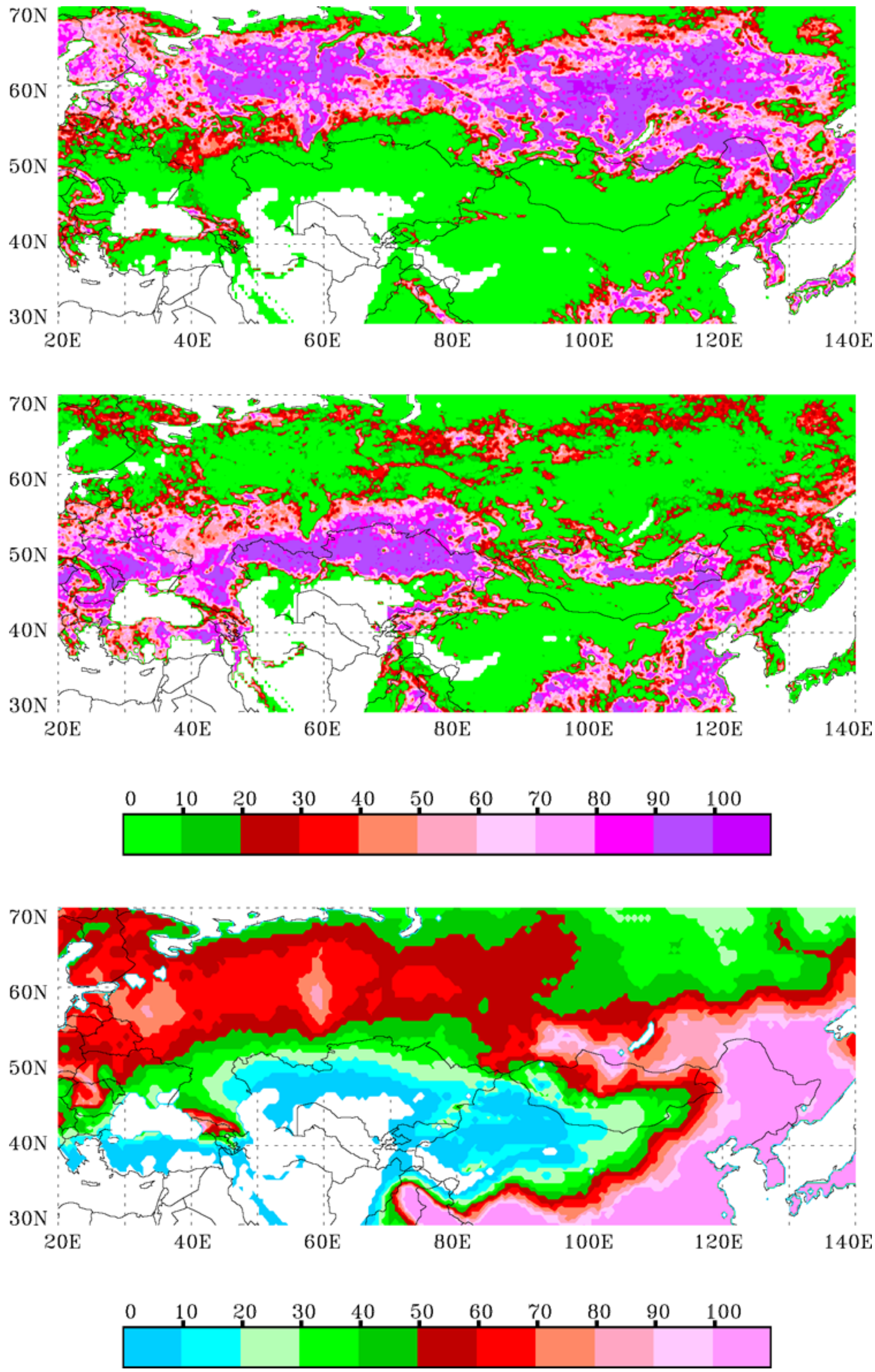

Figure 2. Map of (top) forest fraction, (middle) grass/crop fraction, and (bottom) mean summer precipitation during 1979 to 1993. Forest fraction and grassland fraction are defined as the fraction of each half-degree pixel area occupied by forest and grass/crop land covers.

Table 1. Fractions of Each Defined Land Cover Type Over the Entire Land Area Ranging From 20°E to 150°E and From 20°N to 80°N

Land Cover Types	Fraction, %
Evergreen needleleaf forest	6.064
Evergreen broadleaf forest	0.371
Deciduous needleleaf forest	1.674
Deciduous broadleaf forest	0.823
Mixed forest	4.644
Woodland	11.672
Wooded grassland	14.043
Closed shrubland	5.305
Open shrubland	17.579
Grassland	12.543
Cropland	10.623
Bare ground	14.446
Urban and built-up	0.214

predefined threshold over the entire study period. As the sample size decreases, the pixels with large precipitation but with relatively low forest fraction could be filtered out by the imposed threshold.

3.2. Interannual Variability

[17] The average of soil moisture and precipitation over the entire growing season (April–October) for each year was used to study the interannual relationships between these variables. If any in situ soil moisture or monthly climate data was missing, we omitted the data at that specific location and time from further analysis. The in situ stations were lumped into two groups with either forest or grassland fraction above 50%. The forest fraction was defined as the fraction of forest area within a half-degree pixel area. The interannual variability of soil moisture, precipitation and temperature shows that soil moisture is positively correlated with precipitation and negatively correlated with temperature in both grassland and forest dominant regions (Figure 5). However, the correlation is higher over grassland dominant regions (correlation coefficient = 0.719 for precipitation and −0.380 for temperature) than the forest dominant regions (correlation coefficient = 0.470 for precipitation and −0.138 for temperature). The results indicate that there is a statistically meaningful relation at the $p < 0.05$ level over grassland dominant regions between soil moisture and precipitation averaged over the entire growing season. This result is consistent with the modeling study by *Wu and Dickinson* [2005]. They found over grassland (in the U. S. Great Plains) regions, precipitation is more closely related to evaporation rather than transpiration. The evaporation represents more immediate response of land surface to atmospheric conditions, while transpiration reflects soil moisture memory with considerably longer timescales. Large precipitation and cool air temperature over forest regions may maintain moist enough soil that the trees are never moisture stressed, thus destroying the link between interannual precipitation and soil moisture variability.

[18] We use averaged observations over large regions, such as among all stations in the former Soviet Union, to reduce the impact of random observation errors. We recognize that large-area observation averages may smooth out some important spatial variability signals, which may limit the reliability of our conclusions on the relation between soil moisture and climate. To explore the influences from the spatial average, we arbitrarily gridded the study area into 5° × 10° grid boxes. The station data within each grid box were used to calculate the correlation with precipitation. The correlation coefficients between soil moisture and precipitation in each box where at least two or more stations' data were available for the calculation are shown in Figure 6. Here we assume that averages of two or more observed stations better represent the true average of soil moisture within each box. Most grid boxes have a correlation between soil moisture and precipitation above 0.5, and the correlation coefficients are above 0.7 in 12 of the 24 grid boxes. Although there were 3 in situ stations available in the boxes (60°N–65°N; 30°E–40°E) and (35°N–40°N; 60°E–70°E), data in 1981–1982 in the first box and in 1983–1985 in the second box were missing. No correlation coefficients were calculated in these two boxes. The results at small regional scales are generally consistent with the regional analysis. Therefore the regional studies do show a relationship between soil moisture and precipitation during growing season at an interannual scale that reflects regional-scale variability.

4. Seasonal Soil Moisture and Climate Feedback

[19] Seasonally, there is high soil moisture in the winter and during the spring snowmelt, lower soil moisture during the summer when evapotranspiration increases, and increasing levels of soil moisture from the end of the growing season until the winter [*Robock et al.*, 2000]. Two elements, cold season precipitation and vegetation type, are emphasized in our investigation of relationships between soil moisture and climate. To reduce the effects of the interannual trends on the linear correlation, we remove the trend for each variable (soil moisture, precipitation, or air temperature) by calculating their anomalies. The anomaly is defined as the difference between the mean value of each regression variable at a given time period and the mean value over the entire year. Such data processing will emphasize the seasonal influences by removing their interannual trends from the time series.

4.1. Buildup of Soil Moisture

[20] Winter precipitation stored as snow and ice is released to the soil during the spring season snowmelt. Figure 7a

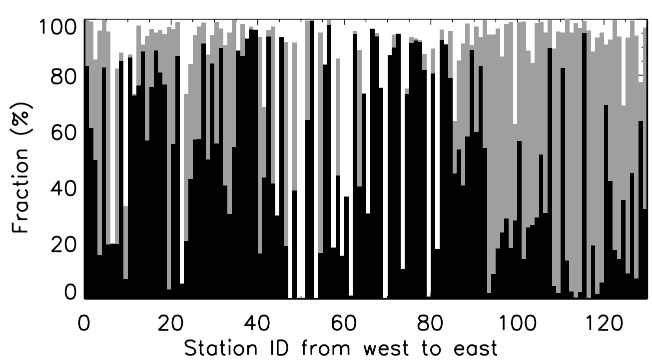

Figure 3. Fractions of each half-degree pixel area under forest (light color) and grass/crop (black color) land covers among the in situ stations in the former Soviet Union.

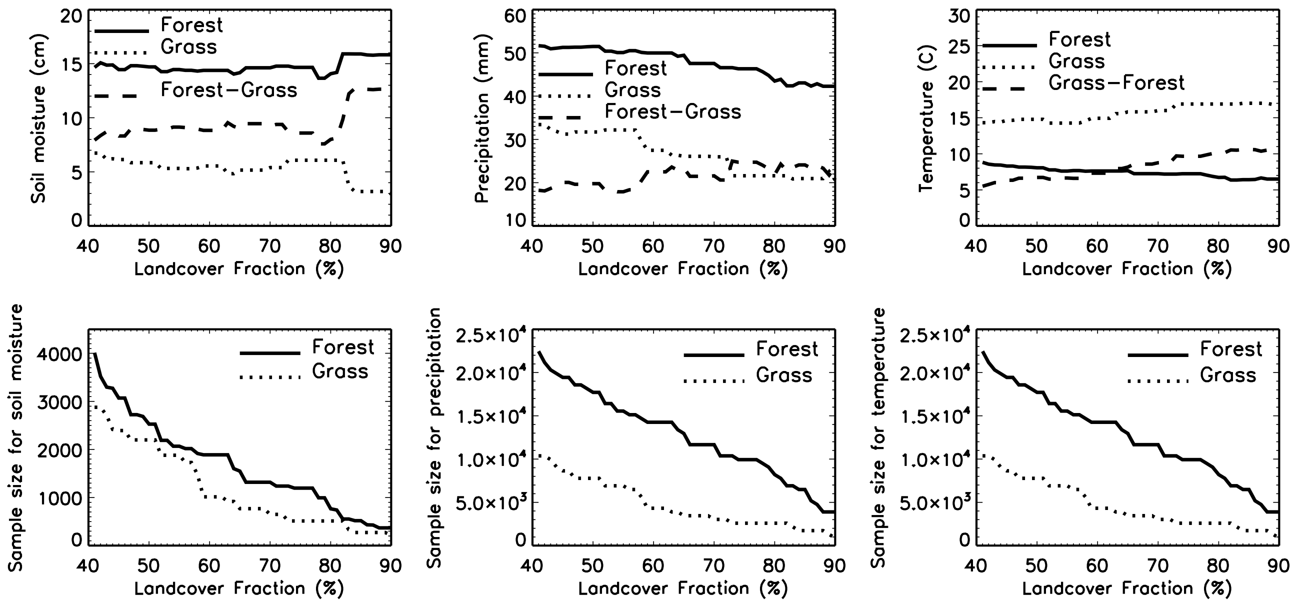

Figure 4. Comparison of soil moisture, precipitation, and temperature averaged over subsamples with the fraction of forest or grassland greater than the indicated threshold. Thresholds are taken from 40% to 90% and their differences (top) and the sample size for each variable and the imposed thresholds (bottom).

shows that mean soil moisture anomaly in spring (March to April) and the average cold season precipitation anomaly in the previous winter among stations in the former Soviet Union are well correlated. We define cold season precipitation as the monthly precipitation when the monthly mean air temperature falls below 0°C. Soil moisture anomaly in spring is strongly correlated with winter precipitation anomaly, with the correlation coefficients reaching 0.642 ($p = 0.086$) for the combined stations in the former Soviet Union. The relation is significant at the $p < 0.1$ level, but not at the

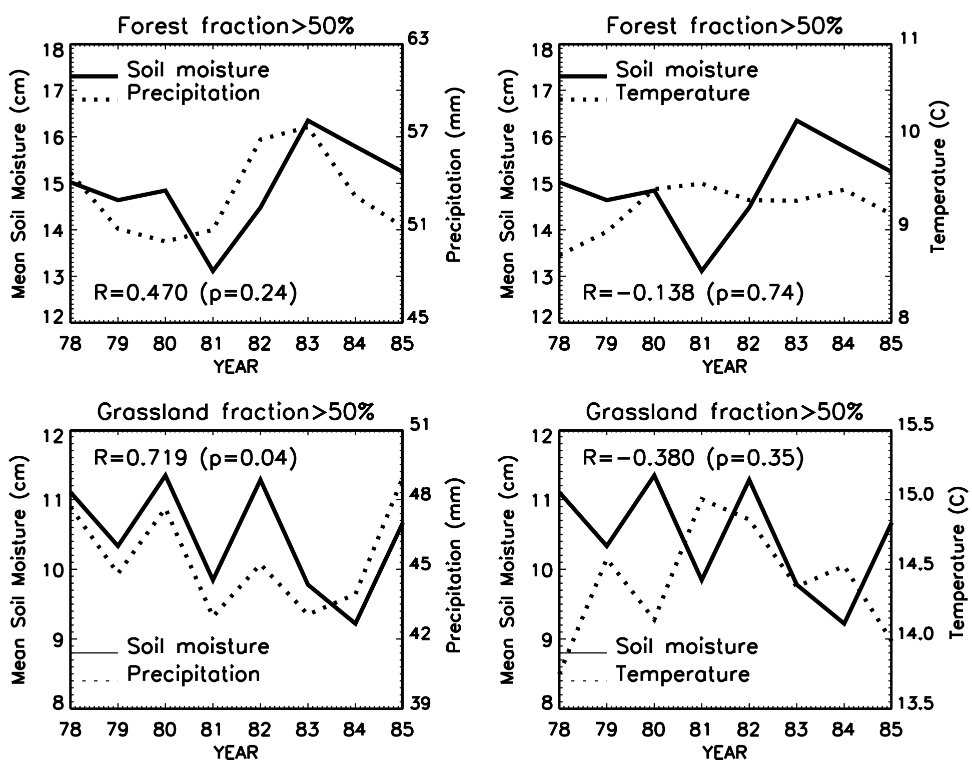

Figure 5. Comparison of the interannual variability between soil moisture and climate among stations in the former Soviet Union averaged over the growing season (April to October). The correlation coefficient (R) and its p-value (p) are shown in each panel.

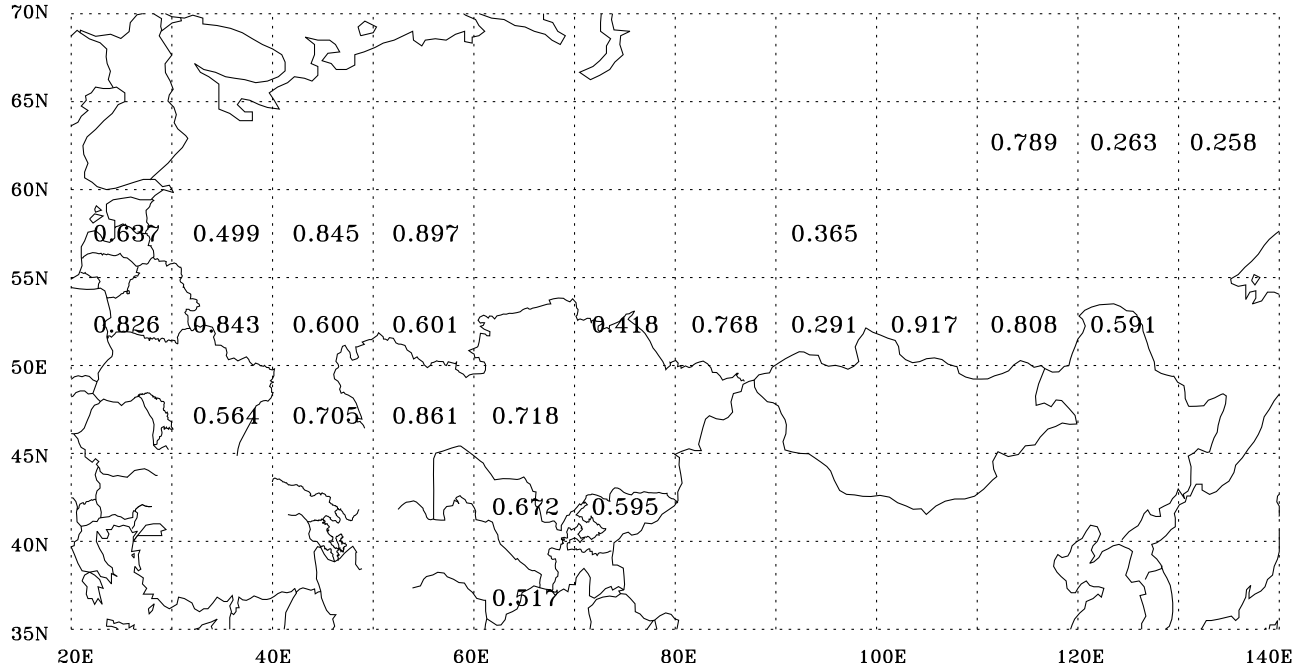

Figure 6. Correlation coefficients between growing season (April–October) soil moisture and climate variable (precipitation) for each 5 by 10 degree grid box in the former Soviet Union.

$p < 0.05$ level. It is not surprising for given the small sample size. The strong relationship indicates that cold season precipitation is an important source of spring soil moisture. The correlation coefficient between spring precipitation anomaly and spring soil moisture anomaly is just 0.182 (Figure 7b). We notice that total precipitation in spring is about 4 times less than the winter total. Although precipitation in spring provides more direct input to soil moisture, the larger amount of cold season precipitation plays a more important role for increasing springtime soil moisture.

[21] The relationship between cold season precipitation and soil moisture for each month from January to December in the following year is further investigated in Figure 7c. High correlations are found for the soil moisture in February to April (r exceeds 0.5) with maximum correlation coefficient reaching 0.83 presumably because of the spring snowmelting process. Since June, the correlation coefficients drop to negative values indicating winter precipitation is negatively correlated to soil moisture in June through December. This result is consistent with *Meschcherskaya et al.* [1982], who found a negative correlation between surface soil moisture and snow depth in May in western Russia (centered at 53°N, 36°E) using soil moisture and snow depth data collected from 1951–1977. Note that they used surface soil moisture data, which is more readily evaporated than evaporation from deep soil [*Wu and Dickinson*, 2005]. Therefore for their case, the negative relationship started in May, rather in June as shown in our study. Apparently strong evaporation or drainage during the early summer months reduces this correlation. *Wu and Dickinson* [2004] indicated that freezing and melting processes also plays a role in high-latitude summer soil

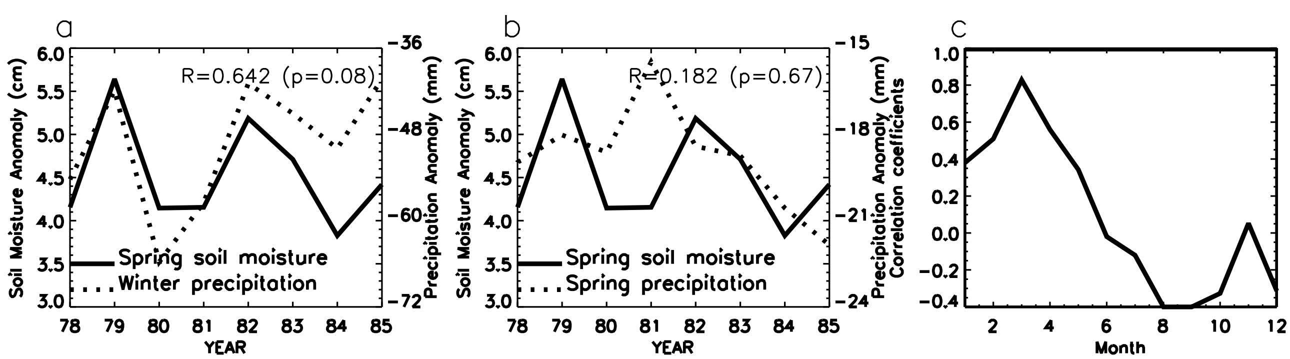

Figure 7. (a) Correlation between mean soil moisture in spring (March to May) and total cold season precipitation during previous winter months with the former Soviet Union data and its p-value, (b) correlation between mean soil moisture and total precipitation in spring and its p-value, and (c) correlation coefficients between the winter precipitation and soil moisture in each month of the following year.

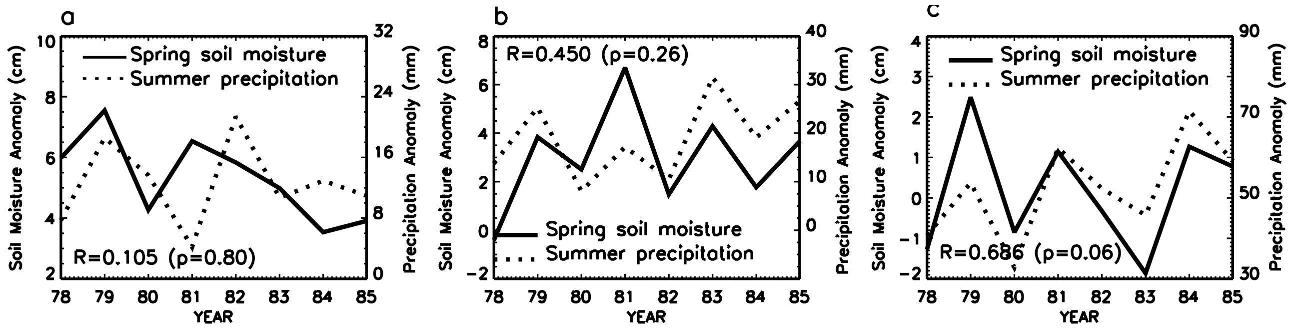

Figure 8. (a) Correlation between mean soil moisture in early spring (March and April) and mean precipitation in subsequent summer (July and August) for the stations with grassland fraction above 50% in a box between 45°N–55°N and 20°E–80°E, (b) with forest fraction above 50% in two boxes between 55°N–70°N and 20°E–60°E, and (c) between 50°N–55°N and 100°E–120°E and the corresponding p-values of each correlation.

moisture memory. Figure 7 demonstrates the role of winter snow accumulation on spring soil moisture, which has an impact on the consequent summer precipitation as discussed in the following section.

4.2. Spring Soil Moisture and Subsequent Summer Precipitation

[22] Among the four factors controlling soil moisture memory: seasonality of atmospheric forcing, evaportranspiration, runoff, and the persistence of antecedent soil moisture [*Koster and Suarez*, 2001], land-atmosphere memory is mostly determined through the fourth factor, which also depends on how evaportranspiration and runoff are partitioned, and the diffusion of water through the soil column. Evapotranspiration is the dominant force changing soil moisture for root zone soil moisture memory. In this study, we explore the correlation between observed precipitation and in situ former Soviet Union root zone soil moisture measurements with the emphasis on evaportranspiration in the relationships.

[23] The former Soviet Union in situ soil moisture observations cover a region with large latitude and longitude variations, ranging between 35°N and 70°N, 20°E and 140°E. Therefore it is unreasonable to assume that the same degree of land-atmosphere interaction is operating equally over the entire spatial domain [*Entin et al.*, 2000; *Koster and Suarez*, 2003]. To consider spatial variability and regional differences, this analysis focuses on the subregions that have forest or grassland as dominant land covers. Figure 8 shows that soil moisture anomaly in spring (March and April) and the subsequent precipitation anomaly in summer (July and August) are well correlated. Again, if the soil moisture data in spring are missing at one location, we omitted the corresponding precipitation data from the analysis.

[24] We selected a relatively small grassland dominant region (45°N–55°N, 20°E–80°E) to investigate the correlation of spring soil moisture anomaly with subsequent summer precipitation anomaly. The correlation coefficient is just 0.105 for the 36 stations with grass fraction greater than 50% in each half-degree pixel area (Figure 8a). Most forest dominant sites are located in three regions. There are a total of 11 catchments in box F1 (55°N–70°N, 20°E–60°E), 10 catchments in box F2 (50°N–55°N, 100°E to 120°E), and 13 catchments in box F3 (59°N–65°N, 110°E–140°E). Because soil moisture data in spring were not collected in box F3, the other two boxes with spring soil moisture available at 6 out of 11 stations in box 1 and 5 out of 10 stations in box F2 (Figure 1) were used to investigate the relation between soil moisture in spring and subsequent summer precipitation on a relatively small regional scale. Spring soil moisture anomaly is closely correlated to summer precipitation anomaly in both boxes, and the correlation coefficients are 0.45 ($p = 0.263$) in box F1 and 0.686 ($p = 0.061$) in box F2 (Figures 8b and 8c). The relatively weak relation in box F1 implies that the atmospheric pattern plays the major role in controlling the precipitation in the western Russia.

[25] These relationships demonstrate the possible role of vegetation in soil moisture and precipitation feedbacks. As mentioned before, evapotranspiration is a primary driver of land-atmosphere interaction. Therefore vegetation transpiration can effectively translate a soil moisture anomaly into an atmospheric boundary layer humidity anomaly, which can be subsequently translated into a precipitation anomaly through atmospheric processes. Our study demonstrates that forests with extensive root biomass are better able to utilize spring soil moisture to enhance summer precipitation than grassland dominant sites. We can speculate that during the early growing season when potential evaporation is low, soil moisture in deeper layers may remain undisturbed. In summer, the extensive root system from forest dominant sites can utilize the soil water from the deeper layers. Indeed, *Kleidon and Heimann* [2000] found that deeper roots lead to pronounced seasonal response. For wet anomalies, evapotranspiration and the associated latent heat flux are considerably increased over large regions, possibly leading to more convective atmospheric conditions. Our result is consistent with the idea that vegetation can modify the local climate through evaportranspiration [*Shukla and Mintz*, 1982].

[26] Our analysis also shows different relationships for both forest dominant sites, with larger correlation coefficients in the east than in the west. That implies that the soil moisture and precipitation relationships are also geographically dependent, presumably due to difference of atmospheric conditions. The climate systems in Russia mainly originate from the Atlantic Ocean, moving from west to east

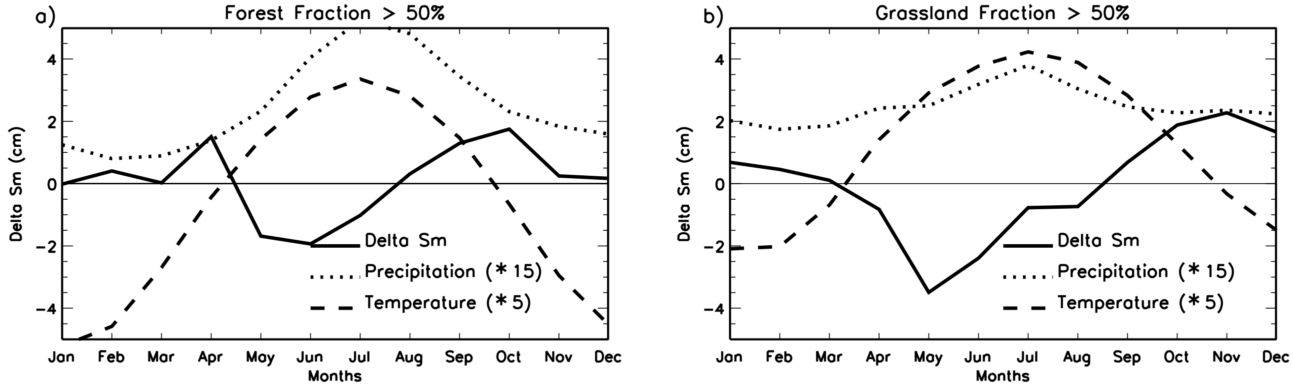

Figure 9. Monthly soil moisture change, precipitation, and mean air temperature averaged over (a) forest dominant sites and (b) grassland dominant sites with data from the former Soviet Union. Multiply by 15 to get the precipitation values and multiply by 5 to get air temperature values.

over Russia. Therefore we see a relatively weaker influence of forest transpiration to modify local precipitation in the west than in the east.

4.3. Possible Mechanism of Soil Moisture Memory

[27] Anything that acts to reduce the distinctiveness between soil moisture states should reduce soil moisture persistence, and thus soil moisture persistence is controlled by a combination of climate properties, land surface characteristics and land-atmosphere interaction [*Koster and Suarez*, 2001]. To better understand how vegetation influences soil moisture memory, and soil moisture and precipitation feedbacks, we compare the soil moisture change in each month with monthly precipitation and temperature over forest and grassland dominant regions separately (Figure 9). The monthly soil moisture change is calculated as the difference between the soil moisture at the end of the current month (day 28 in month i) and the soil moisture at the end of the previous month (day 28 in month $i - 1$).

[28] The monthly soil moisture starts to decrease when the temperature is above 0°C at the beginning of growing season, even though the precipitation has increased. Soil moisture keeps decreasing until August, presumably because evaporation exceeds precipitation. The net loss of soil water over the growing season can be characterized as the area of the soil moisture change curve under the zero line (Figure 9). Soil moisture decreases less during the growing season over forest regions than over grassland regions because of relatively large precipitation and cool air temperature over forests. As a result of this and the fact that spring soil moisture is drier over grassland to begin with, summer soil moistures for grassland tend to be more similar than those for forest (see Figure 10). Over grassland, the larger soil moisture loss tends to bring soil moisture to about the same level, presumably near the wilting level. This is consistent with the idea discussed by *Koster and Suarez* [2001] that the reduced distinction from initial soil moisture states by evaporation will reduce soil moisture memory.

[29] The net result of leveling off grassland summer soil moisture to about the same value each year is a lower spring-summer autocorrelation for grassland. For a threshold of 50% defining the forest and grassland fractions, the spring-summer autocorrelation for forest is 0.8 and that for grassland is 0.53. The slope of the fitted line in Figure 10 represents the ratio of soil moisture variability in summer relative to spring soil moisture variability. Forest retains about 87% of its soil moisture variability from spring to summer, but grassland keeps only 39%. Generally, the residual of the combined precipitation (P), evapotranspiration (ET), and runoff (P − ET − Runoff) is considered as external forcing to influence the timescales of the soil moisture profile [e.g., *Wu and Dickinson*, 2004]. Our results presented in Figure 9 show that soil moisture is reduced less over forest regions in spring than over grassland regions, resulting in longer soil moisture memory in forest.

[30] As for the impact of snowmelt on soil moisture memory in spring, we note that most forest dominant stations are located in the latitudinal belt from 55°N to 70°N, with very cold temperatures (below −20°C) in winter. Winter temperatures over grassland are not as low (−10°C). Therefore a larger amount of snowpack is available in forest dominant regions than in grassland dominant regions. Figure 9 shows that soil water exhibits a sharp increase on April for forest dominant regions due to snowmelt, while there is not such increase seen for grassland dominant regions. Our analysis indicates that snow accumulation and snowmelt influence soil moisture memory

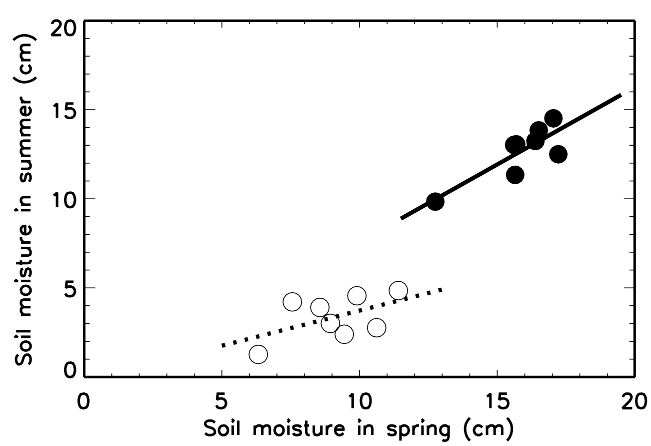

Figure 10. Comparison between spring and summer soil moistures for forests (solid circles) and grassland (open circles). The solid line is the regression fit for the forest site, and the dashed line is for grassland.

and soil moisture and precipitation feedback in forest regions and possibly links to the soil moisture memory in spring to summer. However, this effect is not strong in grassland regions.

5. Summary and Discussion

[31] In this study we utilized independent measurements of soil moisture, monthly near-surface climate, and global land cover to investigate, without the use of a model, the relationships between soil moisture and near-surface climate at seasonal to interannual scales, emphasizing the influences of cold season processes and vegetation types on these relationships. At an interannual scale, a strong positive (negative) correlation between soil moisture and precipitation (temperature) is found over grassland. The correlations are weak over forest regions, because forests may remain moist enough (much greater mean soil moisture) that the trees are never water stressed. The immediate response between soil moisture and precipitation in grassland regions indicates that evaporation in grassland regions transfers water from near-surface soil to the atmosphere, whereas in forest regions, transpiration transfers water from deeper root zone soil to the atmosphere and reflects soil moisture memory with longer timescales [*Wu and Dickinson*, 2005].

[32] At the seasonal scale, accumulations of cold season precipitation are positively correlated with springtime soil moisture, then becoming negatively correlated in the summer. This result is consistent with *Meschcherskaya et al.* [1982], who used a longer observation period (27 years). This indicates that winter snow accumulation plays more important roles than the precipitation in spring because of snowmelting processes. The spring/summer autocorrelation of soil moisture is stronger for forests than for grassland, apparently because the greater loss of soil moisture during the growing season for grassland brings the soil moisture each year to approximately the same low limiting value. Our analysis in Russia is consistent with the idea that soil moisture anomalies can persist into summer, thereby enhancing precipitation in summer in forest dominant regions. This result can be explained by the theory proposed by *Koster and Suarez* [2001], that the residual of the combined precipitation, ET, and runoff acts to prolong the timescales of soil moisture memory over forest regions [*Mahanama and Koster*, 2005; *Wu and Dickinson*, 2004].

[33] The statistical analysis in this study is limited by the short data record, as the correlation is based on only eight data pairs. Monte Carlo analysis suggests that if no intrinsic, physical correlations between spring soil moisture and summer rainfall exist, a false positive correlation of 0.6 could still occur with a probability of about 6%. Inferring causality from the statistics is also dangerous, given that an external mechanism (e.g., persistent SSTs) may be responsible for the high correlation. However, our statistical analysis showed consistent results in many aspects. These are the relationship between soil moisture and precipitation at an interannual scale, and at a seasonal scale the relationship between winter snow accumulation and spring soil moisture and the relationship between spring soil moisture and summer precipitation. Moreover, our findings are consistent with the recent modeling studies [*Liu and Avissar*, 1999; *Wu and Dickinson*, 2004]. In this paper, we are careful in selecting Russia, a region away from monsoon influences as our study area, and we merely note that the statistics are consistent with it. Future modeling studies using longer in situ soil moisture time series is necessary to fully explore and verify these relationships.

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References

Alexeyev, V. A., and R. A. Birdsey (1998), Carbon storage in forests and peatlands of Russia, *Gen. Tech. Rep. NE-244*, USDA For. Serv., Washington, D. C.

Betts, A. K. (2004), Understanding hydrometeorology using global models, *Bull. Am. Meteorol. Soc.*, *85*(11), 1673–1688, doi:10.1175/BAMS.-85-11-1673.

Delworth, T. L., and S. Manabe (1988), The influence of potential evaporation on variabilities of simulated soil wetness and climate, *J. Clim.*, *1*, 523–547.

Delworth, T., and S. Manabe (1989), The influence of soil wetness on near-surface atmospheric variability, *J. Clim.*, *2*(12), 1447–1462.

Dickinson, R. E., and A. Henderson-Sellers (1988), Modelling tropical deforestation: A study of GCM land-surface parameterizations, *Q. J. R. Meteorol. Soc.*, *114*, 439–462.

Dong, J., R. K. Kaufmann, R. B. Myneni, C. J. Tucker, P. E. Kauppi, J. Liski, W. Buermann, V. Alexeyev, and M. K. Hughes (2003), Remote sensing of boreal and temperate forest woody biomass: Carbon pools, sources and sinks, *Remote Sens. Environ.*, *84*, 393–410.

Entin, J. K., A. Robock, K. Y. Vinnikov, S. E. Hollinger, S. Liu, and A. Namkhai (2000), Temporal and spatial scales of observed soil moisture variations in the extratropics, *J. Geophys. Res.*, *105*, 11,865–11,877.

Fennessy, M. J., and J. Shukla (1999), Impact of initial soil wetness on seasonal atmospheric prediction, *J. Clim.*, *12*, 3167–3180.

Giorgi, F., and M. R. Marinucci (1996), An investigation of the sensitivity of simulated precipitation to model resolution and its implications for climate studies, *Mon. Weather Rev.*, *124*, 148–166.

Hansen, M. C., R. S. DeFries, J. R. G. Townshend, and R. Sohlberg (2000), Global land cover classification at 1 km spatial resolution using a classification tree approach, *Int. J. Remote Sens.*, *21*, 1331–1364.

Heck, P., D. Luthi, and C. Schar (1999), The influence of vegetation on the summertime evolution of European soil moisture, *Phys. Chem. Earth.*, *24*, 609–614.

Heck, P., D. Luthis, H. Wernli, and C. Schar (2001), Climate impacts of European-scale anthropogenic vegetation changes: A sensitivity study using a regional climate model, *J. Geophys. Res.*, *106*, 7817–7835.

Huang, J., H. M. van den Dool, and K. P. Georgakakos (1996), Analysis of model-calculated soil moisture over the United Sates (1931–1993) and applications to long-range temperature forecasts, *J. Clim.*, *9*, 1350–1362.

IPCC (Intergovermental Panel on Climate Change) (2001), Chapter 3: The carbon cycle and atmospheric carbon dioxide, in *Climate Change 2001: The Scientific Basis*, Cambridge Univ. Press, New York.

Kleidon, A., and M. Heimann (2000), Assessing the role of deep rooted vegetation in the climate system with model simulations: Mechanism, comparison to observations and implications for Amazonian deforestation, *Clim. Dyn.*, *16*, 183–199.

Koster, R. D., and M. J. Suarez (1995), Relative contributions of land and ocean processes to precipitation variability, *J. Geophys. Res.*, *100*, 13,775–13,790.

Koster, R. D., and M. J. Suarez (2001), Soil moisture memory in climate models, *J. Hydrometeorol.*, *2*, 558–570.

Koster, R. D., and M. J. Suarez (2003), Impact of land surface initialization on seasonal precipitation and temperature prediction, *J. Hydrometeorol.*, *4*, 408–423, doi:10.1175/1525-7541(2003)4<408:IOLSIO>2.0.CO;2.

Liu, Y., and R. Avissar (1999), A study of persistence in the land-atmosphere system using a general circulation model and observations, *J. Clim.*, *12*, 2139–2153.

Luo, L., et al. (2003), Effects of frozen soil on soil temperature, spring infiltration, and runoff: Results from the PILPS 2(d) experiment at Valdai, Russia, *J. Hydrometeorol.*, *4*, 334–351.

Mahanama, S. P. P., and R. D. Koster (2005), AGCM Biases in evaporation regime: Impacts on soil memory and land-atmosphere feedback, *J. Hydrometeorol.*, *6*, 656–669.

Meschcherskaya, V. I., N. A. Boldyreva, and N. D. Shapaeva (1982), District average plant available soil water storage and the depth of snow cover, statistical analysis and its usage (some examples) (in Russian), 243 pp., Gidrometeoizdat, St. Petersburg, Russia.

Mintz, Y. (1984), The sensitivity of numerically simulated climates to land-surface boundary conditions, in *Global Climate*, edited by J. T. Houghton et al., pp. 79–105, Cambridge Univ. Press, New York.

New, M., M. Hulme, and P. Jones (2000), Representing twentieth-century space-time climate variability. part II: Development of 1901–96 monthly grids of terrestrial surface climate, *J. Clim.*, *13*, 2217–2238.

Pan, Z., M. Segal, R. Turner, and E. Takle (1995), Model simulation of impacts of transient surface wetness on summer rainfall in the United States Midwest during drought and flood years, *Mon. Weather Rev.*, *123*, 1575–1581.

Pielke, R. A., R. Avissar, M. Raupach, H. Dolman, X. Zeng, and S. Denning (1998), Interactions between the atmosphere and terrestrial ecosystems: Influence on weather and climate, *Global Change Biol.*, *4*, 461–475.

Robock, A., K. Y. Vinnikov, C. A. Schlosser, N. A. Sperankaya, and Y. Xue (1995), Use of midlatitude soil moisture and meteorological observations to validate soil moisture simulations with biosphere and bucket models, *J. Clim.*, *8*, 15–35.

Robock, A., C. A. Schlosser, K. Y. Vinnikov, N. A. Sperankaya, J. K. Entin, and S. Qiu (1998), Evaluation of the AMIP soil moisture simulations, *Global Planet. Change*, *19*, 181–208.

Robock, A., K. Y. Vinnikov, G. Srinivasan, J. K. Entin, S. E. Hollinger, N. A. Sperankaya, S. Liu, and A. Namkhhai (2000), The global soil moisture data bank, *Bull. Am. Meteorol. Soc.*, *81*(6), 1281–1299.

Schlosser, C. A., A. Robock, K. Y. Vinnikov, N. A. Speranskaya, and X. Yongkang (1997), 18-year land-surface hydrology model simulations for a midlatitude grassland catchment in Valdai, Russia, *Mon. Weather Rev.*, *125*, 3279–3296.

Shukla, J., and Y. Mintz (1982), The influence of land-surface evapotranspiration on the Earth's climate, *Science*, *214*, 1498–1501.

Vinnikov, K. Y., and I. B. Yeserkepova (1991), Soil moisture: Empirical data and model results, *J. Clim.*, *4*, 66–79.

Vinnikov, K. Y., A. Robock, N. A. Speranskaya, and A. Schlosser (1996), Scales of temporal and spatial variability of midlatitude soil moisture, *J. Geophys. Res.*, *101*, 7163–7174.

Wu, W., and R. E. Dickinson (2004), Time scales of layered soil moisture memory in the context of land-atmosphere interaction, *J. Clim.*, *17*, 2752–2764.

Wu, W., and R. E. Dickinson (2005), Warm-season rainfall variability over the U.S. Great Plains and its correlation with evapotranspiration in a climate simulation, *Geophys. Res. Lett.*, *32*, L17402, doi:10.1029/2005GL023422.

Xue, Y., H.-M. H. Juang, W. Li, S. Prince, R. DeFries, Y. Jiao, and R. Vasic (2004), Role of land surface processes in monsoon development: East Asia and West Africa, *J. Geophys. Res.*, *109*, D03105, doi:10.1029/2003JD003556.

Yeh, T. C., R. T. Wetherald, and S. Manable (1984), The effect of soil moisture on the short-term climate and hydrology change: Numerical experiment, *Mon. Weather Rev.*, *112*, 474–490.

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