The Drought and Excessive Moisture Indices in a Historical Perspective in the Principal Grain-Producing Regions of the Former Soviet Union

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ABSTRACT

The paper deals with catalogs (two listing by years) of droughts and conditions of excessive moisture in May–July in the basic cereals-producing area of the former Soviet Union (FSU) for 1891–1995. To calculate catalogs, data on precipitation averaged over the area of administrative regions and temperature at meteorological stations were used.

The problem of the inhomogeneity of precipitation series at stations in the warm period of year is discussed, related to the introduction of corrections for moistening rain gauge bucket. The suggested catalogs of droughts and excessive moisture (index DM) explicitly include the area of distribution of certain precipitation and temperature combinations. This is their principle difference from other authors' catalogs.

The paper studies the relationship between the index DM in the European (EP) and Asian (AP) parts of the territory under consideration with other drought indices and with the anomalies of cereals yield.

Linear trends of the DM index series are presented, as are series of precipitation and temperature in May–July for 105 yr. It is shown that the DM time series for the European part is practically stationary. In the AP territory in May–July, the aridity grows (the positive trends of the DM index are statistically significant). The aridity growth in the AP of the basic cereals-producing area of the FSU is mainly determined by temperature rise; the negative, but statistically insignificant, trend of precipitation intensifies this process.

1. Introduction

The agriculture production of many countries of the world suffers from droughts. It is not a surprise that these hydrometeorological phenomena are covered by voluminous amounts of literature. The droughts in the United States have been studied comprehensively with interest peaking in the 1960s–1970s and the early 1980s (Karl 1983; Diaz 1983; Trenberth et al. 1988; Namias et al. 1983). Much attention has been paid by specialisits to catastrophic droughts in North Africa with the accent on the causes of origination (Newell and Kidson 1984; Druyan 1989; Nicholson at al. 1994).

The territory of basic grain-producing areas in the former Soviet Union (FSU) is also subjected to droughts. Fedorov (1973) reports that only one-third of the cultivated areas in the FSU receive sufficient precipitation for crop development.

Numerous monographs and papers on droughts in the FSU have been published, mainly in Russian (Rudenko 1958; Pokrovskaya 1969; Ped 1975; Loginov et al. 1976; Buchinsky 1976; Drozdov 1980; Rauner 1983; Sazonov 1991). A report has also been prepared under the aegis of the World Meterological Organization and has generalized the mid-1970s, from works on droughts in different countries of the world, including the FSU (World Meteorological Organization 1975).

When studying droughts, of paramount importance is their identification, as well as the preparation of catalogs of years with droughts that cover extensive territories and are therefore particularly dangerous for agriculture. In the FSU, a number of the well-known catalogs of drought are based first of all on cereal crop production (Alpatiev and Ivanov 1958; Pokrovskaya 1969; Drozdov 1980; Rauner 1983).

For this purpose, the anomalies of cereals yield were calculated as percentages of long-term trends caused by agricultural technology improvement. The dry years were considered to be those in which the decrease of cereals yield was 15%–20% and more of the trend values.

Meteorological data were used, but usually as supplementary information. In order to study the physical processes of droughts, however, it is desireable to use drought indices based upon meteorological conditions. Nonmeteorological factors (i.e., insects, plant disease, miscalculations in field management, etc.) can have a large impact on crop production with no change in meteorological conditions and, thus, make it quite difficult

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to relate drought indices based on cereal crop production to meteorological conditions.

For a more rigorous description of droughts, many meteorological indices have been suggested that include precipitation, temperature, relative humidity, air humidity deficit, and other characteristics (Landsberg 1975). In the United States, the Palmer index (Palmer 1965) is used as the basic index of drought and excessive moisture. Three modified versions of this index are known (Soule 1992): an index of monthly moisture anomaly, an index of drought severity, and an index of hydrologic drought. The latter is most widely used.

In the FSU, indices based on joint consideration of precipitation and temperature have been most widespread. These include the hydrothermal coefficients (HTC) of Selyaninov (1928) and the dryness index S_i suggested by Ped (1975).

The former is calculated with the formula

$$\mathrm{HTC} = \frac{\Sigma Q}{0.1\Sigma T}, \qquad (1)$$

where ΣQ are precipitation sums and ΣT are the sums of temperature higher than 10°C for some time period (month and vegetation season).

The latter is calculated with the formula

$$S_i = \frac{\Delta T}{\sigma_{\Delta T}} - \frac{\Delta Q}{\sigma_{\Delta Q}}, \qquad (2)$$

where ΔQ and ΔT are precipitation and temperature anomalies, and $\sigma_{\Delta Q}$ and $\sigma_{\Delta T}$ are their respective standard deviations at station i, calculated from long-term series of data.

It has been shown (Meshcherskaya et al. 1981) that both indices are closely correlated with each other. On average, for 104 administrative regions over the period of May–July between the series of HTC and S_i, the mean value of the correlation factor $r = -0.91$.

It should be noted that many indices, even if they are referred to as drought indices, actually characterize the whole range of meteorological conditions from very dry to very moist, including those close to many-year means (the Palmer drought index, Selyaninov HTC, Ped dryness index, etc.).

Among other indices, Sazonov drought indices (Sazonov 1991) should be mentioned, which are the differences in the number of stations (in tens) at which dry conditions and surplus moisture are observed, as determined by graphic joint analysis of precipitation and temperature series. The disadvantage of these indexes is the artificial restriction of the range of their variations (Meshcherskaya et al. 1989).

In 1977, Meshcherskaya and Blazhevich (1977) suggested two indices: a drought index and an excessive moisture index, which for the first time in explicit form included the areas of distribution of precipitation and temperature in the given gradations.

The approach in this paper is unified: both dry conditions and excessive moisture are characterized by a single index (index DM), which is much more convenient in practical work.

2. Data source

The initial data for analysis consist of time series of monthly mean temperature and precipitation for the above 105-yr period, 1891 to 1995. The precipitation data consist of spatial averages over administrative regions, rather than precipitation data from individual meteorological stations. This approach has several advantages (Meshcherskaya et al. 1978a). The spatial correlation of precipitation is much greater for mean regional precipitation than for precipitation from individual stations, and the correlations extend to much greater distances. Variance of the mean regional rainfall is 1.4 to 1.8 times lower than that of rainfall collected at meteorological stations. The spatial averaging tends to smooth random errors and increases the representativeness of precipitation data.

In contrast to precipitation, time series of temperature for regions were constructed from a single station per region. This approach is fully justified since the spatial and temporal variations of temperature are much smaller in a relative sense than those of precipitation.

The spatially averaged precipitation time series are based on data collected at 1400 meteorological stations located in 104 administrative regions within the limits of the principal grain growing regions of the FSU.

Mean regional precipitation values were calculated by arithmetic averaging of data supplied by meteorological stations located in the territory of a given region. There are from 2 to 23 stations per region. A description of the technique used for calculating areal averages of precipitation may be found in Efremova (1976), Ledneva and Meshcherskaya (1977), and Meshcherskaya et al. (1978a).

The process of spatial averaging of precipitation over the area of administrative regions is complicated by the inhomogeneity of precipitation series at stations. The problems of procedure and errors in measuring precipitation at meteorological stations of the FSU are covered in a number of publications. Corresponding references and the present state of the problem are given, for example, in Groisman et al. (1991).

Two types of inhomogeneity have appeared in precipitation series in the current century (Shver 1976; many-years series 1978; Groisman et al. 1991). The first was due to total replacement of rain gauges with the Nipher shield by Tretiakov rain gauges with a petaled shield, which was produced in the early 1950s (Shver 1965). However the differences in precipitation sums measured from rain gauges and precipitation gauges appear only in the cold period of the year. This paper uses precipitation for May–July, and thus the inhomogeneity of type I does not relate to the series being studied.

TABLE 1. The relation of wetting corrections to four-per-day (q_1) and twice-per-day (q_2) observations depending on the precipitation monthly amount (Q) in the warm season of year.*

Regions	Number of stations		The gradation of the monthly precipitation amount					
			0–10	11–20	21–30	31–40	41–50	>50
Volga	40	a	1.2	1.4	1.0	1.4	1.4	1.3
		b	20	13	8	8	8	8
		c	16	9	8	6	6	6
		b − c	4	4	0	2	2	2
Ural	105	a	1.8	1.3	1.3	1.4	1.2	1.2
		b	23	14	10	9	8	8
		c	13	10	8	6	6	7
		b − c	10	4	2	3	2	1
North Kazakhstan	75	a	1.2	1.4	1.1	1.2	1.1	1.2
		b	20	13	9	8	6	7
		c	17	9	8	7	6	6
		b and c	3	4	1	1	0	1

* Here, a is q_1/q_2, b is q_1/Q in percent, and c is q_2/Q in percent; Q is the measured monthly precipitation amount with the wetting corrections to the twice-per-day measuring of precipitation.

The second type of inhomogeneity is related to the introduction of corrections to the measured precipitation amount for the moisture that remains on the gauge walls, the so-called wetting correction. Wetting corrections have been introduced since 1966. If data for earlier years are also used, the series inhomogeneity appears. There are two possible ways to eliminate it. The first consists of introducing wetting corrections to series before 1966, and the second is to exclude them from series after 1965. The authors of this paper have chosen the second way since they considered it to be more radical, as the problem of the values of wetting corrections has not been developed completely in terms of the dependence of wetting corrections on the number of precipitation measurements, taking into consideration the losses from evaporation. In addition, if wetting corrections introduced since 1967 for every individual month for each station are known, then for the preceding years the number of precipitation measurements is not known, and one can introduce only many-year mean wetting corrections, which results in overestimating the corrections for moistening at large sums of precipitation and underestimating them at small sums.

After excluding the wetting corrections, some inhomogeneity in data series remains due to the change in the number of precipitation measurements per day. In 1891–1934, precipitation was measured once per day, in 1935–65 it was measured twice per day and in 1966–85 it was measured four times per day, except at stations of the sixth, seventh, and eighth time zones. Since 1986, precipitation has been again measured twice per day, except at stations of the second time zone, where precipitation is observed four times per day.

With such different regimes of observations, the differences should be estimated for wetting corrections depending on the number of measurements taken per day.

The wetting corrections have been theoretically developed only for the twice-per-day observations, and in the warm season of the year they are 6%–8% of the many-year normals (Nechaev 1966; *Reference Book on the Climate of the USSR* 1966–69). With the four-per-day observations, the wetting corrections would double if precipitation fell continuously during 24 h and was fixed for all four-per-day observations (Struzer 1975).

Since this is not so, the relation between wetting corrections with the four-per-day and twice-per-day observations is much lower.

At present, abundant factual evidence has been accumulated with wetting corrections, and therefore it is possible to compare them with two- and four-per-day measurements. To this end, mean wetting corrections for 220 meteorological stations were calculated, depending on monthly precipitation amount for two periods: from 1966 to 1979 and from 1986 to 1990. The first one corresponds to four-per-day observations and the second to twice-per-day observations.

Table 1 presents for three regions of the FSU the relation of wetting corrections for the first (q_1) and second (q_2) periods, the portion (in percent) of the monthly precipitation amounts of q_1 and q_2 (as the values of each midgradation of precipitation), and their difference ($b - c$). It should be emphasized that the monthly wetting correction depends directly on the number of precipitation measurements, which is related to a certain extent to the amount of precipitation fall.

Analysis of Table 1 shows that everywhere $q_1/q_2 > 1$, with this relation decreasing with increasing monthly precipitation amount. Of particular interest are the relations of q_1/q_2 for gradations of precipitation with the highest frequency. These are 41–50 mm for the Volga region, above 50 mm for the Ural region, and 31–40 mm for north Kazakhstan. For these gradations, the relation q_1/q_2 varies from 1.2 in north Kazakhstan and the Ural region to 1.4 in the Volga region. The differences in the wetting corrections over two periods for the gradations of precipitation of highest frequency are 1%–2% of the monthly precipitation amount. They argee well on the order of value with the results of Struzer

TABLE 2. Three gradations of air temperature anomalies (degrees Celsius) and precipitation (in percent) for May–July 1891–1995 as percentages of the total number of cases.

Administrative regions (meteorological station)	Anomalies of air temperature (degrees Celsius)			Precipitation		
	$\Delta T < -1°C$	$-1° \leq \Delta T < 1°C$	$\Delta T \geq 1°C$	$Q < 80\%$	$80\% \leq Q < 120\%$	$Q \geq 120\%$
1 Leningradskaya (St. Petersburg)	31	41	28	33	40	27
2 Novosibirskaya (Novosibirsk)	30	41	29	34	37	29
3 Bashkiria, north (Ufa)	29	41	30	37	34	29
4 Tulskaya (Tula)	30	42	28	37	31	32
5 Samarskaya (Bezenchuk)	32	38	30	41	28	31
6 Rostovskaya (Rostov)	26	48	26	37	33	30
7 Kirovogradskaya (Kirovograd)	29	44	27	44	25	31

* Precipitation (as percentages of normal for 1891–1995) were averaged over administrative regions. Temperature anomalies (station data) were calculated as biases from normal for the same period.

(1975), who proved that the many-year mean values (normals) of precipitation in May, with four-per-day observations, are higher by 0.8% than the normals with twice-per-day observations in the central and south regions of the European territory under consideration (EP) and by 2.3%–2.5% in north Kazakhstan and north Altai.

It should be mentioned that with an absolutely correct procedure for determining corrections to four-per-day observations the difference of the wetting corrections under study should be even lower since, with the increase of the number of times of precipitation observations up to four, along with the increase of wetting corrections, evaporation losses decrease, which was not taken into account in 1966.

According to some estimates (Struzer 1975), the wetting corrections introduced to four-per-day observations are overestimated by approximately 30%.

Finally, the problem of the relation of wetting corrections to once-per-day and twice-per-day observations has not yet been worked out. Groisman et al. (1991) accepted that wetting corrections to once-per-day observations amount to half of those the twice-per-day observations (this is the upper limit of possible differences). In this case, the differences of wetting corrections to once-per-day and twice-per-day observations would be not higher than 0.5 q_1/q_2—that is, 0.5%–1% of the monthly amount of precipitation for their prevailing gradations in warm season of year.

There being relatively little difference between wetting corrections to one-, two-, and four-per-day observations in the warm season of the year allows us to consider the prepared series of mean regional precipitation to be quasi-homogeneous and quite representative for carrying out work on monitoring climate and long-range meteorological forecasts, and for analyzing droughts and conditions of excessive moisture.

3. Calculation procedure

Warm seasons in the territory of the principal grain-growing region of the FSU are characterized by a negative correlation between precipitation and temperature anomalies (anticyclones are warm and dry, whereas cyclones are cold and rainy). Using data from 104 regions, Meshcherskaya and Blazhevich (1978) demonstrated this negative correlation for the May–July period. The largest negative values of the correlation coefficients

TABLE 3. Cross-correlation matrix of indices DM and *S*, the mean sum of precipitation, and the mean air temperature anomalies for May–July 1891–1995.

	European part				Asian part			
	DM	Q	ΔT	S	DM	Q	ΔT	S
DM	1.0	−0.77	0.92	0.97	0.11	−0.15	0	0.07
Q		1.0	−0.55	−0.83	−0.06	0.12	0.06	−0.02
ΔT			1.0	0.94	0.18	−0.19	0.11	0.15
S				1.0	0.11	−0.15	0	0.08
DM					1.0	−0.81	0.90	0.97
Q						1.0	−0.58	−0.83
ΔT							1.0	0.93
S								1.0

TABLE 4. Many-year series of the *D*, *M*, DM, and *S* indices, the mean sum of precipitation, and the mean air temperature anomalies for May–July 1891–1995.

	EP						AP					
Year	*D*	*M*	DM	*S*	Q	ΔT	*D*	*M*	DM	*S*	Q	ΔT
1891	46	1	45	1.3	42	1.3	12	12	0	0.3	32	−0.3
1892	27	2	25	0.7	46	0.8	31	0	31	0.7	39	1.1
1893	3	14	−11	−0.3	55	−0.8	20	4	16	0.5	31	−0.2
1894	6	30	−24	−0.9	64	−0.8	8	38	−30	−0.9	52	−0.9
1895	12	13	−1	0	50	−0.4	14	36	−22	−0.7	47	−0.9
1896	6	25	−19	−0.7	65	−0.5	22	21	1	−0.2	51	0.3
1897	35	0	35	1.2	49	1.9	21	13	8	0.1	42	−0.1
1898	22	9	13	0.3	56	0.7	16	16	0	−0.3	40	−0.7
1899	9	15	−6	−0.3	54	−0.6	9	12	−3	0	41	−0.3
1900	1	32	−31	−0.7	60	−0.9	33	4	29	1.0	38	1.4
1901	26	2	24	1.0	44	1.1	20	3	17	0.7	33	0.3
1902	6	23	−17	−0.6	63	−0.4	15	14	1	0.1	43	0.2
1903	21	6	15	0.1	63	0.8	6	48	−42	−1.3	55	−1.3
1904	0	27	−27	−1.1	51	−2.2	11	6	5	0.5	38	0.6
1905	26	11	15	0.4	54	0.7	1	31	−30	−1.0	52	−0.9
1906	30	1	29	1.1	59	2.4	30	10	20	0.4	39	0.4
1907	12	15	−3	0	57	−0.1	3	19	−16	−0.7	41	−1.2
1908	5	25	−20	−0.5	55	−1.0	3	33	−30	−0.8	53	−0.5
1909	3	19	−16	−0.7	62	−0.9	27	4	23	0.5	41	0.7
1910	13	3	10	0.2	57	0.6	9	11	−2	0	43	0.1
1911	14	14	0	−0.1	54	−0.2	31	4	27	0.8	32	0.4
1912	9	32	−23	−1.0	61	−1.2	10	12	−2	−0.3	46	0
1913	0	46	−46	−1.7	72	−2.0	1	19	−18	−0.6	45	−0.8
1914	22	5	17	0.6	46	0.4	1	16	−15	−0.9	47	−1.2
1915	1	16	−15	−0.5	57	−0.6	14	3	11	0.6	51	1.9
1916	1	30	−29	−0.9	62	−1.2	15	6	9	0.3	38	0
1917	20	13	7	−0.1	47	−0.9	23	26	−3	−0.4	46	−0.5
1918	0	19	−19	−1.1	55	−2.2	10	12	−2	−0.3	41	−0.6
1919	5	26	−21	−1.1	61	−1.4	0	30	−30	−1.0	51	−1.3
1920	44	5	39	1.0	42	1.1	30	0	30	0.9	36	1.0
1921	31	3	28	1.1	44	1.4	36	6	30	1.2	34	1.3
1922	8	4	4	0	55	0.2	16	15	1	−0.2	54	0.4
1923	13	8	5	−0.1	57	0	29	14	15	0.7	37	0.7
1924	38	12	26	0.7	48	0.9	20	14	6	0	43	0.1
1925	19	26	−7	−0.5	64	0	2	19	−17	−0.7	43	−1.1
1926	6	16	−10	−0.5	59	−0.6	1	29	−28	−1.1	45	−1.8
1927	11	17	−6	−0.3	61	0	36	3	33	1.0	37	1.2
1928	0	30	−30	−1.1	59	−1.5	3	18	−15	−0.8	56	−0.3
1929	20	13	7	0	54	0.1	40	13	27	0.8	30	0.4
1930	5	14	−9	−0.5	55	−0.9	24	14	10	0.2	40	0.2
1931	30	0	30	1.0	50	1.4	42	2	40	1.4	27	1.1
1932	14	7	7	−0.1	63	0.6	9	13	−4	−0.2	47	0
1933	10	44	−34	−1.2	70	−1.0	9	7	2	0.1	40	−0.2
1934	33	17	16	0	57	0.2	10	26	−16	−0.8	48	−1.0
1935	3	32	−29	−0.7	57	−1.1	26	11	15	0.5	39	0.4
1936	51	1	50	1.7	37	1.7	14	8	6	0.1	33	−0.6
1937	22	14	8	0.1	52	0	15	7	8	−0.2	41	−0.4
1938	26	2	24	1.3	40	1.1	3	30	−27	−1.0	61	−0.4
1939	35	2	33	0.9	45	1.0	22	4	18	0.5	40	0.5
1940	8	5	3	0.2	47	−0.3	26	6	20	0.4	37	0.3
1941	10	41	−31	−1.4	67	−1.8	7	32	−25	−0.9	48	−1.1
1942	1	25	−24	−1.0	67	−0.9	6	15	−9	−0.2	48	0
1943	4	13	−9	−0.4	61	−0.1	13	3	10	0.4	45	1.0
1944	1	15	−14	−0.7	61	−0.6	8	10	−2	0	44	0
1945	0	29	−29	−1.2	61	−1.7	7	30	−23	−0.7	53	−0.5
1946	34	7	27	0.9	44	0.9	1	32	−31	−1.3	55	−1.3
1947	16	8	8	0.2	46	−0.3	0	39	−39	−1.6	56	−1.9
1948	28	12	16	0.7	56	1.5	28	10	18	0.5	40	0.7
1949	31	15	16	0.2	59	0.6	12	21	−9	−0.4	47	−0.4
1950	10	16	−6	−0.2	47	−0.9	4	19	−15	−0.5	50	−0.3
1951	20	15	5	0.3	47	0	42	3	39	1.1	34	1.2
1952	6	21	−15	−0.6	62	−0.4	42	2	40	1.1	35	1.3
1953	22	11	11	0.3	56	0.6	12	8	4	0.1	47	0.7
1954	30	0	30	1.1	52	1.9	17	22	−5	−0.4	44	−0.6
1955	12	20	−8	−0.2	54	−0.4	61	2	59	1.9	26	1.9

TABLE 4. (*Continued*)

	EP						AP					
Year	*D*	*M*	DM	*S*	Q	ΔT	*D*	*M*	DM	*S*	Q	ΔT
1956	13	30	−17	−0.5	59	−0.5	13	19	−6	−0.4	47	−0.3
1957	34	4	30	0.9	46	1.1	35	8	27	0.8	37	0.9
1958	10	25	−15	−0.4	59	−0.3	7	32	−25	−0.7	45	−0.9
1959	28	0	28	1.1	39	0.8	15	13	2	−0.1	47	0
1960	26	4	22	0.5	49	0.4	2	50	−48	−1.8	61	−1.8
1961	25	10	15	0.3	52	0.4	20	8	12	0.2	43	0.3
1962	9	25	−16	−0.8	68	−0.3	39	3	36	1.1	39	1.8
1963	39	13	26	0.9	43	0.8	17	11	6	0.6	34	0.3
1964	20	16	4	0	57	0.2	9	13	−4	−0.2	46	−0.1
1965	1	16	−15	−0.6	57	−0.9	56	0	56	1.6	29	1.9
1966	26	9	17	0.6	50	0.7	18	19	−1	−0.2	44	−0.1
1967	15	4	11	0.6	46	0.8	20	6	14	0.2	49	0.8
1968	21	16	5	0.1	51	0	27	10	17	0.1	41	0
1969	2	26	−24	−0.8	58	−1.3	10	22	−12	−0.4	46	−0.5
1970	13	3	10	0.3	48	0.1	1	17	−16	−0.5	41	−1.0
1971	9	7	2	0.1	52	0	5	16	−11	−0.3	42	−0.4
1972	43	0	43	1.6	42	1.8	10	24	−14	−0.7	47	−1.1
1973	11	15	−4	−0.4	61	−0.1	11	14	−3	−0.2	47	−0.1
1974	1	36	−35	−1.0	67	−0.8	36	2	34	0.9	33	1.0
1975	49	0	49	1.7	41	2.2	38	10	28	0.8	31	0.6
1976	1	31	−30	−1.2	58	−1.7	18	8	10	0.3	42	0.4
1977	9	9	0	−0.1	62	0.5	38	0	38	1.4	35	1.9
1978	0	60	−60	−1.8	70	−2.0	6	9	−3	0	43	−0.2
1979	47	13	34	0.9	41	0.8	17	13	4	−0.1	46	0
1980	8	23	−15	−0.8	64	−0.8	27	12	15	0.4	42	0.6
1981	53	2	51	1.7	36	1.6	34	14	20	0.5	37	0.5
1982	2	25	−23	−0.7	57	−1.0	35	3	32	1.0	35	1.1
1983	10	10	0	−0.1	59	0.2	19	19	0	0.1	43	0.2
1984	27	10	17	0.3	54	0.7	22	6	16	0.4	40	0.5
1985	10	32	−22	−0.8	65	−0.6	6	18	−12	−0.4	41	−0.9
1986	19	2	17	0.4	45	0.1	8	12	−4	−0.5	42	−0.8
1987	16	6	10	0.1	55	0.4	27	7	20	0.5	41	1.0
1988	23	1	22	0.6	59	1.4	26	18	8	0.3	40	0.4
1989	12	9	3	0	62	0.8	37	5	32	1.0	33	1.2
1990	7	26	−19	−0.9	62	0.7	25	3	22	0.4	49	1.2
1991	25	12	13	0.4	57	1.0	56	1	55	1.9	28	2.1
1992	5	12	−7	−0.1	43	−0.9	12	6	6	−0.2	38	−0.9
1993	15	32	−17	−0.9	65	−0.9	7	21	−14	−0.5	48	−0.5
1994	7	27	−20	−0.7	50	−1.5	23	8	15	0.4	41	0.5
1995	21	4	17	0.9	45	1.0	29	4	25	0.6	35	0.6

(approximately −0.6 to −0.7) occur in the regions of the middle Volga Basin, middle Ural, and north Kazakhstan.

This negative correlation between precipitation and temperature was utilized in constructing two indices describing the temperature and moisture characteristics of a region for the warm period. The first index *D* is a measure of the droughtlike character of a region. Drought is definded as occurring when the following two conditions are met:

$$\text{precipitation } Q < 80\% \text{ of the long-term mean value,}$$

and

$$\text{temperature anomalies } \Delta T > 1^\circ\text{C}. \qquad (3)$$

The second index *M* is intended to denote periods when the moisture conditions in a region are well above normal and the temperatures are below normal, as in the following two conditions:

$$\text{precipitation } Q > 120\% \text{ of the long-term mean value,}$$

and

$$\text{temperature anomalies } \Delta T < -1^\circ\text{C}. \qquad (4)$$

The 80% and 120% criteria on precipitation were derived from analyses of precipitation data from 1891 to 1975, which show that approximately one-third of the time periods have precipitation that is less than 80% of the long-term mean and one-third of the time periods have precipitation that is greater than 120% of the long-term mean. Thus, these criteria divide the total precipitation time series into three bins of approximately equal frequency.

This relation refers to the territory under study as a

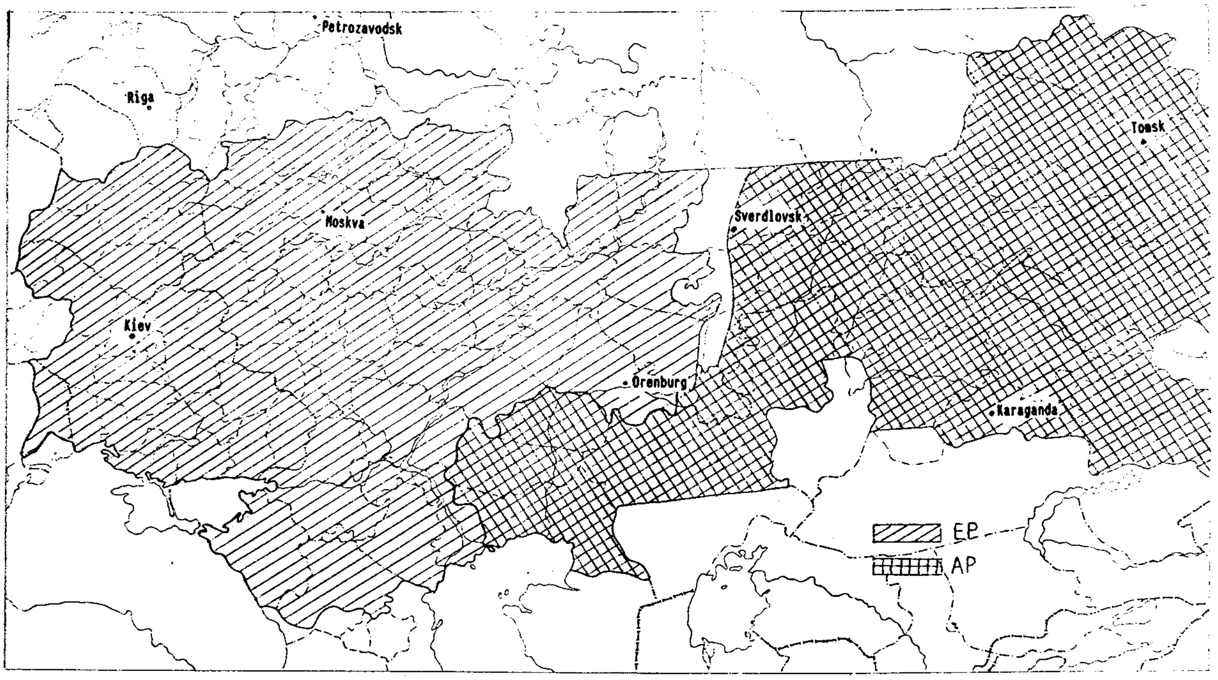

FIG. 1. The European and Asian parts of the FSU for which catalogs of droughts and excess moisture content have been elaborated.

whole, although it changes somewhat depending on moisture types. This is illustrated in Table 2, which presents the distribution of three precipitation gradations in seven administrative regions situated in different climatic zones. Thus in the excessive moisture zone (Leningrad region) 40% of all cases fall within precipitation amounting to 80%–120% of normal and in the arid zone (Kirovograd region) only 25% does.

The criterion for temperature ($\Delta T \pm 1°C$) has been chosen approximately from the same considerations as that for precipitation. For the long-range forecasts of temperature by three gradations (normal, above normal, and below normal), temperature anomalies within $\pm 1°C$ are generally considered to be normal. Since over the territory under study the standard deviations (σ) of monthly mean temperature are about 2°C in May–July, the criterion accepted for temperature is close to 0.5σ.

However, more detailed analysis shows that in spring–summer months (May–July) about 40% of all cases, not one-third, fall within the anomalies to within $\pm 1°C$. In this case, with a decrease in the variability of monthly air temperature from north to south this portion increases by up to 44%–48% (Kirovograd and Rostov regions).

For the warm season, areal averages of the D index and the M index are computed over the EP and the Asian territory under consideration (AP) of the FSU for each year using the following equations:

$$\frac{1}{l}\sum_{j=1}^{l}\sum_{i=1}^{m}100\frac{P_i}{P}\delta_{ij}, \qquad (5)$$

where m is the number of administrative regions, l is the number of calendar months involved in the calculation, P_i is the area of the ith administrative region, and P is the total area of the territory under consideration; and $\delta_{ij} = 1$, if in the ith region in the jth month the condition 3 (when calculating index D) or the condition 4 (when calculating index M) is fulfilled, or $\delta_{ij} = 0$, if these conditions are not fulfilled.

The D and M indices are unilateral. Therefore, their utility for analysis and prediction is somewhat restricted. Thus, apart from the catalogs of areas with drought and areas of excess moisture content, it is advisable to use areal differences (DM), that is index D minus index M.

It should be noted that it is quite rare for anomalies of the same sign to cover the entire grain-growing region at one time. It is much more typical for drought in the west to be accompanied by conditions of sufficient or exessive moisture in the east and vice versa. Therefore, the main grain-growing region of the territory is divided into a European part and an Asian part. The Ural River and Ural Mountains are a natural boundary between them (Fig. 1). The European and Asian parts consist of 62 and 28 administrative regions, respectively. Mountainous regions of the Urals and the northwest part of the FSU were excluded from calculations since those areas do not play a significant role in the production of cereal crops.

In connection with the proposed index DM, a problem arises concerning the quantitative criterion of dryness and excessive moisture. To solve it, the arranged series of index DM was divided into three sections, approximately equal in number. As a first approximation, one can assume that the first third of the series corresponds

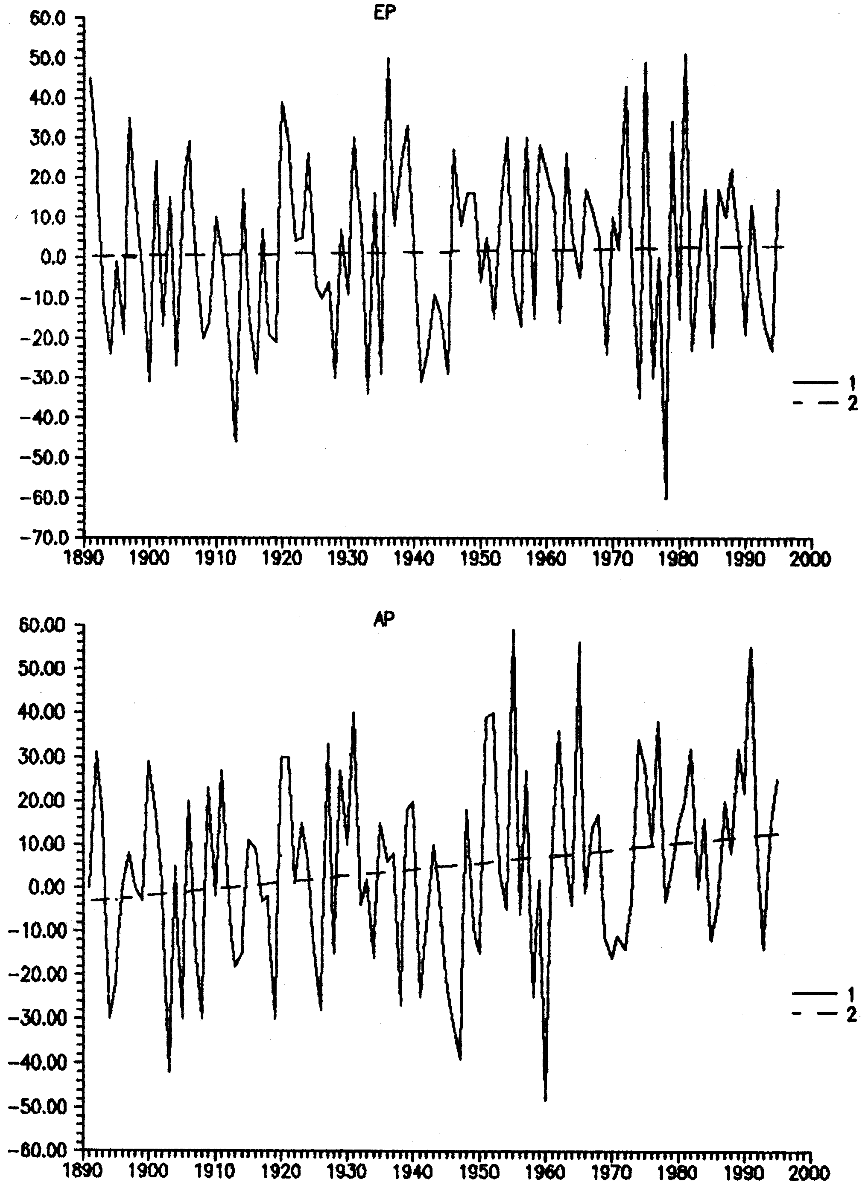

FIG. 2. (a) Many-year series of the DM index (areal differences, in percent) for May – July, 1, and (b) their linear trend, 2, in the European and Asian parts of the FSU.

to dry conditions, the second to temperature–humidity conditions close to many-year means, and the third to the conditions of excessive moisture with the decreased temperature background. In both the Eurpean and Asian parts of the FSU between the first and second thirds of the series the boundary value of index DM = 15%. Between the second and third parts of the series the boundary value of index DM = −10% in the EP and DM = −3% in the AP. This shows in particular that excessive moisture over extensive areas is observed more rarely than dryness, especially in the Asian part of FSU.

Nevertheless, for distinguishing dry and excessively wet years, it is practicable to use a single quantitative criterion. It is suggested that the meteorological conditions be considered as dry if DM $\geq$ 15% and excessively wet and cold if DM $\leq$ −15%.

To characterize the temperature–humidity conditions, including droughts and excessive moisture in basic cereal-producing areas of the FSU, the authors used earlier hydrothermal coefficients and dryness indices *S* instead of index DM. These values were calculated for each of the 104 administrative regions and then generalized for EP and AP.

For this purpose, in the first case (HTC), the first coefficient of HTC expansion in the main components was chosen.

In the second case (index S_i), the mean regional in-

TABLE 5. The parameters of linear trends for 1891–1995 of the indices DM and S, the mean air temperature anomalies, and the mean sum of precipitation for May–July.*

European part				Asian part			
σ	β 105	σ_β 105	$\|\beta\|/\sigma_\beta$	σ	β 105	σ_β 105	$\|\beta\|/\sigma_\beta$
Index DM							
22.7	2.6	7.6	0.3	21.8	15.8	7.3	2.2
Index *S*							
0.8	0.1	0.3	0.3	0.7	0.4	0.2	2.0
Mean temperature anomalies (°C)							
1.0	0.2	0.4	0.5	0.9	0.6	0.3	2.0
Mean sum of precipitation (mm)							
8.1	−1.3	2.7	−0.5	7.2	−2.6	2.4	−1.1

[*] Here, σ is standard deviations of the initial series, β is the regression line slope for 105 yr, and σ_β is the standard deviations of β (Poliak 1979; Meshcherskaya and Belyankina 1989).

dices for each year were averaged for EP and AP by the formula (Meshcherskaya and Blazhevich 1990)

$$S = \frac{1}{l}\sum_{j=1}^{l}\sum_{i=1}^{m}\frac{P_i}{P}S_{ij}, \tag{6}$$

where *i* is region number and *j* is month number.

The generalized indices *S* and HTC characterize the intensity of droughts and excessive moisture with consideration given to the area. This is their advantage over index DM, which at first glance only characterizes the areas of droughts and excessive moisture. However, there is a relationship (the larger the area of dry phenomena, the higher their intensity) between the areas of drought (areas of excessive moisture) and their intensity, which is seen in Table 3. The cross-correlation matrix between indices DM and S is presented here, as is that between the series of precipitation (*Q*) and anomalies of temperature (ΔT) for EP and AP during May–July. The values *Q* and ΔT for each year were calculated from formulas similar to (6):

$$Q = \frac{1}{l}\sum_{j=1}^{l}\sum_{i=1}^{m}\frac{P_i}{P}\frac{Q_{ij}}{\overline{Q}_{ij}} \tag{7}$$

and

$$\Delta T = \frac{1}{l}\sum_{j=1}^{l}\sum_{i=1}^{m}\frac{P_i}{P}(T_{ij} - \overline{T}_{ij}), \tag{8}$$

where Q_{ij} is the amount of precipitation (mm), T_{ij} is the temperature, and $\overline{Q}_{ij}$ and $\overline{T}_{ij}$ are the appropriate long-term means of the Q_{ij} and T_{ij} series, respectively.

The dependence between indices DM and *S* is almost functional: the correlation coefficient $r = 0.97$ for both the EP and the AP (Table 3). It was mentioned above that the mean regional indices of HTC and S were also well cross correlated.

All indices were calculated for the period May–July. This is the most important period for crop development in the principal grain-growing region of the FSU (Meshcherskaya 1983), particularly in the Asian part. In the European part, July is not as important, which follows from analysis of maps of correlation coefficients between the mean regional anomalies of spring and winter wheat yield and the mean regional hydrothermal coefficients (Meshcherskaya et al. 1978b). In the calculations made, the cereal yield is expressed in units of weight per unit area and yield anomalies in yield deviations from square trends.

On the whole, for the EP and the AP, the dependence between the indices considered and the anomalies of cereal yield is rather close. Over the period from 1891 to 1975 in the EP, the correlation coefficient for the anomalies of cereal (all together) yield and the first coefficient of the HTC expansion in the main components for May–July is $r = 0.64$, and when using index *S*, $r = -0.72$. For north Kazakhstan, respectively, $r = 0.65$ and $r = -0.69$ (Meshcherskaya 1983, 1988).

The correlation of index DM with the anomalies of cereal yield is approximately the same ($r \cong -0.7$). In-

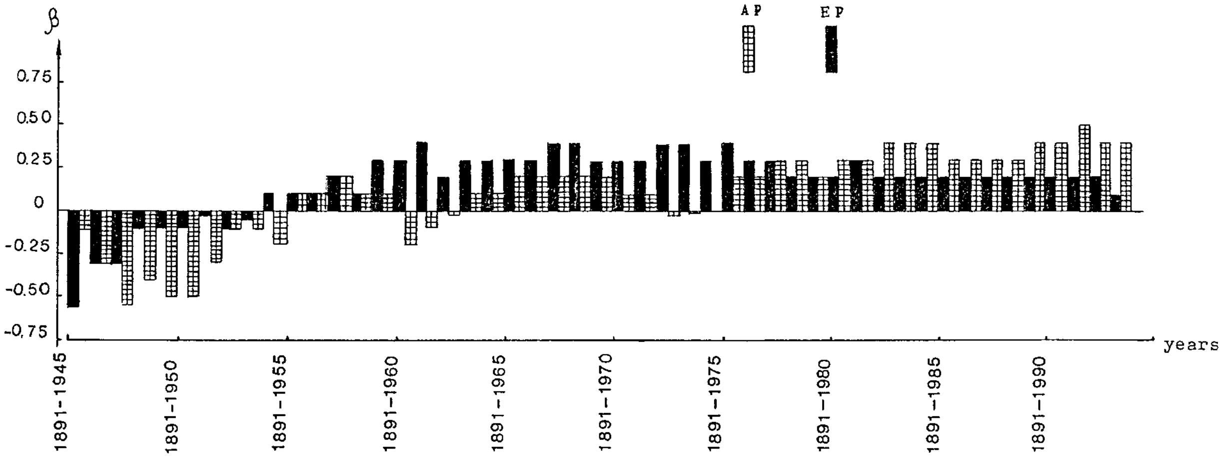

FIG. 3. The May–July regression line slope of the *S* index for variable series lengths: periods 1891–1945, . . . , 1891–1993 over the European and Asian parts of the main grain-growing regions of the FSU.

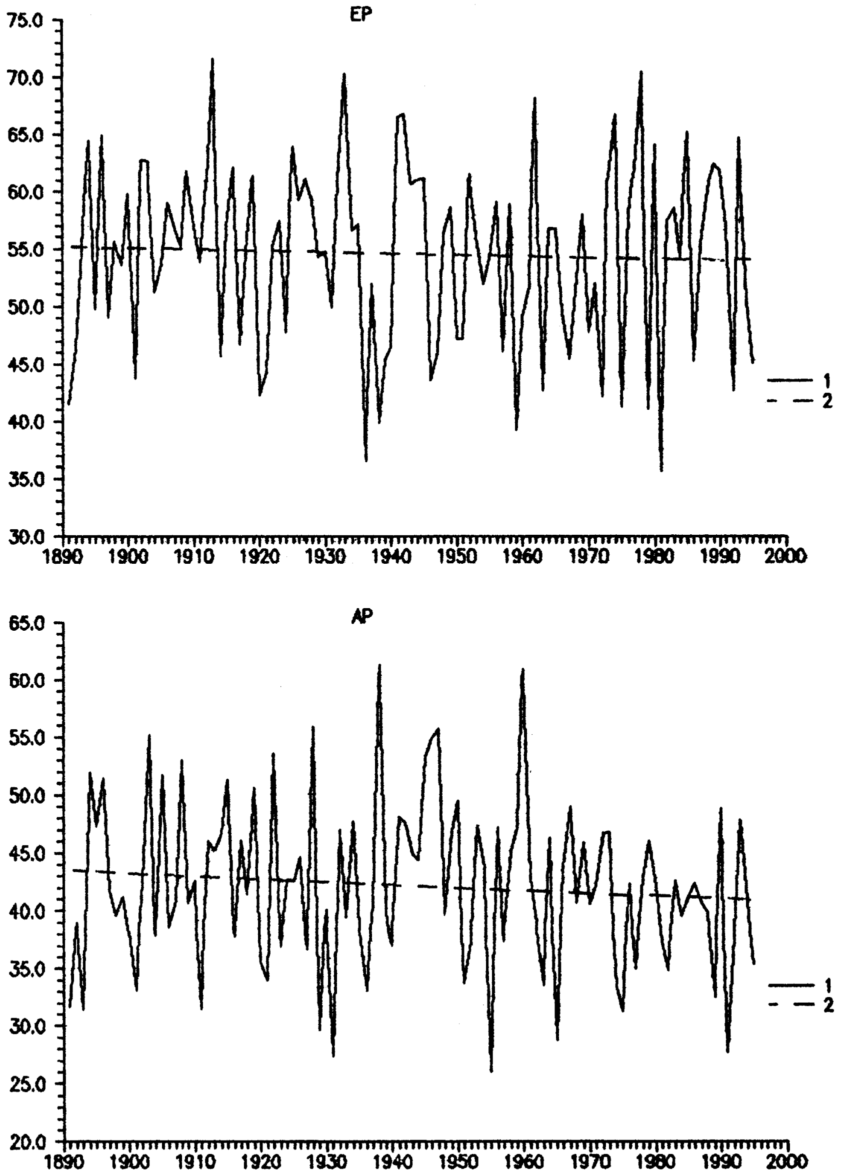

FIG. 4. (a) Many-year series, 1, of mean amounts of precipitation (mm) and (b) their linear trend, 2, for May–July in the European and Asian parts of the FSU.

creased moisture and decreased temperature background contribute to high cereal yield.

4. Discussion

The 100-yr time series of the *D, M,* and DM indices for the May–July period over the European part and the Asian part of the FSU are given in Table 4. In the European part, the most severe drought occured in 1981, when over 53% of the region experienced drought conditions as defined in (3). The next most severe drought years were 1936 (51%), 1975 (49%), 1979 (47%), and 1891 (46%). The years experiencing moist conditions as defined in (4) were 1978 (60%), 1913 (46%), 1933 (44%), and 1941 (41%).

In the Asian part, the most severe drought occurred in 1955 (more than 61%), 1965 (56%), 1951 (42%), and 1931 (42%). The years with the largest *M* index values were 1960 (50%), 1903 (48%), and 1947 (39%).

Time series of the DM index for both the European and Asian regions for the spring–summer months over the past 105 yr are shown in Fig. 2. Linear trends were estimated for each time series by computing linear regressions. The DM time series for the European part is practically stationary. While there is a slight tendency for increasing drought frequency, the slope of the re-

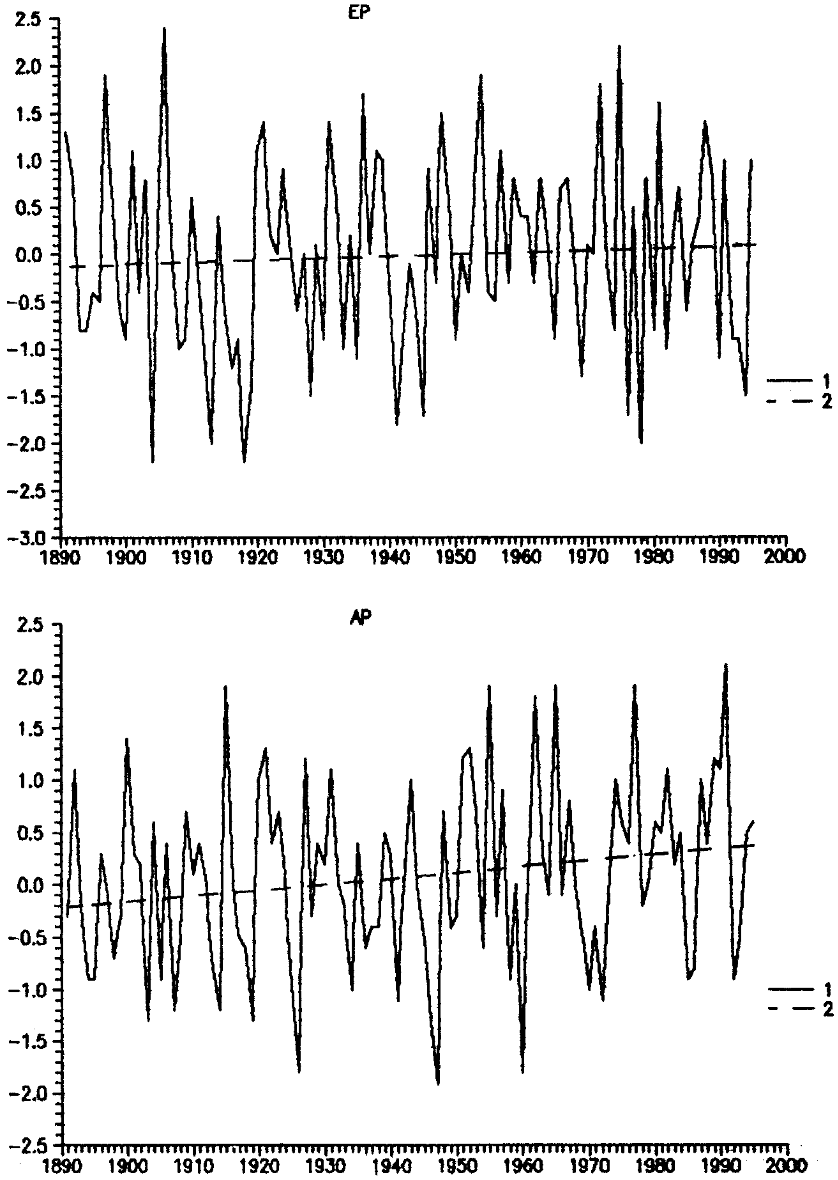

FIG. 5. (a). Many-year series, 1, of mean temperature anomaly (°C) and (b) their linear trend, 2, for May–July in the European and Asian parts of the FSU.

gression line is very small, being 2.6% over the 105 yr. In the Asian part of the FSU (Fig. 2), there is a pronounced trend of increasing aridity. The slope of the regression coefficient is 15.8% over the 105 yr, exceeding $2\sigma_\beta$—that is, it is statistically significant at the 95% significance level.

The estimates of linear trends of DM and *S* indices on the whole agree well (Table 5).

The linear trends over the entire 105-yr period provide a very rough idea of the evolution of the DM and *S* indices over time. Figure 3 shows the index *S* regression line slope for variable series lengths, increasing from 55 to 103 yr. First one value of the trend over the whole period from 1891 to 1944 was calculated, and then the trend was recalculated every time, with the series becoming 1 yr longer. This enables one to follow the variability of index *S* over the period from 1945 to 1993.

Figure 3 indicates that from the late nineteenth century to the mid-1950s in both the EP and the AP, the coefficients of linear regression were negative; that is, moisture was higher than the normal and temperature lower than the normal. In subsequent years in both territories, the meteorological conditions became drier (the sign of linear regression coefficient β changed to positive). The dryness in the EP increased up to the mid-1970s, as indicated by the tendency toward a growth in β from the period 1891–1955 to the period 1891–1975. With the addition of subsequent years (1976, 1977, . . . , 1993), the coefficients of β reach the stationary level.

In the AP, the positive values of β increase from the period 1891–1956 to the period 1891–1991. Thus, the growth of dryness stopped in the EP in mid-1970s and continued in the AP to the early 1990s.

When calculating the S and DM indices, both precipitation and temperature data were taken into account. It is instructive to examine the variations of precipitation and temperature separately to gauge the relative importance of each term in computing these indices.

Time series of precipitation and temperature anomalies for May–July are given in Table 4 and are shown in Figs. 4 and 5 for both the European and Asian parts of the FSU. For the European part, the regression lines (Table 5) indicate that precipitation tends to decrease slightly over the period from 1891 to 1995 [slope $= -1.3$ mm (105 yr)$^{-1}$ or -2% of normal], while temperature tends to increase [slope $= 0.2°$C (105 yr)$^{-1}$]. For the Asian part, changes in temperature and precipitation have the same sign as over the European part, but are of greater amplitude [for the precipitation, the slope is -2.6 mm (105 yr)$^{-1}$ or -6% of normal, and for temperature, the slope is 0.6°C (105 yr)]. Only the time series of the temperature over the Asian part are statistically significant at the 95% level.

In connection with the temperature and precipitation trends presented, a problem arises concerning their agreement with the results of other authors. The temperature rise in May–July of 0.2°C in the EP and by 0.6°C in the AP over the 105 yr corresponds to the ideas formed.

However, it is more complicated with precipitation. According to studies on precipitation trends published in Carbon Dioxide Information Analysis Center (1994) for the Northern Hemisphere continents, there has been a prevailing tendency for the annual precipitation amount to increase over the past 100 yr, although there are exceptions (e.g., western Europe). For the territory of the FSU, according to calculations made by Groisman (Groisman 1990; Vinnikov et al. 1990), precipitation trends are also positive. In May–September over the period of 1891 to 1987 in the EP (to the south of 60°N), $\beta = 3\%$ for 100 yr, and in west Siberia, $\beta = 5\%$. It should be kept in mind that according to Table 5 $\beta = -2\%$ and $\beta = -6\%$, respectively, in the EP and the AP. However, such differences are quite explicable. It should also be kept in mind that in these works the territories are not identical; in particular, west Siberia (Groisman 1990) has twice as large a territory as the northern areas, such as the AP in the present work. In addition, the trends were estimated in the first work for May–September and in the second work for May–July.

In this connection it should be emphasized that according to archive data (Efremova 1976; Ledneva and Meshcherskaya 1977) the estimates of trends differ depending on the above factors. Unlike for the whole EP (Table 5), for the watersheds of the Volga and Ural Rivers, which are only a part of this territory, in April–September the precipitation trend proved to be positive, but also insignificant (Meshcherskaya et al. 1994).

Now let us come back to Table 3 and consider the relationships between drought indices (DM and S) on one hand and temperature and precipitation in May–July on the other hand. The correlation between index DM and precipitation is strong: $r = -0.77$ in the EP and $r = -0.81$ in the AP. The relationship between index DM and temperature is even stronger: $r = 0.92$ and $r = 0.90$, respectively, in the EP and the AP. Close values of the correlation coefficients are found between the series of Q, ΔT, and index S.

As already mentioned, the linear trends of index DM are statistically significant only in the Asian part of the FSU, like the linear trends of temperature for this territory. Therefore, one can claim that the strong growth of dryness in the Asian part of the basic cereal-producing areas of the FSU for the past 105 yr is mainly explained by temperature rise and, to a certain extent, by precipitation decrease.

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