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Scales of temporal and spatial variability of midlatitude soil moisture

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Abstract. Soil moisture observations from direct gravimetric measurements in Russia are used to study the relationship between soil moisture, runoff, and water table depth for catchments with different vegetation types, and to estimate the spatial and temporal correlation functions of soil moisture for different soil layers. For three catchments at Valdai, Russia, one with a grassland, one with an old forest, and one with a growing forest, the interannual soil moisture variations are virtually the same for the 31-year period, 1960-1990. The runoff is higher for the grassland than for the old forest, and the water table depth is not as deep. The runoff and water table for the growing forest vary from grassland-like during the first decade, when the trees are small, to old forest-like at the end of the period. The seasonal cycle of soil moisture is similar at all three catchments, but the snowmelt and summer drying begin a month earlier at the grassland than in the forests. A statistical model of both temporal and spatial variations in soil moisture is developed that partitions the variations into red noise and white noise components. For flat homogeneous plots, the white noise component is relatively small and represents solely random errors of measurement. For natural landscapes with variable vegetation and soil types, and complicated topography, this component is responsible for most of the temporal or spatial variance. The red noise component of temporal variability is in good agreement with theory. The timescale of this component is equal to the ratio of field capacity of soil to potential evapotranspiration, approximately 3 months. The red noise component of spatial variability reflects the statistical properties of the monthly averaged precipitation field. The scale of spatial correlation of this component is about 500 km. The estimates of scales of temporal and spatial correlation do not differ significantly for water content in the top 20-cm and 1-m layers of soil. These results have important implications for both remote sensing of soil moisture and soil moisture parameterization in climate models.

Introduction

This article is the first in series of publications related to analysis of multidecadal hydrometeorological observations at a few small experimental catchments at the Valdai experimental station of the State Hydrological Institute in St. Petersburg, Russia. In this article the data are used for a statistical study of temporal and spatial variability of midlatitude soil moisture for several types of natural vegetation.

The most significant attempts to study temporal and spatial autocorrelation functions of soil moisture fields using data from long-term direct gravimetric soil moisture measurements in agricultural fields of the former Soviet Union (FSU) were made by *Kontorshchikov* [1979] and *Meshcherskaya et al.* [1982]. The estimates published in their papers give valuable information which has not been interpreted properly until now due to the lack of a theory.

Delworth and Manabe [1988, 1993], using the Geophysical Fluid Dynamics Laboratory (GFDL) general circulation model of the climate system, recognized that a statistical model of temporal variability of soil moisture corresponds to a first-order Markov process in which the autocorrelation function $r(t)$ is exponential:

$$r(t) = \exp\left(-\frac{t}{T}\right), \tag{1}$$

where t is the time lag, and T is the scale of temporal autocorrelation, the e-folding time for the damping of soil moisture anomalies in the absence of forcing. They also showed that

$$T \approx \frac{W_f}{E_o}, \tag{2}$$

where W_f is the field capacity of the soil active layer and E_o is

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the potential evapotranspiration. Both these inferences were tested and validated by *Vinnikov and Yeserkepova* [1991] using long-term (14-33 years) gravimetric observations of soil water content in the upper 1-m soil layer at 32 meteorological stations of the FSU with horizontal homogeneous plots covered by natural meadow vegetation, with observations made 3 times per month.

Gandin [1963] showed that an empirically estimated autocovariance function, $\hat{R}(t)$, contains a singularity at the point $t=0$, as a result of the influence of random errors of measurement, which do not influence $\hat{R}(t)$ for lag $t \neq 0$. Let $\hat{\sigma}^2$ be an estimate of the variance of the real soil moisture and $\hat{\delta}^2$ be an estimate of the variance due to random errors of measurement. The empirical estimate of the autocorrelation function $\hat{r}(t)$ from observed data is then,

$$\hat{r}(t) = \frac{\hat{R}(t)}{\hat{R}(t=0)} \tag{3}$$

and it should be corrected for time lags $t \neq 0$ by multiplying by a coefficient equal to $\hat{R}(t=0)/\hat{\sigma}^2$. To receive an unbiased estimate of variance $\hat{\sigma}^2$, *Gandin* [1963] recommended extrapolation of the empirical estimates $\hat{R}(t \neq 0)$ to the point $t=0$ and the use of this extrapolated but unbiased value $\hat{\sigma}^2$ instead of the biased estimate $\hat{R}(t=0) = \hat{\sigma}^2 + \hat{\delta}^2$. Such a method is now classical and is commonly used in statistical meteorology. The ratio $a = \hat{\delta}^2 / \hat{\sigma}^2$ is usually used as a measure of the random error of measurement, which includes the error in using point samples to represent an area. Using this approach, *Robock et al.* [1995] estimated that the root-mean-square error of soil moisture in upper 1-m layer gravimetric measurements at a typical station with homogeneous meadow vegetation does not exceed the value of 1 cm of water. *Vinnikov and Yeserkepova* [1991] showed that corrected empirical estimates of temporal autocorrelation functions of soil moisture in the upper 1-m soil layer for $t \neq 0$ may be successfully approximated by (1). They also found statistical estimates of the timescale parameter $\hat{T}$ to be in satisfactory agreement with (2).

The temporal variability of soil moisture in the GFDL climate model corresponds to a statistical model of red noise. Time series of long-term measurements of soil moisture on idealized land plots with flat horizontal surfaces, and spatially homogeneous soils and natural, mostly meadow, vegetation correspond to a statistical model which is a sum of red noise and white noise components, but the white noise component should be fully attributed to random errors of gravimetric measurement. Hence the theoretical conclusion of Delworth and Manabe that the spectrum of temporal variations of soil moisture corresponds to a first-order Markov process with the decay timescale being equal to the ratio of field capacity to potential evaporation has been confirmed for periods from 20 days to about 10 years [*Vinnikov and Yeserkepova*, 1991].

Natural lands are mostly quite different, however, from the flat, horizontally homogeneous plots which were selected for the soil moisture observation program at Russian meteorological stations. Natural landscapes usually have variable vegetation and soil types and complicated topography. The goal of this paper is to study the statistical structure of soil moisture for natural conditions. To solve this problem, multidecadal soil moisture measurements at three small experimental catchments at the Valdai, Russia, water balance station have been used.

Data

The water balance station Valdai (57.6°N, 33.1°E), in the forest zone of Russia, is operated by the State Hydrological Institute in St. Petersburg, Russia. This station is a scientific center where the methods of water balance measurements were tested and then used for creation of a network of 24 water balance stations in different climatic zones of the FSU [*Zavodchikov and Zhuravin*, 1981]. The Valdai measurements for many decades have been published in annual reference books which have never been available to the international scientific community, but many Russian scientific publications contain the results of scientific analysis of Valdai station data. The most important is the monograph by *Fedorov* [1977], a study of water balance components in the forest zone of the European part of the FSU.

In our research we use data of soil moisture measurements for three small experimental catchments with different vegetation: Usadievskiy, Tayozhniy, and Sinaya Gnilka. At each catchment, measurements of total soil moisture were taken at the end of each month using the gravimetric technique for every 10-cm layer to a depth of 1 m. In this paper we use data from the top 20-, 50-, and 100-cm layers. Every few years for each catchment, soil moisture was measured at regular dense grids to receive a full picture of soil water accumulation. These data were used to choose a smaller amount of representative sites to use permanently. Usually, once chosen, the same points were used continuously to represent each catchment, but in 1979 at Tayozhniy all but two "permanent" points were changed in 1979, as can be seen in Figure 1. Water table depth and runoff are also measured at each catchment. The same triangle weirs with continuous registration of the water level have been used for runoff measurement at the Valdai catchments during the entire time period of our data, 1960-1990.

The area of Usadievskiy is 0.36 km^2 (length about 0.8 km and mean width 0.45 km). This catchment is 81% grassland, 16% swamp, and 3% forest. The relief is hilly. The mean height of the hills is 4 m, with maximum up to 20 m. The mean slope of the catchment surface is 0.076. The soil is varied but is mostly a loam covered by a sandy loam layer of about 0.5 m thickness. The soil moisture is measured at 11 sites which were found to be the best for estimation of the catchment mean values of soil moisture. This study uses 1960-1990 soil moisture data for Usadievskiy catchment. We will refer to this catchment in this paper as Grassland.

Tayozhniy is mainly an old forest (99% of the area). The area is 0.45 km^2 (length 0.9 km and mean width 0.5 km). The forest is mainly spruce and the grove is 100- to 110-years old. The relief is hilly with ridges of 6- to 8-m height on average. The mean slope of the catchment surface is 0.085. The soil is mostly a moraine loam covered by a 0.5-m layer of a sandy loam. The soil moisture is also measured at 11 sites. In this paper we use data for 1960-1990. We will refer to this catchment in this paper as Old Forest.

The catchment Sinaya Gnilka area is only 0.015 km^2. It is comparatively flat, horizontal, and homogeneous in soil and

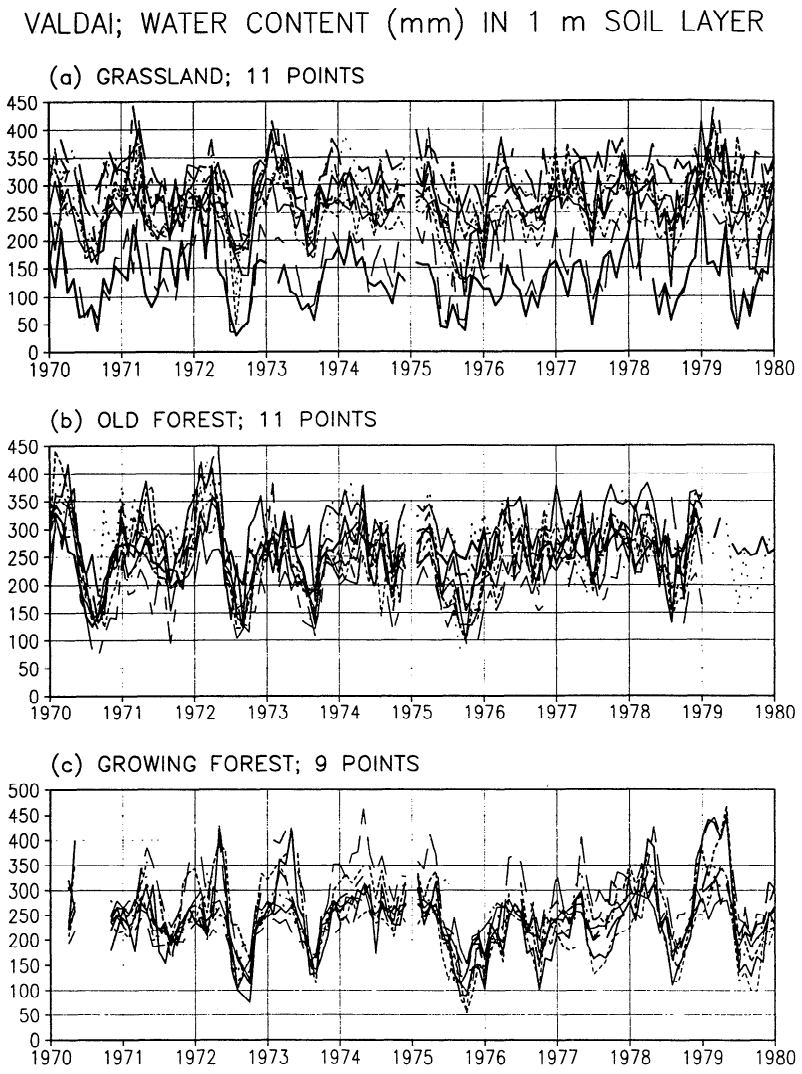

Figure 1. Upper 1 m layer soil moisture content for the different sites (points) at each of the three Valdai catchments Grassland (Usadievskiy), Old Forest (Tayozhniy), and Growing Forest (Sinaya Gnilka) for 1970-1979.

vegetation as compared to the other catchments, and has a mean slope of 0.107. Soils are mostly moraine loams with an upper sandy layer with a thickness of 0.5-1.0 m. This catchment had been an agricultural field up to 1961, when 4- to 5-year-old trees (spruce and pine) were planted with a density of about one tree per 5 m^2. As we show below, during the next decade the soil moisture regime for the catchment did not differ from that of a grassland. Then a period of intensive tree growth began. At the time when the authors of this article visited the catchment in 1991, it looked like a natural forest. It was originally planned that as part of the experiment, once such a forest had grown it would be cut down and soil moisture measurements would continue. It turned out that the forest cutting was forbidden by the Soviet environmental protection service. For this reason and because of subsequent economic difficulties, the experiment was halted. Nevertheless, we will take advantage of the measurements taken before its halt and use soil moisture measurements for Sinaya Gnilka for 1970-1987 taken at nine sites of the catchment. We will refer to this catchment in this paper as Growing Forest.

Interannual Variations

As an example of the detailed measurements, Figure 1 shows the 1970-1979 measurements of upper 1 m layer soil water content at each of the different sites (points) at each of the 3 catchments. Both the interannual component of variation in soil moisture content and the seasonal one are difficult to distinguish in the data for the separate points. There is a particularly large range in soil water content for the different points at the Grassland catchment. There is not any one single point for any catchment which represents the catchment as a whole. It is more or less obvious that measurements from many points inside each catchment must be averaged if the variation of soil moisture for the whole catchment is to be monitored. We will consider some simple statistics for the measurements at separate points in the next section. It is important to note that the monthly sampling strategy here is not as good as the 10-day interval for soil moisture sampling at regular meteorological stations. A significant part of the temporal variability during the summer season can be lost.

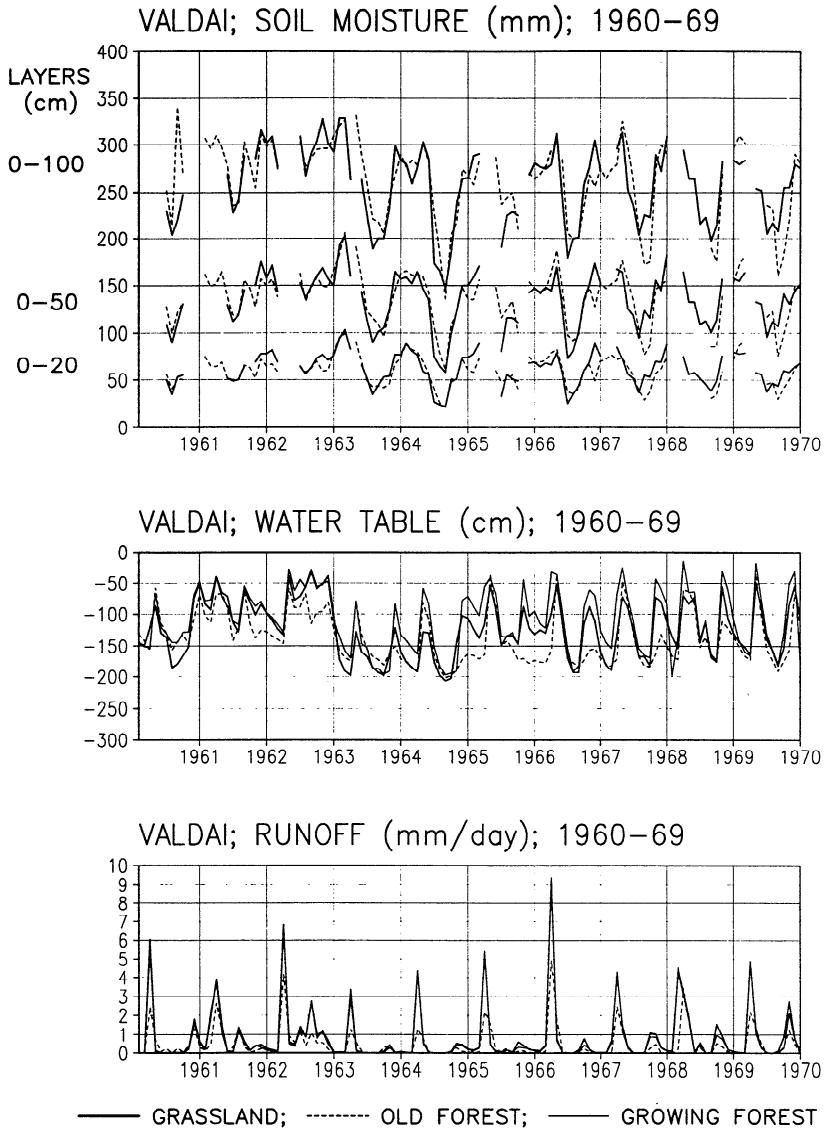

Figure 2. Soil moisture, water table, and runoff observations during all three decades of the period 1960-1990. Observations were averaged from the individual sites of each catchment. The water content of three soil layers, upper 20 cm, upper 50 cm, and upper 1 m, is shown.

Figure 2 shows each catchment's soil moisture measurements during all three decades of the period 1960-1990, for the upper 20-cm, 50-cm, and 1-m layers. We found that differences between catchments in variations of water content in the three soil layers are not as significant as could be expected, with the interannual and seasonal variations of soil moisture comparable in amplitude. In addition, it is almost impossible to recognize which curve in the top parts of Figure 2 is from which catchment.

The similarity of soil moisture for catchments with very different vegetation is very surprising. In some particular years, for example, 1974, the summer minimum of soil moisture is almost absent at all the catchments, but in 1972, 1973, and 1975 the summer soil dryness was extremely well pronounced. One obvious explanation for this is that the same external atmospheric forcing is responsible for the major part of the temporal variations in soil moisture in each of these three catchments. The decisive role of atmospheric forcing in variations of soil moisture has been shown by *Robock et al.* [1995] for six midlatitude meteorological stations. We are now conducting such modeling for Valdai catchments, and expect that they will reveal the role of differences in their topography and land cover.

The physical nature of large soil moisture anomalies can be studied using the information on changes in water table depth and runoff at each of the catchments included in Figure 2. For example, the drought in 1975 was accompanied by a significant increase of the water table depth and by a runoff reduction almost to zero just after the springtime snowmelt. These data show that in the spring and autumn the water table level regularly rises into the upper 1 m soil layer and influences the variation in water content of this layer. A detailed study of the climatology of all the water balance components for Valdai, including results of model calculations, will be the subject of another paper, but we present preliminary observations here.

Figure 3 shows the variations of annual average soil moisture in the top 1 m, snowmelt, runoff, and water table depth for the three catchments for the 31-year period of data, 1960-1990. The catchment-average soil moisture for the

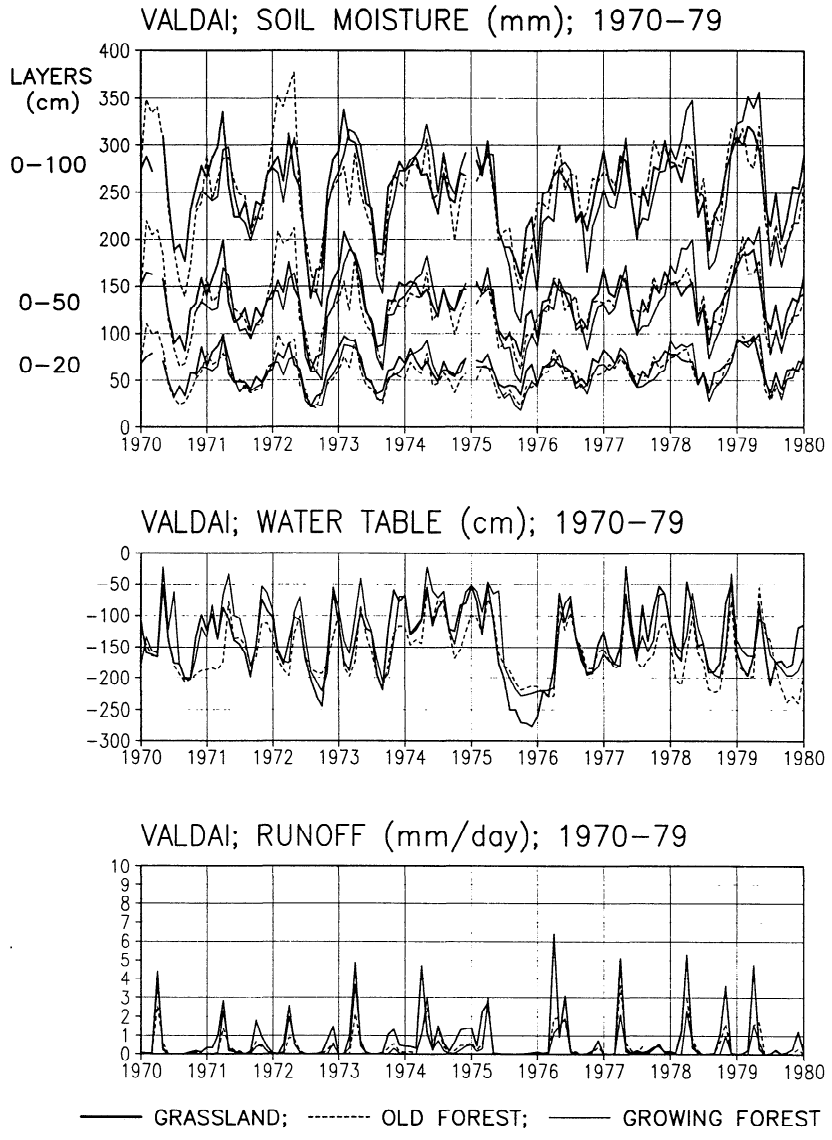

Figure 2. (continued)

three catchments is almost identical, meaning that either vegetation plays a small role in determining soil moisture, or a fortuitous interplay of processes produces the same soil moisture in different catchments for different reasons.

The runoff is quite different. For virtually the entire period, runoff is higher for the Grassland than for the Old Forest. This agrees with previous results of altering vegetation cover in attempts to improve water yields [e.g., *Ward*, 1975, pp. 338-339]. One reason is because of canopy interception in the forest; some of the precipitation reevaporates from the canopy without entering the soil. In addition, the evapotranspiration from the Old Forest is larger than from the Grassland, so that there is less water available for runoff at the Grassland. The runoff for the Growing Forest is virtually identical to the Grassland runoff for the first 10 years, when the trees are small. As the trees get larger, the runoff shifts to the same level as the Old Forest for the next 5 years, and is even less than the Old Forest for the next 10 years, due to the vigorous tree growth and even larger evapotranspiration. The relative roles of canopy interception and evapotranspiration in this difference is the subject of an ongoing project involving modeling and beyond the scope of this paper. Direct observations show that the total amount of precipitation during 1952-1966 for the Grassland was 5% less than for the Old Forest. On average, about 18% of solid precipitation and about 30% of liquid precipitation at the Old Forest catchment are intercepted by the canopy [*Fedorov*, 1977].

Snowmelt and water table depth follow a pattern similar to runoff, but the interannual variations are larger than the differences between the catchments. The snowmelt should be larger at the Grassland, because more snow reaches the ground to be available for melting.

Statistical Structure of Soil Moisture at the Valdai Catchments

Means and Standard Deviations

Let us first consider the simple statistical characteristics of soil moisture. Seasonal variations in monthly means and standard deviations of upper 1 m soil water content are presented in Figure 4 for each point at each of the three

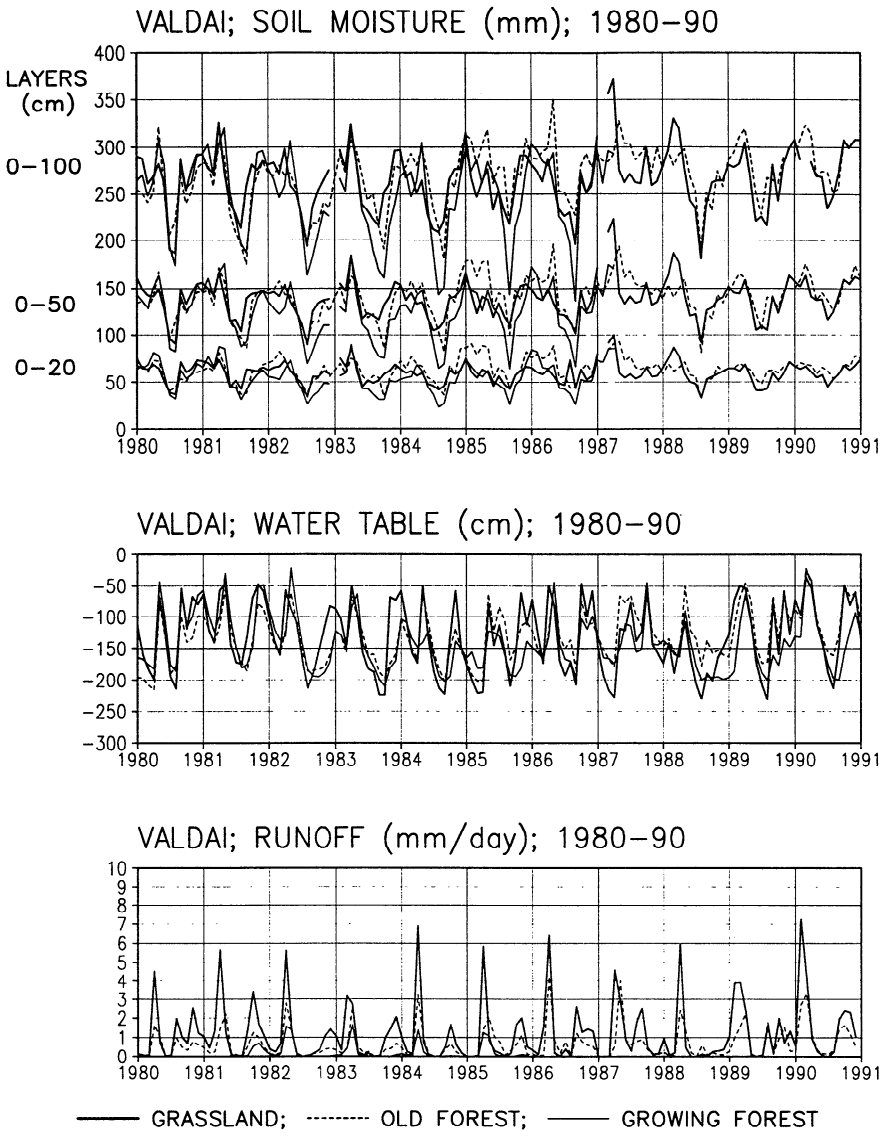

Figure 2. (continued)

Valdai catchments. A considerable spatial inhomogeneity of the monthly means inside each catchment can be seen. The inhomogeneity is particularly large for the Grassland, where the multiyear means for separate points differ one from another by several times. However, the site with the lowest soil moisture during one season is also the driest one during other seasons, and the site with maximum soil moisture continues to be wettest during the entire year compared with the other sites. This conclusion is approximately correct for the two other catchments, also. Thus the curves of soil moisture means for the separate points at each catchment do not cross very much, and almost the same seasonal variations are reproduced at every site of each catchment. Temporal stability of wet and dry sites within a catchment has been shown before from independent experimental studies for different climatic conditions [*Vauchaud et al.*, 1985].

The standard deviations for each site are virtually the same in each catchment, regardless of the means. In addition, there is virtually no seasonal cycle in the standard deviations. Differences between the standard deviation in the sites at three different catchments are also quite small. All these results seem quite surprising.

Seasonal variations of 1-m soil moisture content averaged for each catchment and spatial standard deviations of the monthly means are presented on the bottom right of Figure 4. Such standard deviations are a measure of spatial inhomogeneity of the soil moisture field of the catchment. The data in this figure show some systematic differences in the seasonal variations of soil moisture at the three catchments. Soil moisture for the Grassland and Old Forest catchments are practically the same during January through March. Soil moisture at Grassland reaches a seasonal maximum at the end of March and then quickly decreases. Soil moisture at Old Forest continues to increase and reaches a maximum at the end of April. The soil moisture at Grassland is minimal during July and August. At the Old Forest catchment it continues to decrease, and reaches a seasonal minimum at the end of August, and then during the fall it appears to be less than at Grassland. At the Growing Forest catchment, the soil moisture maximum takes place at

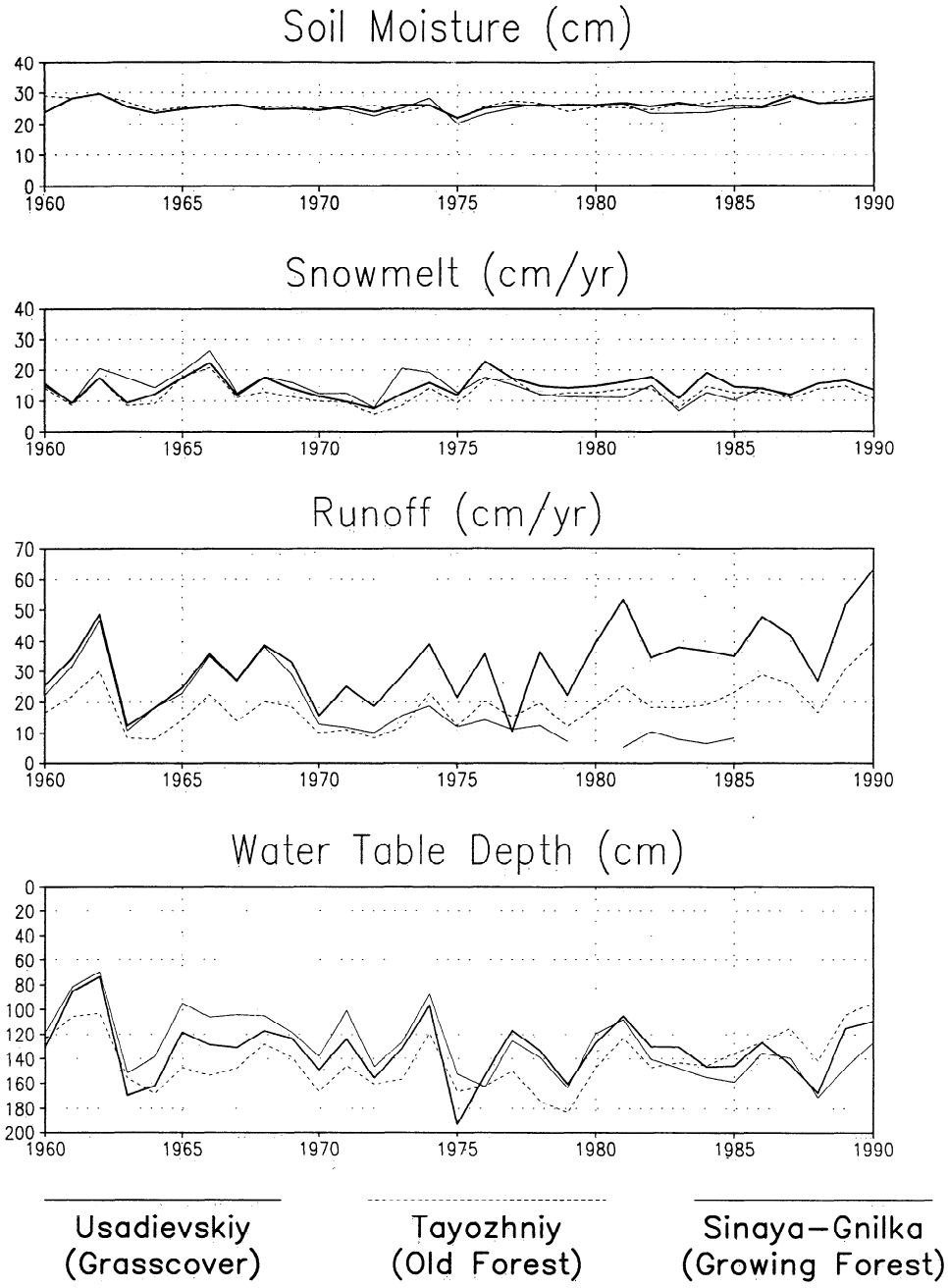

Figure 3. Annual average soil moisture content in the top 1-m layer, snowmelt, runoff, and water table depth for the three catchments for the 31-year period of data, 1960-1990.

the same time and with the same value as at Old Forest, but the summer soil moisture decrease at Growing Forest is greater.

These differences can be explained by timing of the snowmelt and biological processes. The snow melts earlier in open places as compared to in a forest. Checking the snow depth data, not shown here, we verified that this explains the spring soil moisture differences at the catchments. To explain the faster and larger summer soil moisture decrease at the Old Forest and, particularly, at the Growing Forest, it is necessary that biological processes be taken into account. Transpiration by trees, particularly by growing ones, is more efficient than transpiration by grass.

In spite of the small differences pointed out above, the annual-mean and seasonal cycle of soil moisture at all three catchments are remarkably similar. There is no effect of vegetation on the overall level of soil moisture, which is not the case for water table or runoff (Figures 2-3).

Seasonal variations of interannual variability of catchment averaged soil moisture (not shown in Figure 4) are practically absent. Standard deviations for separate months are from 2 to 4 cm. Even during winter, when it seems that moisture in frozen soil should not be changing, the interannual variability is not less than for other seasons.

Spatial Correlation

Estimates of the correlation coefficients between the 1-m layer soil moisture at separate points of each catchment are given in Table 1. Seasonal variations in the means were first subtracted. The estimated correlation coefficients between

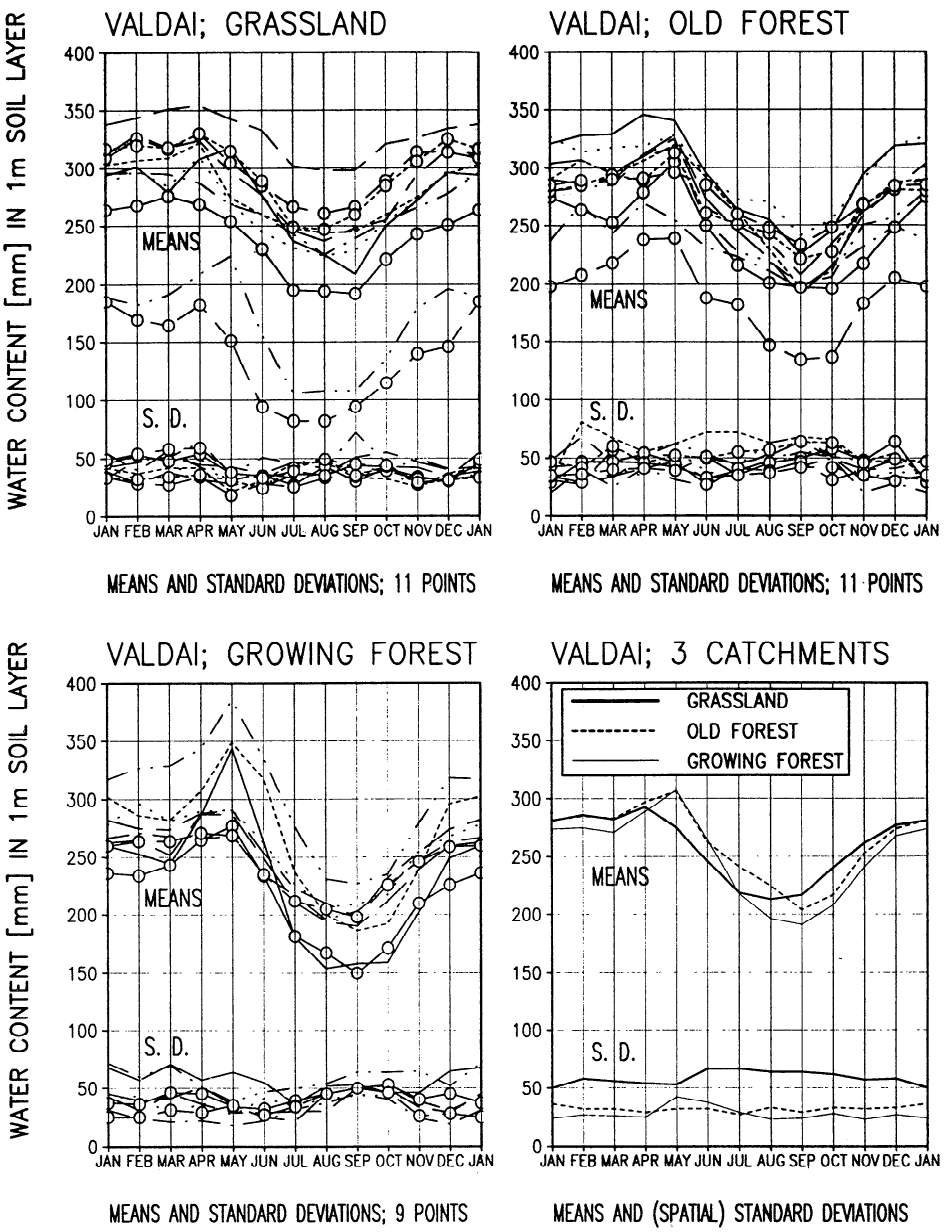

Figure 4. Seasonal cycles, averaged over the entire 31-year period of observations, for the water content and interannual standard deviation at each site of the three catchments. On the bottom right are shown the means of soil moisture over all the sites for each catchment, and the standard deviations of these means, which should be interpreted as the spatial standard deviation. Abscissa labels refer to the first day of the month.

points inside catchments appear to be rather small, though they are everywhere positive. The range of distances between the points is 100-750 m at the Grassland, 100-650 m at the Old Forest, and 20-160 m at the Growing Forest, but the correlation coefficients between points within each catchment do not depend on the distance between the points. There is a slightly higher spatial correlation of soil moisture at the Growing Forest catchment in comparison with the other catchments. This is probably because relief and vegetation at this catchment are much more uniform in comparison with the other two catchments.

Table 2 contains estimates of the correlation coefficients of soil moisture averaged for the catchments. The correlations between catchments are on average larger than correlation between separate sites inside of each catchment. Correlations of the 1-m layer soil moisture are slightly higher then the ones for the upper 50 cm and upper 20 cm layers. This is partially because of random observational errors.

Temporal Autocorrelation

Estimates of temporal autocorrelation functions for 20-cm, 50-cm, and 1-m layer soil moisture averaged over each of the catchments are shown in Figure 5. In addition, the means of the autocorrelation functions estimated for the separate points in each catchment are shown. A logarithmic scale for estimates of autocorrelation functions has been used to simplify the identification of the stochastic process type. It can be immediately recognized that the processes are a

Table 1. Correlation Between Soil Moisture in 0- to 1-m Layer at Individual Sites in Catchment

Point	1	2	3	4	5	6	7	8	9	10	11
Grassland, 11 Points, 0.36 km²											
1	1.0										
2	0.5	1.0									
3	0.3	0.3	1.0								
4	0.4	0.3	0.4	1.0							
5	0.4	0.3	0.4	0.3	1.0						
6	0.3	0.2	0.4	0.3	0.4	1.0					
7	0.4	0.3	0.2	0.3	0.4	0.2	1.0				
8	0.3	0.2	0.3	0.4	0.5	0.2	0.3	1.0			
9	0.3	0.3	0.2	0.4	0.4	0.2	0.3	0.4	1.0		
10	0.4	0.4	0.2	0.4	0.4	0.2	0.3	0.4	0.4	1.0	
11	0.4	0.2	0.2	0.3	0.3	0.2	0.4	0.3	0.2	0.4	1.0
Old Forest, 11 Points, 0.45 km²											
1	1.0										
2	0.5	1.0									
3	0.5	0.5	1.0								
4	0.4	0.4	0.6	1.0							
5	0.4	0.5	0.4	0.3	1.0						
6	0.4	0.5	0.4	0.3	0.4	1.0					
7	0.4	0.6	0.6	0.5	0.4	0.4	1.0				
8	0.5	0.6	0.5	0.3	0.4	0.4	0.5	1.0			
9	0.4	0.7	0.5	0.3	0.4	0.5	0.4	0.5	1.0		
10	0.4	0.5	0.6	0.4	0.3	0.4	0.5	0.3	0.4	1.0	
11	0.3	0.4	0.4	0.4	0.4	0.2	0.3	0.2	0.2	0.2	1.0
Growing Forest, 9 Points, 0.015 km²											
1	1.0										
2	0.6	1.0									
3	0.7	0.6	1.0								
4	0.4	0.6	0.5	1.0							
5	0.4	0.5	0.5	0.6	1.0						
6	0.4	0.5	0.5	0.6	0.5	1.0					
7	0.6	0.6	0.7	0.6	0.6	0.6	1.0				
8	0.6	0.6	0.7	0.5	0.5	0.5	0.6	1.0			
9	0.4	0.5	0.4	0.6	0.6	0.6	0.5	0.4	1.0		

combination of a first-order Markov process signal and added white noise. The best approximation for empirically estimated autocorrelation functions in Figure 5 is

$$r(t) = \begin{cases} 1 & \text{if } t = 0 \\ r_0 \exp\left(-\dfrac{t}{T}\right) & \text{if } t \neq 0 \end{cases} \quad (4)$$

where the parameters r_0 and T can be found from estimates of $r_1 = \hat{r}(t=1)$, and $r_2 = \hat{r}(t=2)$:

$$T = \frac{1}{\ln\left(\dfrac{r_1}{r_2}\right)}, \qquad r_0 = \frac{r_1^2}{r_2} \quad (5)$$

Table 2. Correlation Coefficients of Soil Water Content Between Three Valdai Catchments for Different Soil Layer Depths

	Soil Layer		
	0-20 cm	0-50 cm	0-100 cm
Grassland – Old Forest	0.47	0.55	0.60
Grassland – Growing Forest	0.64	0.68	0.71
Old Forest – Growing Forest	0.40	0.51	0.56

The ratio of the variance of the white noise component to the variance of the red noise signal can be estimated from the expression

$$a = \frac{1 - r_0}{r_0} \quad (6)$$

The theory of such a process was developed by *Parzen* [1966] and *Box and Jenkins* [1970]. It was successfully applied for analysis of long-term climatological time series by *Polyak* [1989]. The theory allows the use of different methods to estimate the parameters of the model, but in this particular case, the observed time series contain much missing data so the accuracy of the autocorrelation function estimates decreases rapidly with increasing lag. A time lag of 1 month is comparable to a scale of autocorrelation of about 3 months, so (5) is probably a good approach for estimating the model parameters r_0 and T. The estimates of T, r_0, and a of the autocorrelation functions shown in Figure 5 are given in Table 3. In the upper part of the table are parameters for the case where soil moisture is averaged over the catchments first. The lower part of the table contains the estimates of the same parameters for the autocorrelation functions which were obtained by averaging of the autocorrelation functions estimated at each observational site in each catchment. The most important parameter is T, the scale of the temporal autocorrelation for the red noise process.

The first impression is that the differences between the estimates of T for the three catchments are more or less random and could be considered as random errors of estimation. The second impression is that there is no dependence of the scale of temporal autocorrelation on soil layer depth. It appears that the same signal exists in variations of soil moisture of the upper 20 cm, the upper 50 cm, and of the 1-m layer.

The best estimate of T based on these observations is 2.8 months. Let us compare this value with the theoretical estimate. Suppose that the 0- to 50-cm layer is sandy and the 50- to 100-cm layer is loamy. Then the value of W_f would be about 14 cm of plant available water. E_o for Valdai station is about 55 cm/yr. Using these numbers, from (2) we estimate $T \approx 3.0$ months.

Let us consider the parameter a estimates given in Table 3. If we suppose that the red noise component is a climatic signal with variance equal to 1, then a is the relative power (variance) of the white noise component. As mentioned above, this component is small or negligibly small for soil moisture measurements at meteorological stations [*Vinnikov and Yeserkepova*, 1991; *Robock et al.*, 1995]. This is connected with the technique of soil moisture measurements

at these regular stations. A few (3-4) soil cores are taken from each plot. The soil moisture of these samples is averaged to obtain the value of soil moisture at the station. At Valdai station there are about 10 soil cores taken at each catchment, but these catchments are not flat and not spatially homogeneous. The time series of 1-m layer soil moisture at an individual site of a catchment has a very large white noise component. This component for the forest catchments is about 55-60% of the signal variance (of the red noise variance), and for the Grassland the white noise component is 1.5 times the power of the red noise signal. The time series of upper 1-m layer soil moisture averaged over a catchment have white noise components of 15-20% for both forest catchments and about 35% for the Grassland. In this case, the error of the gravimetric method of measurements does not increase the white noise component of the variance very much, because observed values are a result of averaging of 9-11 samples. We suggest that this white noise is normal for real nature and is caused by spatial inhomogeneity of relief, soil, and vegetation in the catchments. It can be interpreted as random error in use of point samples to represent the area, a type of measurement error.

The dependence of a on soil layer depth is more complicated. The estimated value of $a = 0.19$ at the Old Forest catchment does not depend on layer depth. At the Grassland catchment, the estimate of a increases with decreasing soil layer depth. It is equal to 0.9 for the upper 20-cm soil layer. For the Growing Forest catchment, the estimates of a also increase with layer depth, but much less than for Grassland. It looks as if spatial inhomogeneity is much larger for a 1-m soil layer than for upper 20-cm and 50-cm layers.

Large-scale Spatial Variability

The Valdai data come from a small region not large enough to be used to estimate the largest scale of spatial variability of the soil moisture field. Therefore we take such estimates from a previous study. *Meshcherskaya et al.* [1982] estimated the spatial autocorrelation functions of mean monthly soil moisture of the upper 20-cm and 1-m soil layers for a few months of the year measured at winter rye, oats, and wheat fields. They used soil moisture measurements of the European part of the FSU for 1950-1977. The data were preliminary averaged over 58 administrative districts with an average area equal to about 30,000 km^2. There are about 6 stations in each district. It is fortunate that all the initial data and results were published, and now are available for further interpretations. Estimates of the spatial autocorrelation functions of soil moisture for May and June are reproduced in Figure 6. These are the only 2 months for which estimates of the spatial structure of both soil moisture and precipitation (discussed next) exist. We use here a logarithmic scale for spatial autocorrelation functions as was done earlier for temporal autocorrelation. We can conclude that (1) The statistical model of soil moisture spatial variability can be represented as the sum of red and white noise, exactly as was done for temporal variability

$$r(l) = \begin{cases} 1 & \text{if } l = 0 \\ r_0 \exp\left(-\dfrac{l}{L}\right) & \text{if } l \neq 0 \end{cases} \qquad (7)$$

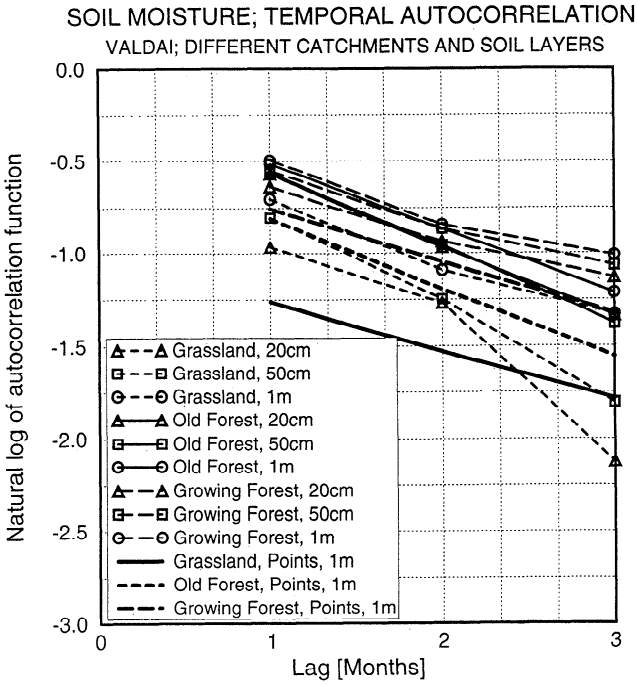

Figure 5. Estimates of the temporal autocorrelation functions of soil water content in three different soil layers at three Valdai catchments. Also included are means of the autocorrelation functions estimated for separate points inside of each catchment, as calculated in the text.

where $r(l)$ is the spatial autocorrelation function, l is distance, L is the scale (radius) of spatial autocorrelation, and r_0 is the ratio of the variance of a red noise signal to the empirically estimated variance. Note that if we were to use estimates of the correlation function for distances exceeding the linear size of the averaging region, then spatial averaging would not affect the empirical estimate of L [*Kagan*, 1979]; (2) The radius of correlation L does not depend on soil layer depth, and equals 400-800 km, depending on the month; and (3) The relative power of the white noise component for the upper 20-cm soil layer is considerably smaller than for the upper 1-m soil layer.

Discussion

Estimates of the spatial correlation functions of precipitation (monthly totals averaged over the same administrative districts) from *Lugina and Meshcherskaya* [1978] are also presented in Figure 6. The radius of spatial correlation for atmospheric precipitation fields depends on the season and on the period of temporal averaging [*Czelnai et al.*, 1976]. It appears that the scale similarities of spatial correlations of the mean monthly soil moisture and monthly total precipitation fields in June (when precipitation is the only source of soil moisture) are natural and reflect the connection between spatial variability of these fields for the summer season. In May the radius of soil moisture field correlation is slightly less than that for precipitation. These estimates, however, are for the European part of the FSU, where precipitation is not the only source of soil moisture in May. In spring, air temperature anomalies influencing snowmelt and evaporation processes have a significantly larger natural scale of spatial variability as compared to the

Table 3. Estimates of the Parameters T (months), r_0, and a of the Model of Soil Moisture Temporal Autocorrelation Functions at the Valdai Catchments as Shown in Figure 5

	Grassland			Old Forest			Growing Forest		
Layer	T	r_0	a	T	r_0	a	T	r_0	a
				Soil Moisture Averaged Over the Catchments					
0-20 cm	3.3	0.52	0.92	2.5	0.84	0.19	3.4	0.71	0.41
0-50 cm	2.2	0.70	0.43	2.6	0.84	0.19	3.2	0.78	0.28
0-100 cm	2.6	0.73	0.37	2.9	0.84	0.19	2.9	0.86	0.16
				Autocorrelation Functions for Points Averaged Over the Catchments					
0-100 cm	3.7	0.37	1.70	2.6	0.65	0.54	3.4	0.63	0.59

precipitation field. Therefore the estimates for May support the conclusions made for June.

If the scale of soil moisture field spatial correlation is about 400-800 km, all the measurements at the Valdai catchments were done practically at the same geographical point, because the maximum distance between the catchments is not more than a few kilometers, and that between the sites in each catchment is not more than a few hundred meters. The average correlation coefficients between soil moisture measurements in separate sites, evaluated for the data from Table 1, are 0.35 for the Grassland, 0.43 for the Old Forest, and 0.54 for the Growing Forest. These averaged estimates can be considered as values of the spatial soil moisture autocorrelation function for zero distance $r(l=0)$. These values are close to the estimates (0.37 for Grassland, 0.54 for Old Forest, and 0.59 for Growing Forest) of the parameter $r(t=0)$ of the temporal soil moisture autocorrelation functions of the sites averaged over the catchments (Table 3). The similarity of the $r(l=0)$ and $r(t=0)$ estimates suggests that the red noise component of temporal soil moisture variability is, at the same time, the red noise component of spatial variability. This signal has the same scales for the upper 20-cm layers as for upper 1-m soil layers. A similar conclusion could be derived from analysis of the spatial autocorrelation function estimates published by *Kontorshchikov* [1979] for the same soil layers in the forest-steppe zone.

The coincidence of the $r(l=0)$ and $r(t=0)$ estimates means that white noise components of the spatial and temporal soil moisture variability are similar, too. Because, for the spatial variability this component is mainly caused by the inhomogeneity of soil relief and catchment vegetation, we can conclude that the same reasons are the source of white noise

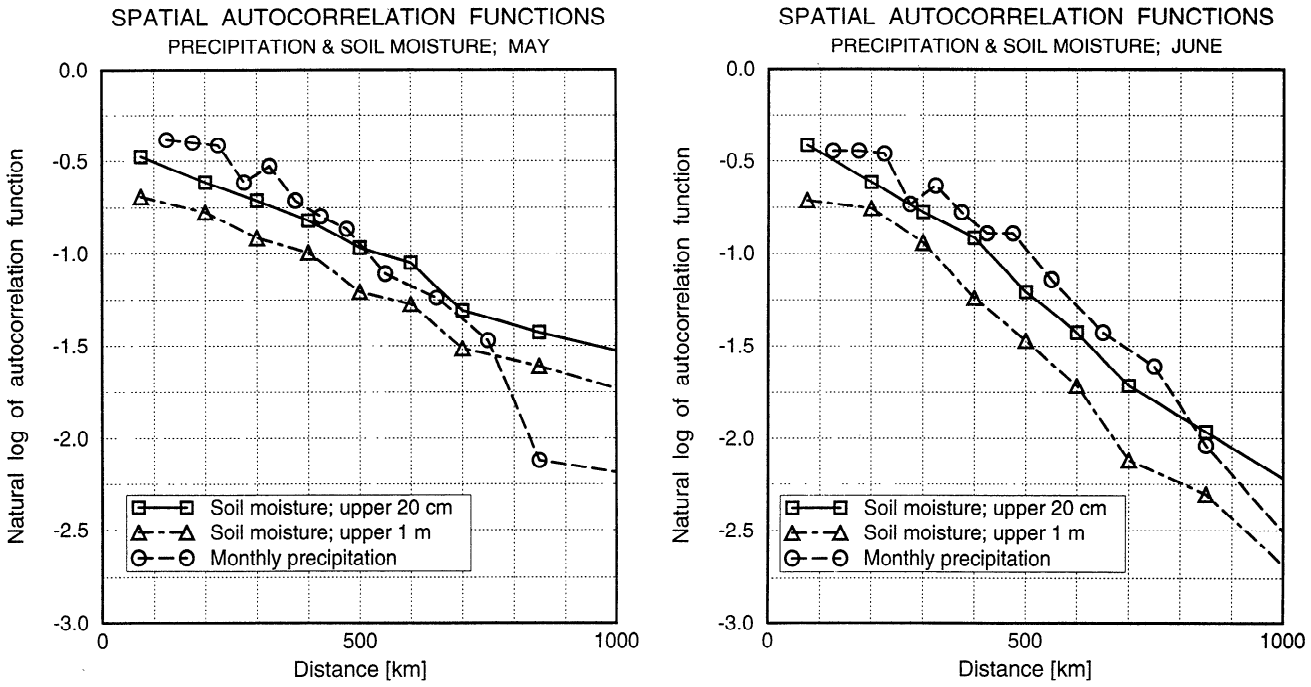

Figure 6. Estimates of the spatial autocorrelation functions for May and June for soil moisture in 1-m and 20-cm soil layers from *Meshcherskaya et al.* [1982] and for monthly totals of precipitation from *Lugina and Meshcherskaya* [1978].

in the temporal variability of soil moisture. Hence the power of the white noise component in the soil moisture measurement data describes not only random measurement errors but also spatial inhomogeneity of natural conditions around the site where measurement was performed.

There is no sense in analyzing the white noise component, as we are interested only in the signal, the red noise component. One of the traditional empirical methods to eliminate white noise consists of spatial averaging of all measurements of stations inside separate administrative districts. It is possible that methods of remote sensing by satellite of soil moisture would have an advantage compared to measurements at stations, because a spatial average could be performed automatically by the selection of the instrumental spatial resolution.

We can also suggest that only large-scale and long-term variability of soil moisture, which is related to the scales of atmospheric forcing, is significant for global atmospheric circulation modeling.

Conclusions

1. The observed interannual soil moisture variations of three typical midlatitude catchments with different vegetation types (grassland, growing forest, and old forest) do not differ significantly. Moreover, their seasonal cycles of soil moisture are similar, except that for the grassland, the snowmelt and summer drying begin a month earlier. Runoff, however, is higher for the grassland than for the old forest, and the water table depth is not as deep.

2. A statistical model of both temporal and spatial variations in soil moisture has been developed and it contains both red noise and white noise components.

3. The white noise component is small and represents solely random errors of measurement for flat homogeneous plots. This component is much larger for natural landscapes with variable vegetation and soil types, and complicated topography, and can be responsible for most of the temporal or spatial variance.

4. The red noise component of temporal variability is in good agreement with the theory of *Delworth and Manabe* [1988, 1993].

5. The red noise component of spatial variability reflects statistical properties of the precipitation field.

6. The most important part of upper layer (up to 1 m) soil moisture variability in the middle latitudes of the northern hemisphere has a spatial correlation scale of 400–800 km and a temporal correlation scale equal to about 3 months. This has important implications for both remote sensing of soil moisture and soil moisture parameterization in climate models. However, it should be noted that regions with vastly different precipitation regimes might have different scales.

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