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EVOLUTION OF DROUGHT SEVERITY FOR A 118-YEAR PERIOD IN THE REPUBLIC OF MOLDOVA

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Abstract: The Republic of Moldova is among several Balkan countries affected by extreme drought. Some districts in the country suffer from severe droughts approximately once every 3rd year, with serious consequences for the agricultural and food sectors. Any contribution to understanding and predicting drought conditions will be a step toward minimizing drought impacts. Droughts in Moldova were evaluated using meteorological data since 1955 and/or a long time series (1891–2009) recorded at Moldova's State Hydrometeorological Service. Evolution of drought severity for the 118-year and/or 54-year time series is based on the S_i-m drought index, using temperature and precipitation series for the calculations. In addition to meteorological data, the crop yields for corn (*Zea mays* L.), a crop widely grown in Moldova, were used to demonstrate drought impact. The S_i-m shows an increasing tendency toward more intensive and prolonged severely dry and extremely dry summer months. The analysis shows that 86% of the lower yield years were recorded for corn when drought occurred during April and July–August. Corn yield is also highly sensitive to the occurrence of a short drought spell in August (e.g., 1994, 1999, 2003 and 2007). Finally, the negative regression coefficient for corn yield indicates that corn is most vulnerable to extremely droughts during April. This was the second cause for poor yields, and particularly in southern districts during 1946, 1947, 2000 and 2009. In these dry steppe areas, extremely dry Aprils may explain 38% of the variability in corn yield.

Keywords: S_i-m index, drought, dry, corn, variability, yield.

1. Introduction

The recent economic crisis has sent shock waves over Europe, reaching all sectors of the agricultural system. In addition, recent severe European droughts (e.g., 2003 in Central Europe, 2005 in Western Europe, 2007 almost throughout Europe, and 2009 in southern and southeastern Europe) have underscored just how significant can be the impact on European economies (Potop et al., 2008; Livada and Assimakopoulos, 2007; Loukas and Vasiliades, 2004; Vicente-Serrano and Cuadrat-Prats, 2007). The case of the Republic of Moldova, which had severe drought in 2007, presents a recent illustration of how a country can be affected by, and respond to, the dual challenge of extreme drought events and high international cereals prices. Aggregate yields of winter and summer crops fell by 63% for that year, thus reducing crops production overall (FAO, 2007). A severe spring drought was seen across Moldova, beginning as a consequence of poor winter snowfall and little spring rain. From October 2006 until July 2007, rainfall was just 50% to 75% of the long-term average. In the south of the country, it reached only 25%. Then, during the summer months, drought affected 80% of Moldova's territory (Potop and Soukup, 2009). For the entire period of meteorological observations in Moldova, similar extreme events occurred only at the end of the 19th century (in 1892) and in the mid-20th century (1946 and 1947). The 2007 drought was due to an almost continuous persistence of tropical heat waves, such that two summer months, June and August, were the warmest in 120 years. Additionally, in July 2007, the heat was linked to persistent anticyclonic situations favoring the advection of dry air masses. The synoptic at the 500 hPa isobaric area was characterized by a prevalence of tropical continental air from North Africa and a movement of warm air into the inferior troposphere (Bogdan et al., 2008).

The objective of this study is to provide an overview of a methodology for assessing drought in

Moldova. The main aim is to propose usage of the *Si* drought index and to discuss its potential use for studying the evolution of drought severity in Moldova. To be used for drought characterization, the *Si* index must meet requirements that it (a) can be calculated using data available from actual data collection systems, (b) has a direct relationship with vulnerable agriculture systems; and (c) can be used for predictions and early monitoring systems.

A climate diagram provides a convenient way to summarize much information about the drought condition of a locality. This paper focuses also on the graphical method of representing drought spells, which serves for modeling the time aspect of such an event. In particular, we have applied Walter and Lieth climate diagrams in monitoring and analyzing droughts. This method is very useful in studies describing dryness and drought spells in forest steppe and/or steppe regions (Bogdan and Niculescu, 1999; Potop and Soukup, 2009, Potop, 2009). In these regions, we used Walter and Lieth diagrams while assuming that a ratio of temperature/precipitation of 1:2 represented drought spells and that of 1:3 represented dryness spells. Moldova is located in a region of insufficient precipitation and has limited water resources. Average annual precipitation is 370 mm in the south and 560 mm in the north. Rainfall events, and especially 80% is abundant ones, are highly variable in time and space. A predominantly rural country, 76% of Moldova's total area is agricultural land while 9.6% is under forests. More than 20% of cultivated land is under irrigation.

2. Data and methods

Droughts in Moldova have been evaluated while taking into consideration either meteorological data since 1955 and/or a long time series (1891–2009) recorded by the National Fund of Hydrometeorological Data at the State Hydrometeorological Service in the Republic of Moldova. Evolution of drought severity for the 118-year and/or 54-year time series is based on the S_i-m drought index using temperature and precipitation series in the calculations. The Chisinau station (the central part of the Republic of Moldova) is the site with the longest uninterrupted series of air temperature and rainfalls records in the Republic of Moldova, dating back to 1891. For 14 meteorological stations the statistical sequence covers the interval from 1955 to the present (Fig. 1). In addition to meteorological data, the yields for corn (*Zea mays L.*), a crop widely grown in Moldova, were used to demonstrate drought impact. Agricultural databases containing the yield series for 1955–2007 were available for individual districts as reported by the National Bureau of Statistics of the Republic of Moldova. The S_i-m index has been used as a tool for identifying drought's severity, frequency and time occurrence. This index provides a measure of the long-term intensity of drought conditions derived from precipitation and temperature anomalies and their combined effects on soil water availability to plants. A detailed approach for calculating S_i-m is shown in Potop et. al. (2010). S_i is expressed by the following equations (1-4):

$$Si(\tau) = \frac{\Delta T}{\sigma T} - \frac{\Delta R}{\sigma R} - \frac{\Delta E}{\sigma E} \qquad (1)$$

where: $\Delta T = t_\tau - t_n$; $\Delta R = r_\tau - r_n$ and $\Delta E = e_\tau - e_n$, i and τ - climatological station and time, respectively, t_τ – monthly mean air temperatures in τ – a specific year, t_n – long-term monthly mean air temperatures, r_τ – monthly precipitation amounts in τ – a specific year, r_n – long-term monthly precipitation amounts, e_τ – monthly amount of moisture in a 0-100 cm soil layer in τ – a specific year, e_n – long-term amount of moisture in a 0-100 cm soil layer, σT, σR, and σE – root-mean-square deviation in monthly temperature, precipitation and moisture of

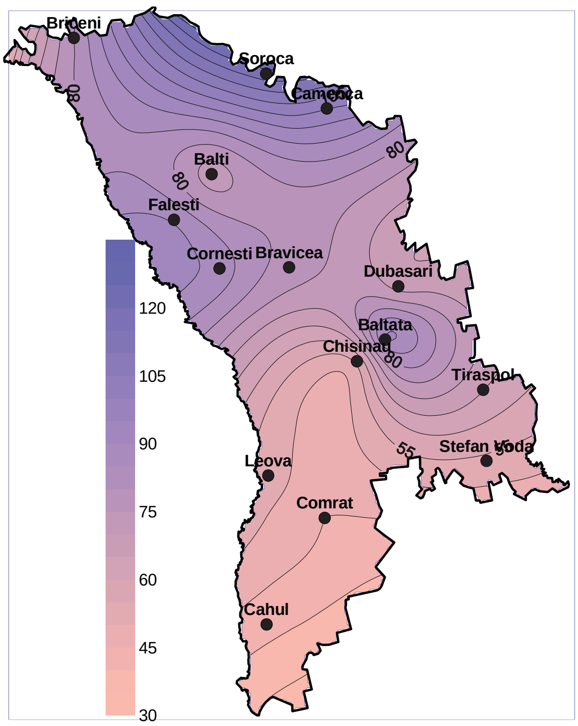

Fig. 1. Station network used for the analysis of drought months over 1955-2009 and the Chisinau station for the years 1891-2009. It includes the spatial distribution of percent of normal rainfall in the warm half of the 2009 year (April-October).

soil, respectively.

In case of the identification of meteorological drought only the first and second parameters of the equation 1 can be calculated:

$$S_i - m(\tau) = \frac{\Delta T}{\sigma T} - \frac{\Delta R}{\sigma R}$$

or

$$S_i - m(\tau) = \left(\frac{t_\tau - t_n}{\sigma T} \right) - \left(\frac{r_\tau - r_n}{\sigma R} \right) \quad (2)$$

Pedological drough (drought in the soil) can be formulated by equation 3:

$$S_i - p(\tau) = \frac{\Delta E}{\sigma E}$$

or

$$S_i - p(\tau) = \left(\frac{e_\tau - e_n}{\sigma E} \right) \quad (3)$$

Agricultural drought as a complex event may also be identified by equation 4.

$$S_i - a(\tau) = \left(\frac{t_\tau - t_n}{\sigma T} \right) - \left(\frac{r_\tau - r_n}{\sigma R} \right) - \left(\frac{e_\tau - e_n}{\sigma E} \right) \quad (4)$$

In a previous study, we proposed three methods for calculating the Si index that we characterized as meteorological drought (S_i-m), pedological drought (S_i-p), and agricultural drought (S_i-a). The advantage of the complete *Si* index (S_i-a, S_i-p, and S_i-m) is in its capacity to utilize calculations that are based on available data. In addition, the S_i-m can accurately predict drought based on temperature and rainfall data alone. By contrast, S_i-a and S_i-p indices must be combined in order to predict an agricultural drought. Because of its ability to detect drought and wet periods and/or distinguish meteorological drought from agricultural drought, S_i-m has been used as the indicator for monthly meteorological drought in the present study (Table 1). For *S_i-m*, the categories interval ranges from extreme drought (S_i-m≥3) to extreme wet (S_i-m≤-3). So, positive values of S_i-m correspond to dry periods, negative to wet periods. Another interpretation can be made as follows: positive values of S_i-m correspond to a warmer thermal regime during some period, whereas the negative ones reflect a colder thermal regime.

Table 1. Drought criteria proposed for Si index

	Drought severity classification			
	mild	moderate	severe	extreme
Meteorological drought *(S_i-m)*	0≤S_i-m <1	1≤ S_i-m <2	2≤ S_i-m <3	S_i-m ³3
Agricultural drought *(S_i-a)*	1≤ S_i-a <2	2≤ S_i-a <3	3≤ S_i-a <4	S_i-a ³4
Pedological drought *(S_i-p)*	0≥ S_i-p >-1	-1≥ S_i-p >-2	-2≥ S_i-p >-3	S_i-p ≤-3

In order to assess dryness condition more effectively in this study, we used a nontraditional concept representing one year and which consists of two half-years: the first half is cold and the second half is warm. We selected 1 October as the beginning for this agrometeorological year, the winter half of which ends in March. The summer half-year, from April to September, coincides with the growing seasons for most crops. The civil calendar year is inconvenient for agricultural application, because the winter season is divided into two parts that are not linked to one another and the warm part of the year is situated between them. For most annual plants, the weather conditions of the previous growing season (represented by accumulated water in the soil) have more importance than do those of the current growing season. Similarly, perennial or biennial plants, and especially winter crops, begin their growth with six months of cold that can often be a critical period (Koznarova and Klabzuba, 1993). Also, from the viewpoints of soil tillage, hibernating pests, development of diseases, frost damage and drought occurrence it is not possible entirely to ignore the period of the previous winter. Thus, the method for evaluating dry spells in separate years utilized Walter and Lieth climatic diagrams, which facilitate detailed analyses, and especially in the critical period of crop growth and development (Walter and Lieth 1961). The reason for using this method is that drought can start at the end of one month and extend into the next month, or it can continue for several successive months. This makes it possible to determine the drought spells without needing to resort to using indices. The index of fluctuations in corn yields over time (Cm) was used to assess the impact of drought conditions in the process of corn crop formation in the various regions of the country. The Cm was calculated on the basis of equation 5:

$$C_m = \frac{1}{y}\sqrt{[\sum_{i=1}(y_i - \bar{y})^2 - \sum_{i=1}(y_t - \bar{y})^2]/(n-1)} \quad (5)$$

where y_i = average yield per particular year, y = long-term average crop yield, y_t = detrended yield, and n = number of years in the investigation.

3. Results and discussion

In accordance with the *S_i-m* index, extreme drought months were recorded in the winter season for December of 2006, 1972, 1898, and 1974; January of 1902, 1989, 1936 and 1994; and February of 2002, 1925, 1989 and 1959 (Table 2). As

Table 2. Si-m ranking of the 21 most severe and extreme warm and drought months from 1891 to 2009 at the Chisinau reference station.

Ranking	Warm and drought winter			Warm and drought spring			Hot and drought summer			Warm and drought autumn		
	December	January	February	March	April	May	June	July	August	September	October	November
1	***2006***	1902	2002	1990	1968	1907	***2007***	***2006***	1999	1994	1896	1926
2	1972	1989	1925	1959	***2009***	1958	1946	1935	1992	1892	1960	1923
3	1898	1936	1989	1938	1994	***2007***	1964	1993	1946	1932	1935	1969
4	1974	1994	1959	1961	1948	2003	1924	2000	1951	1937	1923	1963
5	1958	1925	1998	1906	1972	1963	1981	1930	2001	1982	1932	1990
6	1915	1930	2008	1921	1986	1986	1953	1937	1905	1975	1984	1977
7	1989	1921	1995	1972	2000	2000	1975	1952	1929	1909	1959	***2006***
8	1964	1983	1990	1994	1975	1950	1938	1927	***2007***	1896	1907	1898
9	2000	1939	1904	1975	1947	2002	1968	1938	2008	1924	2008	1938
10	1910	1961	1987	1983	1899	1996	1935	1956	1892	1963	***2006***	2003
11	2004	1975	1914	1930	1989	1982	***2009***	1895	1939	1986	1967	1967
12	1932	1993	1950	1897	1952	1997	1892	1905	1962	1952	1927	
13	1901	1998	1957	1913	1946	1923	1951	1950	1986	1983	1917	
14	1912	1952	1974	1925	1998	1924	2000	1894	1909	1897		
15	1950	1991	1892	1912	1926	1892	1996	1945	1952	1950		
16	1951	1949	1894	1934	1967	1947	1998	1922	2003	1954		
17	1985	1990	1893	***2007***	1973	1968	1896	1958	1897	1961		
18	1975	1898	1958	2008	1971	1908		2004	1938	1999		
19	1979	1899		1927	1951	1969		1965	1900	1923		
20	1982	1962		1937	1927	1901		1896	1921	1967		
21	1993	***2007***			1913	1905		1900	1990			

can be seen from figure 2, the period from 1890 to 1950 contains a larger number of severe drought months especially in the autumn season. By contrast, the

period from 1950 to 2009 clearly shows a large number of extreme drought months in spring and summer. The period 1990–2009 ranks as having drought most frequently in all months. It can be noted that the summer drought months of 2007, 2006 and 1999 were ranked highest in severity by the S_i-m drought index. In June 2007, the S_i-m values were equal to or greater than 3. This made June 2007 the driest June since 1891 at the Chisinau station and the driest on record for all climatological stations since 1955. The severity of the June drought of 2009 ranks only 11th (Table 2). During the month of July 2006, more than 65% of the country's S_i-m values were equal to or greater than 4 (which indicate disaster drought impact). At the majority of climatological stations, August 1999 was the driest and warmest August ever recorded. In addition, severe heat waves occurred across central and southern Moldova during much of August. From these comparisons, we conclude that the most extreme droughts in the summer months have occurred in the last decade. This is true also for the winter months, such as December (2006) and February (2002), but January 1989 is ranked as the 2nd-most extreme for warmth and drought in that month. Indeed, the longest enduring drought and the most severe autumn-winter-spring-summer drought started in October 2006 and ended in September 2007. That drought, which prevailed over Moldova and neighboring countries during spring and summer of 2007, was exceptional in regard to both severity and duration. According to one recent study (Bogdan et al., 2008), in the 2007 drought there developed unusual climatic conditions for the temperate-continental area of Moldova and Romania. For instance, summer temperatures occurred two weeks earlier than usual. Moreover, warm spells during the wintertime, accentuated the drought event in the later seasons. The summers of 2003, 2006, 2007 and 2009 are evaluated as exceptional droughts for Southeast Europe, and crop production was reduced by more than 20%. The S_i-m index has registered the highest positive values (extreme heat and drought) for July 2006 and August 1999. By contrast, the index's greatest negative value (extreme wet) occurred in September 1996. During this month there was a heavy precipitation event, hence similar high

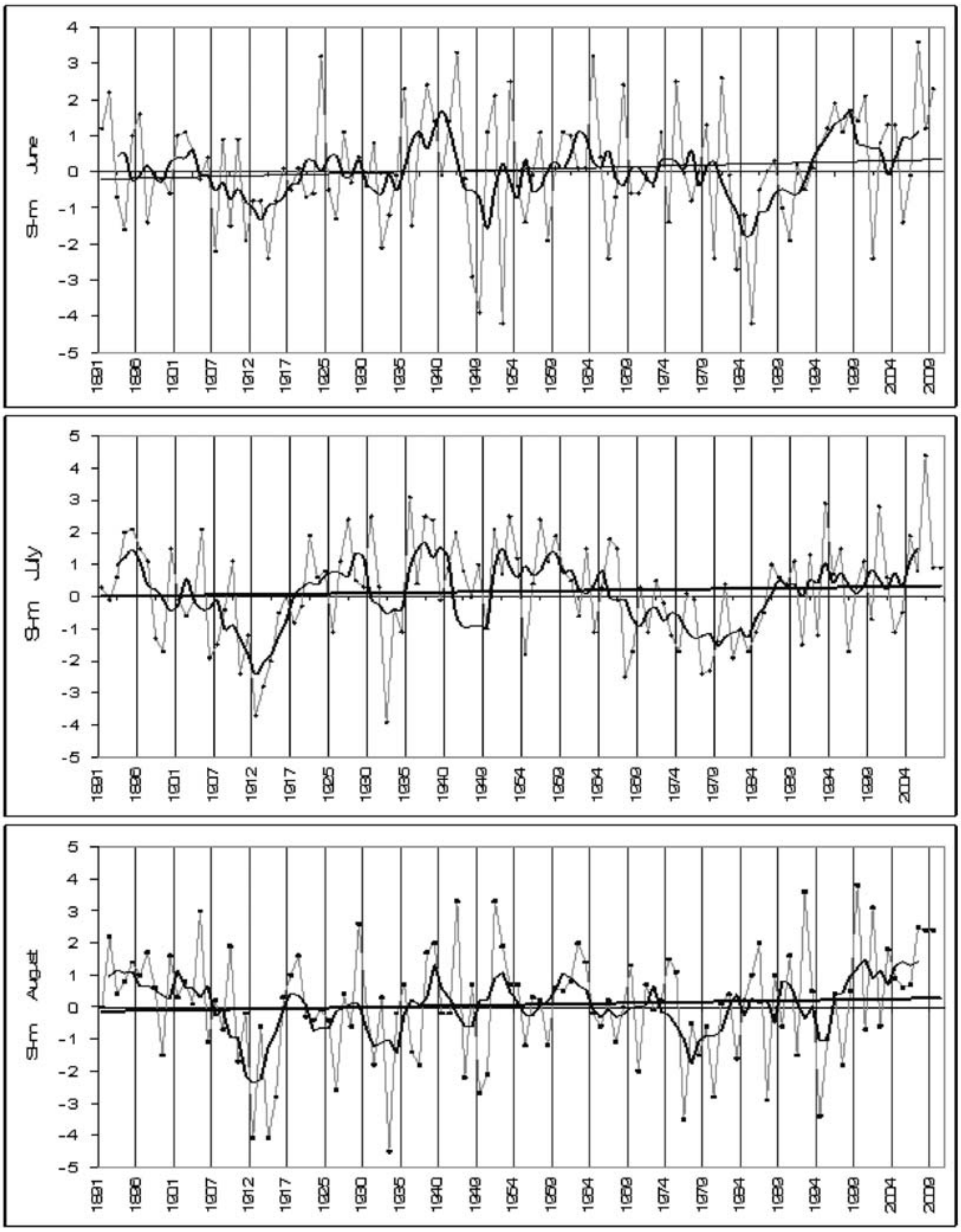

Fig. 2. Fluctuations in individual summer months of Si index over the territory of Moldova during the period 1890–2009, including linear trends and smoothing of the series by 5-year Gaussian filter.

negative values of S_i-m≤-2 were registered for the majority of weather stations. Thus, the S_i-m index has a high capacity to identify both drought and wet months on the territory of Moldova. The long-term variability of S_i-m for summer drought and smoothing of the series using a 5-year Gaussian filter in the period 1891–2009 are illustrated in figure 3. The S_i-m shows an increasing trend in the period studied and an increasing tendency toward more intensive and prolonged dry summer months. As a result prolonged drought periods in the summer months during the early 1900s, early 1920s, late 1930s, middle 1940s, late 1960s, early 1980s to late 1990s, and early 2000s were observed. From the total number of drought months in the summer half-year, 53% of those months are May, June and July. By contrast, from the total number of drought months in the winter half-year, 44% of the months are October, December and February. In the last decade, the following severe drought months were recorded: April (2009 and 2000), July (2006, 2000), August (2003, 2007 and 2009) and September (2005). Having analyzed the characteristic features of drought in Moldova, we can state that approximately once every three years the country suffers from severe drought during the spring and/or summer. In addition, extreme summer drought events are often accompanied by heat waves, as exemplified in the years 1994, 1999, 2000, 2006, 2007 and 2009. Extreme winter droughts are often accompanied by warm spells, such as in 1989, 1994, 1998 and 2006/2007. The winter of 2006/2007 was determined to be the warmest and driest in the entire period of observation. For the majority of climatological stations, the longest drought period was observed in the decade of 1990 to 2000. After the 1990s, the frequency of intense droughts increases. Because this tendency is gradually leading to increased soil loss, wind erosion and degradation of soil fertility, it threatens the agricultural economy and the wealth of the rural population.

The impact of droughts on yields proved to be higher when analyzed on the basis of crop development stages. This is explained by the higher occurrence of dry spells during development stages sensitive to water deficit. For corn, this is during tasselling, grain formation and grain filling. The highest yield reductions by drought occurring in the flowering and grain filling stages on the whole territory of Moldova were in the following years: 1946 (0.6 t/ha), 1953 (1.0 t/ha), 1957 (1.7 t/ha), 1967 (2.8 t/ha), 1983 (3.7 t/ha), 1986 (3.1 t/ha), 1990 (3.4 t/ha), 1992 (2.5 t/ha), 1994 (1.6 t/ha), 2000 (2.1 t/ha), 2003 (2.8 t/ha) and 2007 (0.7 t/ha). A tendency of decreasing average yields of corn has been noted during the last 10 years. This fact is linked with increasing drought conditions observed for this period, as well as with such other conditions as inappropriate agrotechnical measures and lack of irrigation that contribute to corn crops' decreasing drought resistance. According to data of the National Bureau of Statistics documenting corn yield losses, the most significant losses in corn production were in 1946 and 2007. The severity of Moldova's 2007 drought is comparable only to the worst situation that occurred in 1946, known as the year of the famine, when many Moldovans starved to death following the loss of the spring cereal harvest (FAO 2009). According to the climatic diagram, the longest period of the phenomenon in 2007 was 6 consecutive months (Fig. 4). The continuous period without precipitation varied between 30 days (north region) and 70 days (south region) and the number of days with relative air humidity ≤ 30% ranged from 50 to 80 days, which is three times greater than normal. The number of tropical days (tmax ≥ 30°C) was 36–45 days, which is three times higher than normal (Cazac et al. 2007). The main factors affecting production in 2006/2007 were increasing drought severity and adverse agricultural terms of trade. This suggests that the more extensive are the drought areas, the

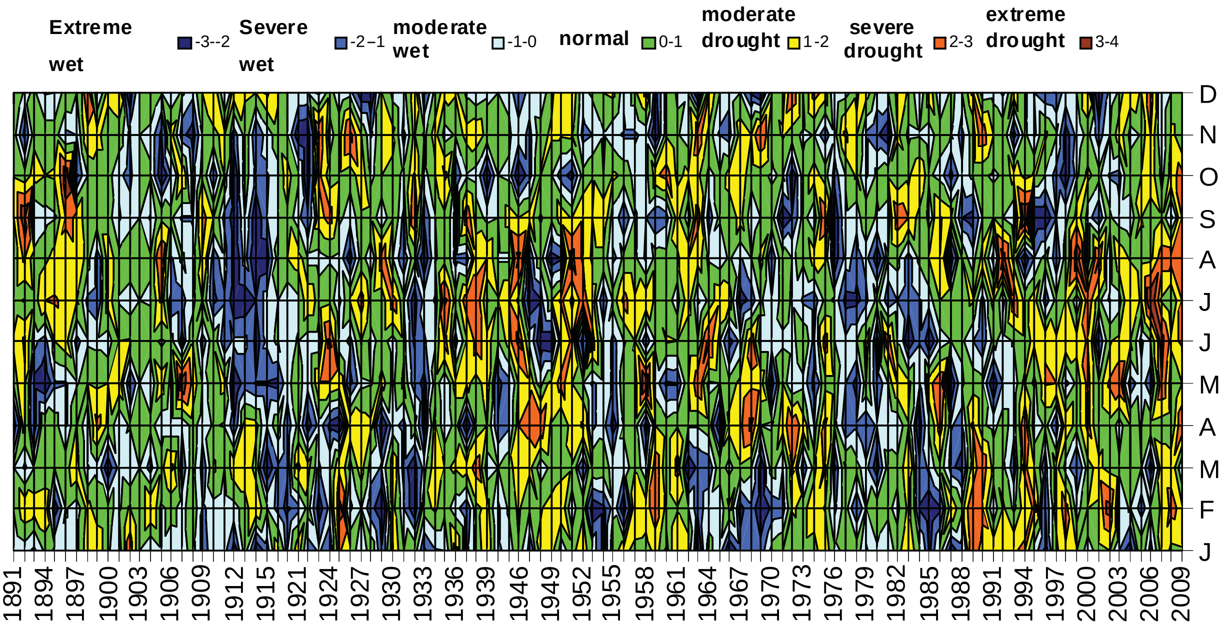

Fig. 3. Evolution of drought severity for the 118-year time series in the central region of Moldova.

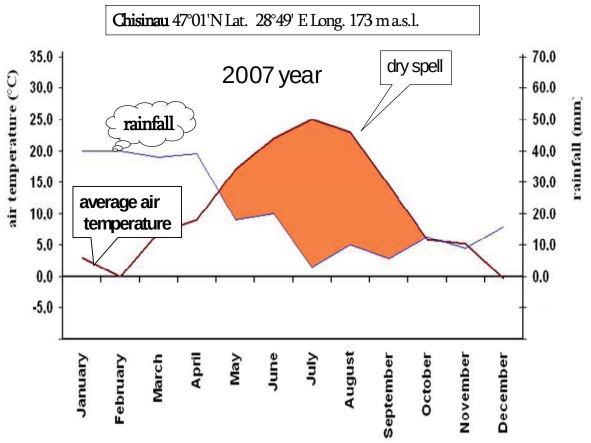

Fig. 4. Climatic diagram showing drought spell in 2007 at the Chisinau reference station.

greater are the variability and reduction in cereal crops yields. High variability of the corn yield is characteristic of those districts where the average yield is lower than the average yield for the country as a whole (Fig. 5a-b). On the territory of Moldova non-uniform spatial differentiation of Cm is observed. The spatial distribution of Cm suggests that three types of districts can be differentiated, those with stable yield (Cm = 0.2 to 0.25), moderately stable yield (Cm = 0.25 to 0.30), and vulnerable yield (Cm ≥0.30). The greatest part of the territory of Moldova can be characterized by stable and moderately stable yield, the exception being in the south and southwest parts of the country. In these regions, droughts are more frequent than in the other districts of country. Table 3 shows the effects of drought on corn yield. The drought impact on corn yield was analyzed by indentifying the relationships between the variability of corn yield (Cm) and drought (S_i-m). In the majority of districts a greater probability of S_i-m≥2 was observed from April to July. The regression equation from Table 3 shows that 86% of the lower yield years were recorded for corn when drought occurred during April and July–August. On the other hand, the corn yield is also highly sensitive to the occurrence of a short drought spell occurring in August (e.g., 1994, 1999, 2003 and 2007). Those years with pronounced drought during August indicate large reductions in the harvest, as that month coincides with increased demands for moisture. Finally, the negative regression coefficient for corn yield indicates that corn is most vulnerable to extreme droughts during April. This was the second cause for poor yields, and particularly in southern districts (1946, 1947, 2000 and 2009). In these dry steppe areas, extremely dry Aprils may explain 38% of the variability in corn yield. As has been shown in various papers (e.g., Constantinov and Nedealcov, 2007; Koleva and Alexandrov, 2008; Mavromatis, 2007) the impacts of drought are very significant for grain production in many Balkan countries, including the Republic of Moldova.

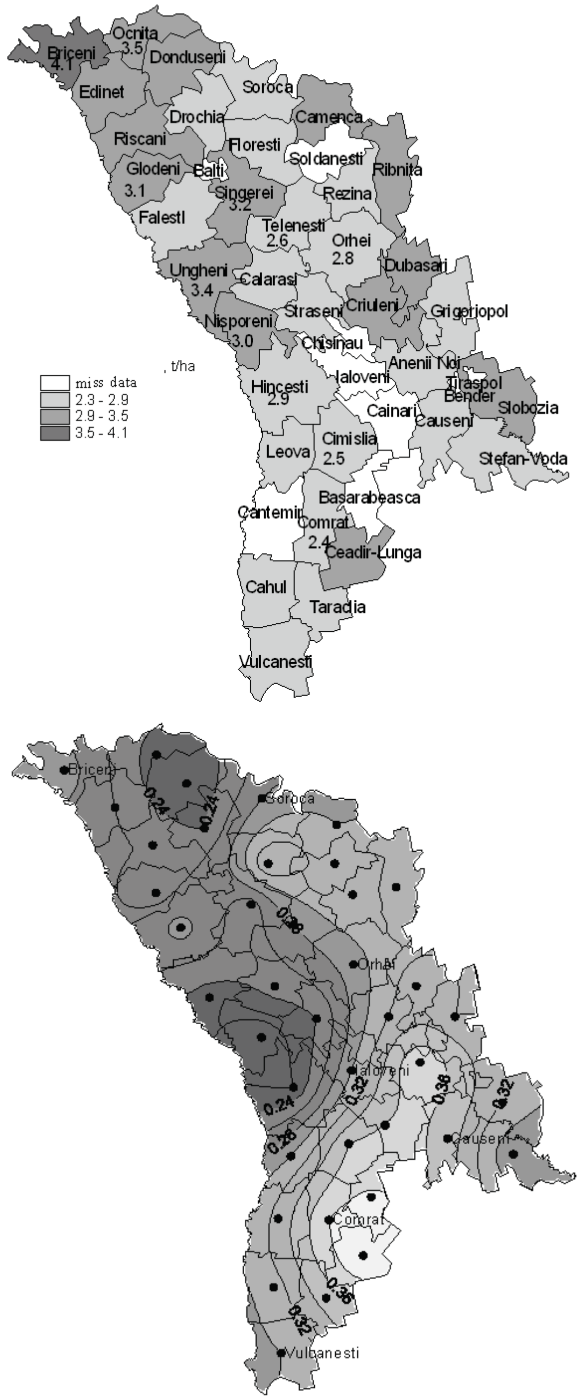

Fig. 5. Long-term corn yield per district (up) and variability of corn yield (down) in Moldova

Table 3. Stepwise regression dependence of variability of maize (Cm) on the drought conditions (S_i-m) of a growing period

Drought impact	Regression coefficients for individual months						R^2	p
	April	May	June	July	August	September		
S_i-m	-3.83	0.22	0.99	-3.52	-4.35	0.85	0.86	0.01
Regression equation	$Cm = 5.63 - 4.10\ S_i\text{-m}_{April} - 3.52\ S_i\text{-m}_{July} - 4.35\ S_i\text{-m}_{August}$							

4. Conclusions

The frequency of extremely dry months and the past variability of drought months were estimated using the S_i-m index. An analysis of spatial-temporal variability of corn yield was made and the influence of drought on corn's productivity was studied. Drought events for the Republic of Moldova were established as a climate risk event in corn production. Corn yield in this region is most vulnerable to prolonged droughts during summer months (particularly in July–August) and to extremely dry spring months. The growth stages of corn show the negative signs of S_i-m index in given months when drought conditions are significant for determining yields. Increasing severity of drought spells and their increasing frequency result in an increasing probability for drought stress to occur, and that is accompanied by decreased mean corn yields and increase in their variance.

The most extreme drought months for the entire reference period were the following: April (1968, 2009), May (1907), June (2007, 1946), July (2006, 1935), August (1999, 1992), September (1994), October (1895), November (1926), and December (2006). The longest drought spells were recorded during four months in 1946, 1953, 1994, 2006, 2007 and 2009. Extreme droughts lead to unusual situations and profound crises in Moldova's agricultural and food sectors. The last 5 years have demonstrated once again that agriculture is the most vulnerable and risky sector of the national economy. The corn yield in 2007 was the lowest within the past decade. As a result, drought is having a major impact on the financial situation of farmers and is causing partial loss of the seeding fund.

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