The current and projected drought-caused loss of the spring wheat yield in the south of European Russia

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Abstract. The study focuses on the linkage between droughts at the beginning of the crop growing season and the yield of spring wheat in southern regions of European Russia. Its extrapolation into the future helps to analyze possible climatic risks in the spring wheat growing. It was found that moderate droughts from May to June, detected by using Standardized Precipitation Index data, in most cases have led to low yields. It was revealed that changes in the air moisture conditions in late spring and early summer in the period 1991-2018 compared with the previous thirty-year period were generally more favorable for the cultivation of spring wheat in most southern regions of European Russia. These positive changes were due to a decrease in the frequency of droughts. At the same time, a significant increase in the frequency of such droughts was observed in Samarskaya and Orenburgskaya oblasts, where the largest sown areas of spring wheat are situated. According to model projections of the future climate, similar changes in the air moisture conditions in the study area will generally remain favorable by the middle of the 21st century. Unfavorable regional forecasts associated with a possible increase in the frequency of droughts at the start of the crop growing season are predicted in Kuban, the east of the Volga region, and the north of the Lower Volga region and the southeast of the Central Black Earth region, in the North-Western Caspian Sea region.

1. Introduction
A regional assessment of agricultural risks related to projected climate changes is important when making management decisions for the climate change mitigation. Weather factors, including extreme climatic events observed during different vegetative stages of grain crops, play a significant role in grain production in main grain-growing regions of Russia. These factors can be both positive and negative. For instance, on the one hand, a warm spring can help plants grow faster. On the other hand, the growth of plants and the accumulation of the vegetative mass often slowdown in years with spring-summer droughts, and the quality of crops suffers [1].

Global warming has led to an increase in heat availability for crops, in an average temperature during the cold season and in duration of the growing season over the past few decades. The changes had a positive impact on the productivity of grain crops in Russia [2]. Meanwhile, agroclimatic changes were favorable not for all regions of European Russia (ER). The feature of the climate in the south of ER is in particular in the strong inter-annual variability of the atmospheric precipitation regime. The water availability, primarily due to the rainfall amount, is a key factor for the growth of crops in conditions of non-irrigated agro-technique. The drought is one of the extreme events in natural climate variability. However, droughts of varying intensity during the growing season are
observed almost every year in a particular region of ER. Severe droughts during the growing season are associated with a significant decrease in gross grain harvest and yield. Previous studies of the authors have revealed a relationship between the quasi-biennial oscillation of the stratospheric equatorial wind with the recurrence of severe droughts in May in the Central Black Earth and CIS-Azov regions and the yield of spring wheat in Belgorodskaya, Voronezhskaya and Rostovskaya oblasts of ER [3]. In [4], the growing possibility of summer droughts in the southeastern ER in the modern period, when sea surface temperatures in the North Atlantic Ocean are warmer than during its previous period, was identified. In [5], it was found that long-term fluctuations of sea surface temperature in the North Atlantic significantly affect the fluctuations of atmospheric centers of action of the NAO, as well as East Atlantic/Western Russia pattern. The negative phase of the latter is associated with the observation of atmospheric blockings over ER, including summer ones.

Sown areas of spring wheat are inferior to the areas of winter wheat in ER. However, the value of spring wheat is much higher. High-protein varieties of strong and hard spring wheat, which are especially highly valued in both domestic and foreign markets, are already being cultivated in the Transvolga region [6]. Spring wheat also can be a guarantee crop during the years when seedlings of winter crops are partially lost after winters with little snow [7]. The main area of spring wheat cultivation covers southwestern regions of ER with favorable climatic conditions, as well as the Kuban region and the right bank of the Volga river, where the amount of precipitation is much higher than in eastern forest-steppe and steppe zones of the Transvolga region [7].

Atmospheric and soil conditions of the heat-moisture ratio during the initial phase of the growing season have a significant impact on the crop formation. This phase occurs in May and June, according to the statistics for the southern regions of ER. Reserves of productive spring topsoil moisture play an important role in the formation of the spring wheat harvest in ER. In [6], the importance of predicting the crops state using the satellite vegetation index NDVI is shown. Its values in May can be considered as an indicator of the plants response to atmospheric-soil conditions of the heat-moisture ratio during the previous months.

The purpose of this study is to investigate the linkage between changes in atmospheric precipitation, including their extremes in late spring and early summer, and the climate-related spring wheat yield in southern regions of ER. Also, an attempt to study the current and expected changes in the frequency of atmospheric droughts in the south of ER was made.

2. Data and Methods

The study area is a subboreal plain landscape in the south of ER. It is located in a moderate continental climate area with long winters and unsustainable inter-annual precipitation patterns during the growing season. A large part of this area is covered by dry lands [8]. The northern border of dry lands (the northern border of dry sub-humid lands) with an arid climate passes through typical steppe and dry steppe landscapes [9]. Most of the croplands with prevailing fertile black soils (chernozem) are located in the south of ER (figure 1a).

The variability in precipitation and its extremes in the south of ER in the period of 1961-2018 was explored using the Standardized Precipitation Index (SPI) recommended by the World Meteorological Organization (WMO) for meteorological droughts identification [10]. The SPI index values are obtained by transforming the probability function of the gamma distribution, which approximates the empirical distribution of precipitation, into a normal distribution function with zero mean and standard deviation equal to one [11]. The 1-month SPI in May and June and the 2-month SPI in June were calculated from the average monthly precipitation in May and June. According to the algorithm, negative values of the SPI index mean a lack of precipitation. The values of the SPI ≤ −1, according to statistics occurred in 15.87% of cases [12], indicate meteorological droughts caused by a precipitation deficit. A strong precipitation deficit is observed at values of the SPI ≤ −1.5 and an extreme one at values ≤ −2. Positive SPI values indicate sufficient rainfall. The Standardized Precipitation Evapotranspiration Index (SPEI) also was calculated. According to it, dry and wet conditions are
identified not only by the amount of precipitation, but also by the impact of evapotranspiration on moisture anomalies. The SPEI calculation algorithm was similar to the SPI calculation algorithm.

![Figure 1. Distribution of croplands in 2010 (yellow points) obtained from Space Research Institute of the Russian Academy of Sciences (Source: http://smiswww.iki.rssi.ru/files/maps/croplands_of_russia_2010_ru_s.jpg) and the location of 12 subjects of the south of ER (a); the linkage of the 2-month SPI (dimensionless) in June with the climate-related yield of spring wheat (detrended, scaled) (SWY) (dimensionless) in 1961-1990 (b) and 1995-2018 (c); the difference in the frequency (%) of moderate drought from May to June according to SPI data between 1991-2018 and 1961-1990 periods (d). Significant changes of the drought frequency are indicated by dots in (d). SPI values $\leq -1$ (moderate drought) in (b) and (c) are located in the red rectangle, the SPEI $\geq 1$ (moderate excess precipitation) are in the green rectangle.](image)

In this study, the values of the SPI and SPEI indices were calculated using the tools created at the Iberian Institute of Ecology (Instituto Pirenaico de Ecologia) [13]. To calculate the SPI, the data of the global archive of mean monthly precipitation CRU TS 4.3 with a spatial resolution of 0.5°x0.5° of the University of East Anglia were used [14]. To calculate the SPEI, not only monthly precipitation was used but also the data of the total monthly evapotranspiration from the same dataset. The dynamics of the SPI and the SPEI in May and June in the south of ER was studied in the period of 1961-2018. Changes in the frequency of droughts in the period of 1991-2018 were estimated in comparison with the period of 1961-1990. The statistical significance of the differences in the frequency of severe droughts was assessed by the chi-squared statistics.

The connections between the SPI index and the yield of spring wheat in 12 southern sub-federal regions of ER (figure 1a), which can be called key areas of the European grain belt of Russia, were
analyzed. Sowing of spring wheat in the most southern regions of ER starts in April or May after the melting of the snow cover, the drying and warming up of the croplands soil layer, and the air temperature transition through 10°C. Since the beginning of 1985, a new method for calculating the yield in regions of the Russian Federation was introduced. It is based on the estimation of the amount of grain received per hectare of the harvested area of the field. Prior to this, the yield was calculated per hectare of the sown area of the field. Different methods of yield accounting have led to the heterogeneity of the time series. The positive trend of spring wheat yield in the south of ER in 1961-2018 is a consequence of both agro-technical and climatic changes. It is rather difficult to separate these components. This study attempts to assess the climate-related yield. Statistics on the spring wheat yield on average for southern regions of ER for the periods of 1961-1990 and 1995-2018 were obtained from the dataset of the Federal State Statistics Service (Rosstat) [15]. Period of 1991-1994 was excluded from the study, since yield statistics for these years were not published in publically available sources. To eliminate the heterogeneity of yield values, the linear trend was removed from its time series for each province of the study area. This procedure was applied separately to the data for every period. It was assumed that the removal of the trend excludes the influence of agro-technical reasons (such as the use of new progressive technologies, new varieties with a higher productivity potential, mineral fertilizers). We investigated changes in yields that were not related to the current warming trend. The normalization of the values after the trend removal made it possible to carry out a regional comparison of yield changes.

The data of numerical experiments with the global coupled atmosphere-ocean general circulation models (GCM) from CMIP6 (Coupled Model Intercomparison Project Phase 6) model ensemble used for these calculations were taken from the global archive of the Center for Environmental Data Analysis [16]. Ensemble estimates of the frequency of droughts by the middle of the 21st century compared to the base period of 1961-1990 were obtained by averaging the 2-month SPI data, calculated from the GCMs data on total precipitation in May and June of CNRM-ESM2-1, GFDL-ESM4, MPI-ESM1-2-HR, MRI-ESM2-0 and NorESM2-MM models. Three scenarios SSP126, SSP245 and SSP585 reflecting the shared socioeconomic pathways in the 21st century and the level of greenhouse gas emissions were used. Relative error in reproducing the frequency of droughts from May to June by an ensemble of climate models in the period of 1961-1990 was calculated as the ratio of the difference in the average frequency of droughts based on the data of the ensemble of models and climatic data to the average frequency of droughts based on the climatic data.

3. Results and Discussion

3.1. The linkage between the precipitation in May-June and climate-related yields of spring wheat in the period of 1961-2018 in the south of ER

The study showed that climate-related yields of spring wheat in southern ER in 1961-2018 are more related to the 2-month SPI in June than to the 1-month SPI in May and June (see table 1). This linkage reflects the dependence of yield on total precipitation, since the SPI index correlates with total precipitation with a correlation coefficient of at least 0.96 at each grid point.

It is worth mentioning that empirical assessments are often leading in taking a decision on starting a sowing campaign in many southern regions of ER. This, like many other factors, leads to the fact that key periods of plant development occur on different calendar dates each year. Therefore, it is difficult to identify stable links between the yield and the moisture supply, as well as the heat availability of crops during the growing season. Thus, the changes of the 2-month SPI in June in all 12 southern subjects of ER explain only 24% of the variability in the yield of spring wheat in 1961-2018. Taking evapotranspiration into account in addition to precipitation has not significantly affected the result; it has increased the proportion of variability in the 2-month SPEI in June to 26% in the explained variability in yield in the same area over the same period.
Despite the relatively small contribution of rainfall variability from May to June in spring wheat yields, the impact of events with extreme precipitation can be significant. Severe atmospheric droughts from May to June are able to slow down the increasing trend of grain yields due to the agricultural technologies development, as happened in several areas of the Volga region in 2005-2019 compared to 1990-2004 [6]. Also, it is known that the precipitation deficit during the sowing-ripening period, accompanied by sufficient soil moisture reserves, is extremely detrimental to winter crops, whereas the spring wheat yield can reduce significantly.

It is quite logical that insufficient rainfall from May to June leads to low yields of spring wheat more often in comparison to insufficient rainfall only in May or in June. As shown in Figures 1b and 1c, 22% of all years with abnormally low yield of spring wheat in 12 southern sub-federal regions of ER in the period of 1961-2018 fell on years of moderate droughts (SPI ≤ -1) caused by a deficit of precipitation from May to June. 83% of such events of moderate droughts in all the subjects (70 out of 84 events with droughts) were accompanied by negative anomalies in the climate-related yield of spring wheat, that is, the yield was lower than average long-term values. Two thirds of these events were associated with extremely low yields. Therefore, a moderate drought in late spring and early summer in the south of ER guarantees a shortage of grain. Events of a moderate excess of precipitation from May to June in all regions were associated with higher yields in 76% of cases. It is important to note that other weather events, both happening during the growing season and outside it, accompany droughts. Thereby they can strengthen or weaken the impact of droughts in late spring and early summer on the yield of spring wheat in the south of ER.

The results are supported by other researchers’ analyses based on the assessment of the precipitation amount and the Hydro-thermal Coefficient of Selyaninov (HTC). For instance, the closest direct (positive) links between crop yields in the regions of Middle Volga and Transvolga were observed with the moisture supply of crops in May and June (the amount of precipitation and HTC during these months, as well as the average HTC values in May-June) [6]. This confirms the leading role of the May-June period in the grain harvest formation. In [6], it is noted that shoots of spring crops appear during this period, and a precipitation deficit causes rare seedlings; plants are rooting, tillering, and spikelet are formed in a spike of wheat. This study also points out that the deterioration in the moisture supply of plants during this period causes a sharp decrease in the productivity of grain crops, and with its improvement the yield increases [6]. However, the complexity of comparing the obtained results with the results of other researchers is due to the use of different drought indicators, determining the gradations of drought intensity in different ways.

Table 1. Correlation coefficients between time series of climate-related yields of spring wheat and 1 month SPI in May (I) in June (II), 2 months SPI (III) and SPEI (IV) in June in the regions of the south of ER in the period 1961-2018.

| Sub-federal region | Central Black Earth (Chernozemie) | Middle Volga | Lower Volga | Transvolga | North-Western Caspian Sea | Cis-Azov region | Stavropol | Kuban |
|--------------------|----------------------------------|--------------|------------|------------|--------------------------|----------------|-----------|-------|
| I                  | 0.2                              | 0.4          | 0.31       | 0.4        | 0.52                     | 0.26           | 0.3       | 0.4   |
| II                 | 0.03                             | 0.2          | 0.4        | 0.56       | 0.62                     | 0.43           | 0.53      | 0.38  |
| III                | 0.11                             | 0.3          | 0.44       | 0.61       | 0.71                     | 0.65           | 0.55      | 0.49  |
| IV                 | 0.27                             | 0.5          | 0.6        | 0.64       | 0.7                      | 0.7            | 0.26      | 0.65  |

Significant correlation
3.2. Changes in the frequency of droughts in the period 1961-1990 compared to 1991-2018 in the south of ER

The dynamics of the moderate droughts frequency from May to June in the regions of ER was studied in connection with the importance of their influence on the yield of spring wheat. As shown in Table 2, the frequency of such droughts in 1961-2018 ranged from 9 to 19 events / 100 years. Samarskaya, Kurskaya and Rostovskaya oblasts suffered from droughts most frequently (16-19 events / 100 years).

Table 2. The frequency of moderate droughts from May to June (number of events / per 100 years) in the periods 1961-2018 (I) and 1961-1990 (II) in the provinces of the south of ER, its changes (%) (III) in 1991-2018 compared to 1961-1990 according to CRU data.

| Sub-federal region | Kurskaya oblast | Belgorodskaya oblast | Voronezhskaya oblast | Samarskaya oblast | Saratovskaya oblast | Volgogradskaya oblast | Orenburgskaya oblast | Republic of Kalmykia | Astrakhanaya oblast | Rostovskaya oblast | Stavropol Krai | Krasnodar Krai |
|--------------------|----------------|---------------------|---------------------|------------------|---------------------|---------------------|---------------------|---------------------|-------------------|------------------|---------------|---------------|
| I                  | 19             | 14                  | 10                  | 16               | 14                  | 12                   | 10                  | 10                  | 9                 | 17               | 9             | 14            |
| II                 | 17             | 17                  | 17                  | 10               | 13                  | 17                   | 7                   | 13                  | 10                | 23               | 7             | 17            |
| III                | 29             | -36                 | -79                 | 114              | 7                   | -57                  | 114                 | -46                 | -29               | -54              | 61            | -36           |

Significant changes

The regional impact of modern climate changes has been reflected in a decrease of the drought frequency in the 7 of 12 sub-federal regions in 1991-2018 compared to 1961-1990 (see table 2, figure 1d). Thus, droughts were observed during this period less often by 29-79% in the south and southeast of the Central Black Earth region, in the Kuban region, in the Cis-Azov region and practically throughout the Lower Volga region. On the contrary, the frequency of droughts has increased in the Transvolga region, in the south of the Middle Volga region, in Stavropolie and in the west of the Central Black Earth region (Fig. 1d). The statistically significant increase in the frequency of droughts by 114% was observed in Orenburgskaya and Samarskaya oblasts (table 2).

The most extensive droughts from May to June, covering from 6 to 10 regions of the south of ER, were observed in 1972, 1975, 1979, 1981 (figure 2a), 1998 (figure 2b) and 2018. Despite the fact that the study explored the years with moderate drought on average for each of the 12 subjects, many parts of these areas experienced severe and even extreme drought at the same time (see figures 2a-2b). An attempt to extrapolate the revealed linkage between droughts from May to June and low climate-related yield of spring wheat to the future periods was made.

Figure 2. The spatial distribution of 2-month SPI values in June in the south of ER in 1981 (a), 1998 (b). The orange shading reflects the lack of moisture. The grey contours are drawn with a step of 0.5. The boundary of moderate drought is shown with a bold black line; the boundaries of subjects are marked with a red line.
3.3. Changes in the frequency of droughts by the middle of the 21st century in the south of ER based on GCM's data

As shown in table 3, the frequency of moderate droughts in 1961-1990 is overestimated by the ensemble of climatic models in most southern sub-federal regions of ER (except for the Astrakhanskaya oblast and the Republic of Kalmykia). E.g., an overestimation of the frequency of droughts by more than twice was observed in Orenburgskaya, Saratovskaya, Voronezhskaya oblasts and Krasnodar Krai. The biggest distortion of the frequency of droughts by 4 times is revealed in Saratovskaya oblast.

Table 3. Changes in the frequency of moderate droughts in May-June (%) in 2041-2060 compared to 1961-1990 according to the ensemble of climate models according to the scenarios SSP 126 (I), SSP 245 (II) and SSP 585 (III) and ensemble error (%) (IV).

| Sub-federal region | Khakassia | Belgorodskaya | Voronezhskaya | Samarskaya | Saratovskaya | Volgogradskaya | Orenburgskaya | Republic of Kalmykia | Astrakhanskaya | Rostovskaya | Stavropol Krai | Krasnodar Krai |
|--------------------|-----------|--------------|---------------|------------|--------------|----------------|---------------|-------------------|----------------|-------------|---------------|---------------|
| I                  | -100      | -62.5        | -78.6         | -57.1      | -62.5        | -75            | -78.6         | 12.5              | 50             | -62.5       | -62.5         | -10           |
| II                 | -14.3     | -25          | 28.6          | 0          | 25           | 20             | -50           | 0                 | 50             | 6.25        | 62.5          | 20            |
| III                | -62.5     | -62.5        | -78.6         | -78.6      | -0.17        | -78.6          | -75           | -50               | -25           | -70         | -43.7         | 20            |
| IV                 | 100       | 60           | 133           | 40         | 300          | 20             | 133           | 0                 | -40           | 14          | 60            | 150           |

Significant changes

There is an uncertainty about both the preservation of the timing of spring wheat sowing in April-May and the estimations of the ensemble model projections of the future climate by the middle of 21st century in the south of ER.

Scenario forecasts generally indicate an improvement in the moisture supply for crops in the period of late spring and early summer in the south of ER in 2041-2060, due to a decrease in the frequency of moderate droughts predicted in most subjects of the study area (table 3). At the same time, the ensemble of climatic models suggests that unfavorable moisture changes at the beginning of active plants vegetation in the south of ER in the middle of the 21st century in comparison to the 30-year period in the second half of the 20th century can occur in following sub-federal regions: Saratovskaya oblast (SSP 245 scenario), Astrakhanskaya oblast (scenarios SSP 126 and 245), the Republic of Kalmykia (scenarios SSP 126), Voronezhskaya oblast (scenario SSP 245) and Krasnodar Krai (scenarios SSP 245 and 585) (see table 3). The biggest concern is caused by the possible negative consequences of these changes for Voronezhskaya oblast and Krasnodar Krai, where the largest harvests are collected, and for the Saratovskaya oblast with significant sown areas of spring wheat.

4. Conclusions

The linkage between precipitation anomalies in May-June and the climate-related yield of spring wheat in 12 sub-federal regions of the south of ER has been investigated. It has been shown that the contribution of the variability of the 2-month SPI in June, closely related to the total precipitation in May-June, to the variability of the yield of spring wheat in 1961-2018 was 24%.

A moderate drought from May to June guarantees a grain shortage, since 83% of such drought events in total in all regions of the south of ER were associated with lower than average spring wheat yields. A similar drought in the study area more often occurred in Samarskaya, Kurinskaya and Rostovskaya oblasts. It was found that the observed changes in the amount of precipitation at the beginning of the growing season were more favorable for the spring wheat vegetation in most regions of the south of ER in the period 1991-2018 in comparison to the previous thirty years. These favorable changes were due to a decrease in the frequency of moderate droughts. However, the same moisture conditions had worsened in the Transvolga region, in the north of the Lower Volga region, in
Stavropolie and in the west of the Central Black Earth region, where the frequency of droughts increased in the same period.

According to model projections of the future climate, changes in moisture conditions expected by the middle of the 21st century from May to June in the study area will generally remain favorable. The unfavorable forecast, associated with a possible increase in the frequency of moderate droughts at the beginning of the growing season, concerns Kuban, the North-Western Caspian Sea region, the east of the Transvolga region, the north of the Lower Volga region and the southeast of the Central Black Earth region. Nonetheless, in the view of the unfavorable regional forecasts of an increase in the drought frequency, the results will be useful for breeding programs for creation of new spring wheat cultivars that will be resistant to droughts from May to June in the listed, most sensitive to future climate changes, regions of southern ER.

Acknowledgement
The study of the linkage between droughts and the spring wheat yield was conducted in the framework of the scientific theme no. 0148-2019-0009 (AAAA-A19-119022190173-2). Analysis of the frequency of droughts was carried out with the financial support of the Russian Science Foundation (the project 19-17-00242).

References
[1] Samofalova N E, Dubinina O A, Samofalov A P and Ilichkina N P 2019 The role of weather factors in the formation of winter durum wheat productivity Zernovoe hozjajstvo Rossii 5(65) pp 18-23 doi: 10.31367/2079-8725-2019-65-5-18-23
[2] Vilfand R M, Strashnaya A I and Bereza O V 2016 About the dynamics of the agroclimatic indicators of conditions of sowing, wintering and formation of the yield of the main grain crops Proceedings of Hydrometcentre of Russia 360 pp 45–78
[3] Cherenkova E A, Bardin M Yu and Zolotokrylin A N 2015 The statistics of precipitation and droughts during opposite phases of the quasi-biennial oscillation of atmospheric processes and its relation to the yield in the European part of Russia Russian Meteorology and Hydrology 40(3) pp 160-169 doi: 10.3103/S1068373915030024
[4] Cherenkova E A, Bardin M Yu, Platova T V and Semenov V A 2020 Influence of long-term variability of North Atlantic sea surface temperature and changes in atmospheric circulation on the frequency of severe atmospheric droughts in the South of the East European Plain in summer Russian Meteorology and Hydrology 45(12) pp 819–828 doi: 10.3103/S1068373920120018
[5] Semenov V A and Cherenkova E A 2018 Evaluation of the Atlantic oscillation impact on large-scale atmospheric circulation in the Atlantic region in summer Doklady Earth Sciences 478(2) pp 263-267 doi: 10.1134/S1028334X18020290
[6] Strashnaya A I, Bereza O V and Pavlova A V 2020 Agrometeorological conditions and forecasting of grain crops yield based on the integration of ground and satellite data in the subjects of the Volga Federal District Hydrometeorological Research and Forecasting 3(377) pp 71-91 doi:10.37162/2618-9631-2020-3-71-91
[7] Egorov I V 2011 Big Encyclopedia of Farmer Big Encyclopedia of Farmer (Russia: Eksmo) 512 p
[8] Zolotokrylin A N, Cherenkova E A and Titkova T B 2018 Bioclimatic Subhumid Zone of Russia Plains: Droughts, Desertification, and Land Degradation Arid Ecosystems 8(1) pp 7-12 doi:10.1134/S2079096118010122
[9] Zolotokrylin A N and Cherenkova E A 2011 Area of Russia’s Arid Plain Lands Arid Ecosystems 1 pp 8-13 doi: 10.1134/S2079096111010100
[10] WMO 2009 Experts agree on a universal drought index to cope with climate risk Press Release 872 https://www.preventionweb.net/news/view/12077
[11] Guttman N B 1999 Accepting the standardized precipitation index: a calculation algorithm
[12] Edwards D C and McKee T B 1997 Characteristics of 20th century drought in the United States at multiple time scales Climatology Report 97 - 2 Colorado State University Fort Collins Colorado 155 p

[13] Vicente-Serrano S M, Beguería S and López-Moreno J I 2010 Multi-scala drought index sensitive to global warming: The Standardized Precipitation Evapotranspiration Index – SPEI J. Climate 23 pp 1696–1718 doi: 10.1175/2009JCLI2909.1

[14] Harris I, Jones P D, Osborn T J and Lister D H 2014 Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset Int. J. Climatol. 34(3) pp 623–642 doi: 10.1002/joc.3711

[15] ROSSTAT: Russian Federal State Statistic Service. Regions of Russia. Socio-economic Indicators http://eng.gks.ru/

[16] CEDA: Center for Environmental Data Analysis. CMIP6-GCM’s output http://data.ceda.ac.uk/badc/cmip6/