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A comparison of bioclimatic potential in two global regions during the late twentieth century and early twenty-first century

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Abstract

Changes in the general circulation of the atmosphere have been taking place during the latter part of the twentieth century and the early part of the twenty-first century. In the Belgorod region of Southwest Russia, this has been manifested in the more frequent occurrence of stationary anticyclones, including those referred to as blocking anticyclones, especially during the summer season. Also, there has been a general increase in regional temperatures during the growing season over the period mentioned above, and combined with the more frequent occurrence of anticyclones has led to less humid conditions. In the Missouri region of the Central USA, variability in the circulation on differing time scales within the Eastern Pacific plays a strong role in the conditions that impact the growing season. As a result of changes in climate and climate variability, the benefit to agriculture during this period produces mixed results for both regions. This work will evaluate the growing season conditions using indexes that combine growing season temperature and precipitation such as the hydrothermal coefficient (HTC) and the bioclimatic potential (BCP). Also, the interannual variability of these indexes in both regions was examined. In the Belgorod region, the increase in temperature combined with little change in precipitation produced mixed results in interpreting these indexes. This was accompanied by more variable conditions as revealed by these indexes in the early twenty-first century. In the Missouri region, there was little trend in either index over the time period and the tendency was toward less climatic variability in the HTC and BCP.

Keywords Climate change · Climate variability · Agriculture · Atmospheric blocking · Bioclimatic potential · Hydrothermal coefficient

Introduction

Interannual and interdecadal variability in surface weather conditions (e.g., temperature, precipitation, and humidity) are topics of general interest to the climatic and agricultural community (e.g., Gershunov and Barnett 1998; Enfield and Mestas-Nuñez 1999; Hu and Buyanovsky 2003; Lupo et al. 2012a; Mokhov et al. 2014). It is well known that there is a link between the climate of the warm season and agricultural productivity (e.g., Losev and Zhurina 2001; Hu and Buyanovsky 2003; Henson et al. 2017). Given the possible changes in climate that could occur during the twenty-first century (IPCC 2013), it is necessary to understand changes and variability in regional climate (e.g., Changnon and Winstanley 1999; NCA 2014).

Henson et al. (2017) examined the interannual variability of temperature and precipitation and the relationship to corn and soybean yields in the state of Missouri. They showed that yields for both crops have increased over the course of the twentieth century. This trend is likely associated with better agricultural practices and technology and is likely to continue into the future (e.g., Edgerton 2009 and references therein). However, an examination of the Henson et al. (2017) work suggests that while technology has somewhat ameliorated issues of productivity, it could be argued that, for their region of study, yield vulnerability to climate variability has increased with time at least for corn. In particular, Henson et al. (2017) found that higher yields in both corn and soybean in certain parts of the state were associated with summers that were classified as La Niña or transitioning toward El Niño. This

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study examined temperature and precipitation separately and their co-variance when comparing to the crop yields. While crop yields are expected to continue to increase due to technology, the impact of climate change on future yields may be more difficult to gauge given the large range of possible climate change scenarios (e.g., IPCC 2013). Anticipating crop yields under various climate change scenarios has also been a priority area of study (e.g., Reddy and Panchepsky 2000). Additionally, the current changes in climate may be actively influencing agricultural production, which is the most weather-dependent sector of the economy in either region (Ashabokov et al. 2012; Henson et al. 2017).

The current change in climate has led to increased bioclimatic potential of the Belgorod region, which has been generally positive for agriculture. However, the frequency of hazardous agroclimatic phenomena that cause damage to agricultural production also is changing. Since the beginning of the twenty-first century, the probability of agriculturally hazardous hydrometeorological events has increased for all seasons of the year. In winter, the probability of cold temperature and related damage to the plants has increased, during the summer excessive dry periods, or intense rainfall accompanied by strong winds and hail have increased (e.g., Lebedeva and Krymskaya 2008; Petin et al. 2014; Lebedeva et al. 2015, 2016). As in the Missouri region, the influence of climate on productivity in the Belgorod Oblast by the end of the twentieth century has gradually decreased. This is also due to the development of the agroindustrial complex in the region.

Thus, empirical indexes or statistical models that incorporate both variables, such as the hydrothermal coefficient (HTC) (Selyaninov 1928; Tarankov 1991; Matveev et al. 2016) might be useful in evaluating potential for agricultural productivity. Matveev et al. (2016) examined the interdecadal variability in tree ring diameter in connection with the HTC for the Voronezh region in southwestern Russia, and this work showed that HTC has trended toward drier conditions at the start of the twenty-first century. Other indexes such as the moisture index (Sapozhnikova 1970) and bioclimatic potential (BCP) (Shashko 1985) can also be used to evaluate growth potential as related to observed climate. More recently, statistical models devoted to particular crops such as corn have been developed and used to study the impact of climate change (e.g., Lobell and Burke 2010). Alternatively, model data output from climate models (e.g., Reddy and Panchepsky 2000; Coupled Model Intercomparison Project or CMIP5-Wuebbles et al. 2014) can be used as inputs in order to compare productivity associated with future climates with those of today for crop production. Wuebbles et al. (2014) used a similar approach to examine the future occurrence of extreme weather such as the occurrence of extreme precipitation events.

The goal of this work is to demonstrate the efficacy of indexes that combine temperature and precipitation by comparing the output from the HTC, BCP, and moisture indexes during the late twentieth century and the early twenty-first century for two different areas of the globe. These indexes may be related to productivity of agrocenoses in the Belgorod region of southwest Russia and the state of Missouri in the Central USA. This study will include an examination of the changes in the character of atmospheric circulation published in recent decades for both regions (e.g., Petin et al. 2014; Lebedeva et al. 2016; Newberry et al. 2016) in order to explain climate-related trends and variability in these indexes. Section 2 describes the data and definitions used as well as the locations of the study regions. Section 3 will review the climatological character of both regions and discuss the comparative results of the index study.

Data and methods

Data

In order to meet the objective of this research, the temperature and precipitation available to crops during the vegetation period or growing season for the Belgorod region (Russia) and Missouri, USA will be examined. Here, we will refer to this period generically as the warm season, except when referring to other studies. The temperature and precipitation data sets for the Belgorod region were provided by the Belgorod Center for Hydrometeorology and Environmental Monitoring. Six stations have been maintained within the region during the period from 1899–present, and we use the data from 1988 to 2014 here. For Missouri, USA, the atmospheric data used here were provided by the Missouri Climate Center (MCC) for four stations, which is housed at the University of Missouri.

Since the early 1990s, the Missouri weather stations are Automated Surface Observing System (ASOS) (http://nws.noaa.gov/asos) stations, and they are located across Missouri (Fig. 1 and Table 1). There were no discernable differences in the temperature and precipitation data provided by the previous instrumentation (e.g., Birk et al. 2010). The daily and monthly mean temperature (°C) and precipitation (mm) is provided and used for each station; however, the final results are the regional means. The six meteorological stations in the Belgorod region (Fig. 1 and Table 1) are provided by the Russian Federal Hydrometeorology Service and environmental monitoring in the Belgorod Oblast has been done since the late nineteenth century. The stations are located uniformly and they are characteristic and representative for the surrounding area. ASOS was introduced in the Belgorod Oblast during 2008–2009. Parallel observations with the previous instrumentation and the automated system show good convergence for the observations. The same observations as for the Missouri region are used here.

Fig. 1 Location of the two study regions: **a** Russia (superior) and Belgorod Oblast (inferior) and **b** the USA (superior) and State of Missouri (inferior)

Additional material used in this research was the catalog of sequential variations for elementary Northern Hemisphere circulation regimes according to the classification system proposed by Dzerdzeyevskii (e.g., Sapozhnikova 1970; Zolotokrylin and Titkova 1998). Also, the blocking archive at the University of Missouri (http://weather.missouri.edu/gcc) was used to calculate the number of blocking events occurring in this region.

Temperature and precipitation indexes

One important index used in the study of warm season climate is the hydrothermal coefficient (HTC) and has been used recently by Gustokashina and Maksutova (2006), Strashnaya et al. (2011), or Matveev et al. (2016). The expression is given by:

$$HTC = \Sigma P / \left(0.1 \Sigma T^{*}\right), \tag{1}$$

where P is the precipitation (mm) and T* is the mean daily temperature for the period with active plant vegetation (months with daily average temperature above 10 °C—in the Belgorod region, this describes May–September—in Missouri, this could be as early as March and as late as November but taken to be April–October). This index shows the connection between temperature and moisture which are linked to plant growth (e.g., Matveev et al. 2016).

The meteorological data were used also to calculate characteristics for climatic indexes connected to agricultural productivity such as the BCP (see Shashko 1985) index. For this reason, we use the BCP baselined for our region (Gordeev et al. 2006). BCP is a function of complex of meteorological factors that determine the potential growth and development for plants in order to evaluate the agricultural productivity of climate. This index takes into account the difference between the surface temperature and dew point, or the humidity deficit. In addition to the BCP, we also calculate the moisture index (Cp).

As indicators characterizing the agricultural conditions of a region, the BCP as proposed by Shashko (1985) was chosen also for use here. According to Shashko (1985), the maximum biological productivity is determined by the

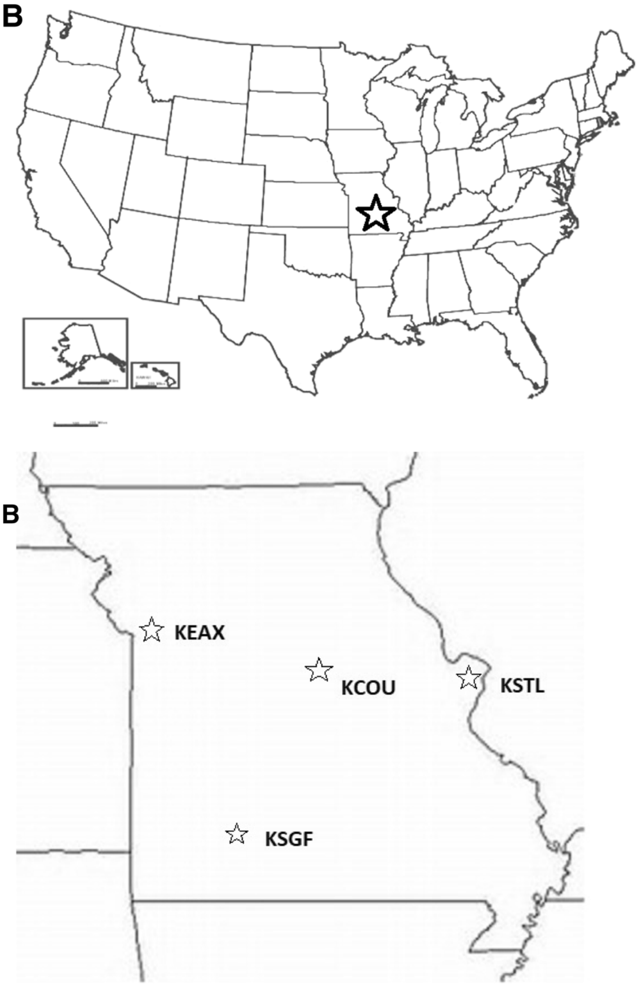

Fig. 1 continued.

total influence of heat, moisture, and soil fertility. For the conditions of a particular region with similar soil conditions, the potential yields index can be reduced to a function of heat and moisture expressed as a ratio. In particular, the BCP is the ratio of the sum of the average daily temperatures over the period of active vegetation (°C) to the analogous sum for the reference territory (°C), multiplied by the coefficient reflecting the influence of moisture on agricultural yield. The formula is:

$$\mathrm{BCP} = \mathrm{C}_{\mathrm{p(CH)}} \frac{\sum T^{*}}{\sum T_{\text{àê}(\text{áàç})}}$$

where BCP is the relative bioclimatic potential, $\mathrm{C}_{\mathrm{p(CH)}}$ is the annual growth coefficient of atmospheric humidification rate, $\sum T^{*}$ is the same as in Eq. (1), $\sum \mathrm{T}_{\text{àê}(\text{áàç})}$ is the base sum of the average daily temperatures for the period of active vegetation (19.0 °C).

The growth coefficient in Eq. (2) is represented by the ratio of the yield under the observed conditions of moisture supply to the maximum yields under the conditions of the optimal available moisture supply. Here we will use the term moisture index for this quantity. This was approximated empirically by the expression in Shashko (1985) as:

$$\mathrm{Cp}_{(\mathrm{CH})} = 1.5lg(20\mathrm{CH})–0.21 + 0.63\mathrm{CH}–\mathrm{CH}^{2} \qquad (3)$$

where CH is the coefficient of annual atmospheric humidification, equal to the ratio of rainfall to the sum of the average daily values of atmospheric humidity deficit.

The work of Sapozhnikova (1970) proposed the following formula for the calculation of the basic indicator of the moisture index:

$$\mathrm{Cp}_{(\mathrm{CH})} = \frac{0.5P_{x} + P_{m}}{0.18\sum T_{\triangleright 10^{0}}}$$

where $\mathrm{Cp}_{(\mathrm{CH})}$ is the coefficient of humidification (moisture index); and 0.5 is coefficient characterizing the influence of precipitation for the cold period of the year on the yield formation;

P_{x} is the total precipitation (mm) during the cold period (October–March);

Table 1 List of stations and location for both study regions. Location is in hundredths of degrees latitude

Belgorod Oblast	Missouri, USA
Valyiki (50.22° N 38.10° E)—111 m	Kansas City NWS WFO (KEAX) (39.32° N 94.72° W)—313 m
Gotnya (50.80° N 35.77° E)—225 m	St. Louis NWS WFO (KSTL) (38.75° N 90.38° W)—162 m
Noviy Oskol (50.75° N 37.87° E)—139 m	Columbia Airport (KCOU) (38.82° N 92.22° W)—271 m
Belgorod (50.63° N 36.58° E)—223 m	Springfield NWS WFO (KSGF) (37.22° N 93.38° W)—387 m
Stariy Oskol (51.30° N 37.88° E)—216 m	
Belgorodtskoe-Fenino (51.17° N 37.35° W)—223 m	

P_m is the total precipitation (mm) for the warm period (April–September); and $0.18\sum T_{\triangleright 10^0}$ is the evaporation for the year.

The Sapozhnikova (1970) moisture index is preferable for the evaluation of regional water availability as it considers precipitation and the duration of the warm and cold period of the year. This is more consistent with the actual moisture regime, since the ability of the atmosphere to hold moisture increases exponentially with an increase in temperature. This is the expression used here (Eq. 4).

The results of the BCP and moisture index calculations over the Belgorod (Missouri) region in general were carried out for two periods: (1) 1988–2000 (1980–1998) and (2) 2001–2014 (1999–2016) in order to do a comparative analysis of the years immediately preceding the end of the twentieth century and those following the start of the twenty-first century. The division of years for the Missouri region was based on Birk et al. (2010) and others who showed that the phase of the Pacific Decadal Oscillation (PDO) changed just before the year 2000 (see Table 2). Also, the Wiedenmann et al. (2002) blocking climatology examined Northern Hemisphere blocking up to 1998. We can evaluate the impact of the changes in the character of atmospheric circulation including the effect of heat and moisture supply on plants.

ENSO and PDO

El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) are the teleconnections considered for this research (e.g., Birk et al. 2010; Nunes et al. 2017). These teleconnections have the strongest correlation with long-term regional weather in the Missouri region (e.g., Birk et al. 2010), and ENSO has a strong influence on the Belgorod region weather (e.g., Lupo et al. 2014). The North Atlantic Oscillation (NAO) also influences the Belgorod region weather and climate (Nunes et al. 2017), but a longer data set would be needed to examine this correlation as the phase of the NAO changed near 2008.

The Japan Meteorological Agency (JMA) ENSO index is available through the Center for Ocean and Atmospheric Prediction Studies (COAPS) from 1868 to present on line (http://www.coaps.fsu.edu/jma). The JMA SST ENSO Index has been used extensively (see references in Birk et al. 2010; or Newberry et al. 2016) (Table 2). The JMA classifies ENSO phases using SST within the bounded region of 4° S to 4° N, 150° W to 90° W. The JMA defines the inception of an ENSO year as 1 October, and its conclusion on 30 September of the next year.

The PDO positive and negative modes are cataloged also by the Center for Ocean-Atmospheric Prediction Studies (COAPS). The characteristics of these modes are less pronounced than those for ENSO due to the 50- to 70-year cycle of PDO (e.g., Henson et al. 2017). The PDO phases (Table 3) can be described as follows: the positive (+) PDO phase is characterized by cold SSTs in the north central and western Pacific Ocean, warm SSTs off the western coast of North America, and a deep Aleutian low. The negative (−) phase of the PDO is characterized by warm SSTs in the north central and western Pacific Ocean, cool SSTs off the western coast of North America, and no pronounced Aleutian low.

Table 2 Center for Ocean-Atmospheric Prediction Studies (http://coaps.fsu.edu) Japan Meteorological Agency El Niño Southern Oscillation Index, 1979 to present. Modes are El Niño (EL), La Niña (LA), and Neutral (NEU); see also Birk et al. (2010). El Niño year 1982 begins 1 October 1982 and ends on 30 September 1983

El Niño	Neutral	La Niña
1982	1979–1981	1988
1986–1987	1983–1985	1998–1999
1991	1989–1990	2007
1997	1992–1996	2010
2002	2000–2001	
2006	2003–2005	
2009	2008	
2014–2015	2011–2013	

Results

Regional climate of Belgorod and Missouri

The two regions studied here were chosen since they each have different climate characteristics, but both are important agriculture regions. The Belgorod region can be characterized as Dfb using the Koeppen Scheme (e.g., Khromov and Petrosyants 2006; Ahrens 2012) with shorter summers and colder winters. The summer season (June–July–August) mean temperatures for the 30-year period 1981–2010 are 19–20°C and the total mean precipitation is about 170–175 mm, mainly in the form of convective events associated with mid-latitude cyclones (e.g., Lebedeva et al. 2016). The Missouri region is within the Cfa Koeppen climate region which characterizes much of the southeast USA. These regions are associated with warm humid summers and shorter winter seasons. The summer season mean temperature for the same period identified above is 23.5–24.5°C and the total mean precipitation is approximately 320–330 mm, primarily as the result of convection associated with weak weather systems, or occasionally

Table 3 Center for Ocean-Atmospheric Prediction Studies Pacific Decadal Oscillation Index, 1977 to present (see Birk et al. 2010). For the PDO, modes are positive and negative

Year range	Mode
1977–1998	+ PDO
1999–2014	− PDO

the remnants of tropical systems especially later in the period (e.g., Dawson et al. 2010). The general characterization of both regions according to the Koeppen scheme has not changed appreciably in the last 30 years (see Chen and Chen 2013), although the climate in each region has changed as will be discussed below.

However, both regions experience strong interannual variability that can be associated with El Nino and Southern Oscillation (ENSO) or more particularly the transition from one phase of ENSO to another. In the Missouri region, the transition toward El Nino results in milder summers with ample precipitation, while the transition toward La Nina conditions is associated with hotter and drier conditions (Birk et al. 2010; Newberry et al. 2016; Henson et al. 2017). In the Belgorod region, the summers associated with a transition toward El Nino or more atmospheric blocking days (Lupo et al. 2014; Lebedeva et al. 2016).

HTC results

The HTC, which includes daily mean temperature and daily precipitation during the warm season is one of the main indicators of agricultural growth (e.g., Matveev et al. 2016; Henson et al. 2017). As an important agroclimatic indicator that defines resources and heat demand of crops, the sum of daily mean temperatures greater than 10 °C is viable because it describes the period of active vegetation for a majority of plants. Then, changes or spatial variations in the HTC for the warm season are a function of changes or spatial variations in the daily mean temperatures for the period with temperatures above 10 °C. Since the middle of the twentieth century, temperature has varied from 25.5 °C (28.0 °C) in the northern (southern) part of the Belgorod region (Agroclimatic Resources of the Belgorod region, Leningrad 1972). Additionally, over the past 15 years, there has been an increase in the surface temperatures during the warm season of about 1.3 °C (Lebedeva et al. 2015; Federal Hydrological Monitoring), which is significant at the 95% confidence level using Analysis of Variance (ANOVA) (e.g., Neter et al. 1988). The increase in Belgorod regional temperatures for a longer-term period (1971–2015) was accompanied by an increase in the length of the warm season or vegetated period of 5 to 7 days and an increase in warm season mean temperature (0.4 °C—significant at the 90% confidence level). The start of the active vegetation season has shifted to earlier dates, now the beginning of April consistent with earlier studies (e.g., Lebedeva and Krymskaya 2008). Summer and warm season temperatures in the Missouri study region have increased slightly since 1980 (e.g., Lupo et al. 2012a; Nunes et al. 2017), but monthly mean dew point temperatures have increased significantly (e.g., Lupo et al. 2012a) across all warm months. However, dew point temperatures are not part of the calculations performed here.

The total precipitation for the Belgorod region since the beginning of the twentieth century, for the annual mean, and during the warm period of the year did not change significantly. Nonetheless, there was a slight increase in annual precipitation observed (e.g., Lebedeva and Krymskaya 2008). Within the Missouri region, annual precipitation increased over the course of the twentieth century (Karl and Knight 1998; Hu et al. 1998), but there has been little trend since 1980. However, rainfall events have trended toward fewer, larger rainfalls and total seasonal rainfall has become more variable, results consistent with NCA (2014).

On the longest time scales within the Belgorod region, the mean of the HTC was 1.11 and the index varies from 1.20 in the northwest part of the region to 0.90 in the southeast of the region. Adverse weather conditions for the cultivation of agricultural crops occur during years when the value of the HTC is 1.00 to 1.40, particularly favorable drought conditions are created in the years with HTC of less than 1.00 (Losev and Zhurina 2001; Kolomeychenko 2007). Since the late 1980s, there was a weak decrease of the HTC characteristic on a background of variability ranging from to 0.67 to 3.30 (Fig. 2a). Within the Missouri region, the trend was negligible as well (Fig 2b).

In an extreme season for Belgorod, such as that of the spring and summer of 2010 (Lupo et al. 2012b), the HTC for the main part of the warm season (May–August) was 0.67, and this value refers to a severe drought. Such conditions have led, in many parts of the Central Chernozem region, to experience agricultural and meteorological drought and significant crop losses. For example, the key factor in wheat yield in the region is heat and humidity conditions during the warm season (60–75%). In low yield years, the influence of weather factors increases by 20% (Chendev 2016). In the Missouri region, the extreme HTC values of 0.99 and 1.10 were associated with the drought summers of 1980 and 2012, respectively, these years being well known for low yields in Missouri (e.g., Hu and Buyanovsky 2003; Henson et al. 2017).

Significant changes in the thermal conditions during the warm season have occurred since 1998, which is linked to changes in the circulation conditions (e.g., Kononova 2009; Lebedeva et al. 2016). The large-scale character of the atmospheric circulation has a significant influence on the regional-scale surface weather conditions and largely influences the occurrence of extreme values in meteorological parameters (e.g., Lupo et al. 2014; Petin et al. 2014).

A statistically significant increase in the occurrence and duration (nearly by a factor of two) of the blocking anticyclones is observed over both Eastern Europe and Western Russia (Lebedeva et al. 2016) (Fig. 3), and the Eastern Pacific (Newberry et al. 2016) (Fig. 4) for the twentieth century and the first part of the twenty-first century. Blocking anticyclones are quasi-stationary and persistent ridging in the mid-latitude flow (e.g., Agayan and Mokhov 1989;

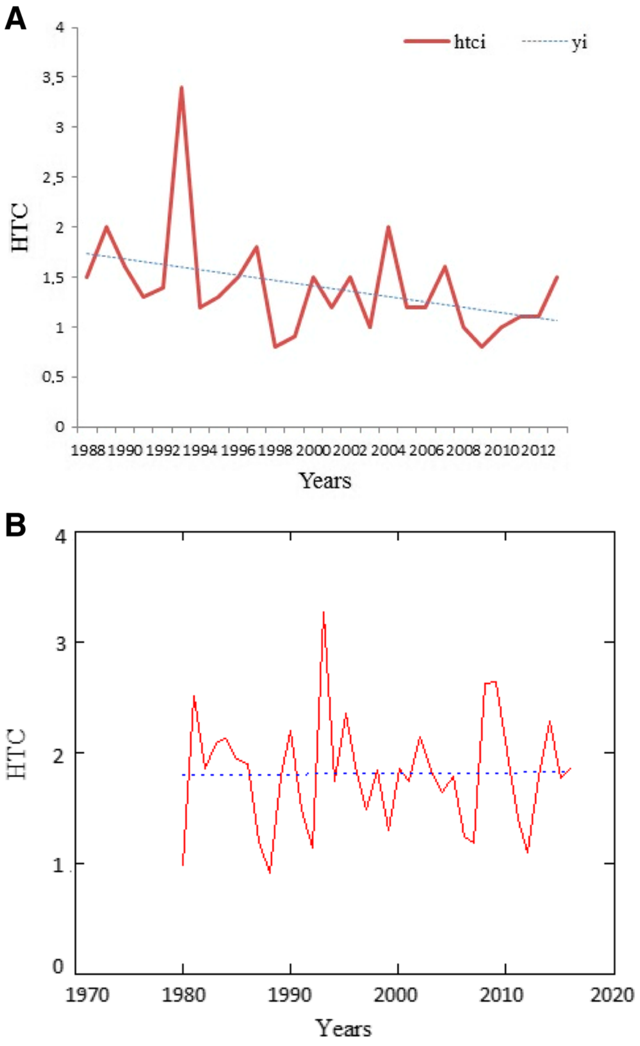

Fig. 2 The values of the HTC for the **a** Belgorod region (1988–2014) and **b** Missouri region (1980–2014). The red solid line is HTC and the blue dotted line is the linear trend line

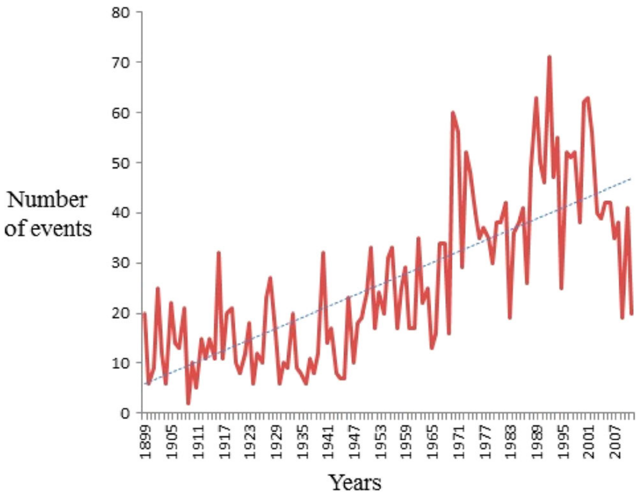

Fig. 3 The total number of stationary anticyclones days per year in the Belgorod region since 1900 (red, solid). The blue dotted line is the linear regression model

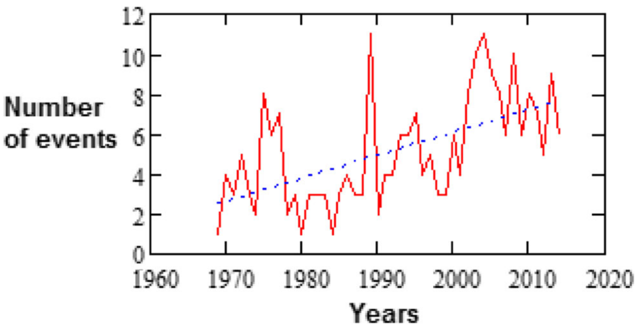

Fig. 4 The total number of East Pacific Region spring and summer blocking events per year since 1969 (see Newberry et al. 2016) (red, solid). The blue dotted line is the linear regression model

Wiedenmann et al. 2002), and blocking was responsible for the disastrous 2010 drought over western Russia (e.g., Mokhov 2011; Lupo et al. 2012b). During the summer season (June–August), blocking has been correlated to an increase in temperatures and the likelihood of droughts and natural fires in Russia (Mokhov et al. 2006; Mokhov 2011). All these factors are detrimental to crops during droughts in this region often occur during the flowering stage of regional crops. For the Missouri region, however, summer season blocking occurring over the Eastern Pacific is associated with more moderate summer season conditions (e.g., Lupo et al. 2008). The occurrence of more blocking in the Eastern Pacific does not readily explain the lack of trends in Missouri region temperature or HTC and further study is needed in order to determine whether the increase in blocking is having an influence on Missouri warm season conditions.

Bioclimatic potential and moisture index

The qualitative characteristics of the moisture index ($Cp_{(CH)}$—Eq. 4) changes for both regions are presented in Table 4. This quantity is discussed first as it is a constituent of Eq. 2. The actual average values of the moisture index in the Belgorod region have deteriorated in the early twenty-first century, from 0.99 in the earlier period to 0.89 during the most recent period. Table 4 also demonstrated that there were more values that were considered low moisture in the first part of the twenty-first century. The corresponding values for Missouri were 1.19 for the early period versus 1.12 for the most recent period (Table 4). The higher values for the Missouri region reflect the longer period of active vegetation and greater warm season precipitation. The moisture index was below 1.00 units at the beginning of the twenty-first century at stations throughout the Belgorod region. This contrasts with conditions at the end of the twentieth century where the moisture index was higher (1.03–1.06) in the western and northeastern portions of the region. In the Missouri region, the latter period was associated with fewer extremely low and high values overall but more years considered moderate, or a less variable climate. This

Table 4 The value of the moisture index ($Cp_{(CH)}$) and expressing these as a percentage of occurrence with respect to the means during 1988–2014 for Belgorod and 1980–2014 for Missouri. The occurrence of relatively low, moderate, and high values from Eq. (4), where low and high values are expressed as one standard deviation less than or greater than the entire period mean

Moisture (Cp)/Belgorod	1988–2000	2001–2014
Low	0	43
Moderate	62	57
Elevated	38	0
Moisture (Cp)/Missouri	1980–1998	1999–2014
Low	22	24
Moderate	67	76
Elevated	11	0

Table 5 As shown in Table 4, except for the Bioclimatic Potential (BCP) and expressing these as a percentage of occurrence with respect to the means during 1988–2014 for Belgorod (1.83) and 1980–2014 for Missouri (1.71). The occurrence of relatively low, moderate, and high values from Eq. (2), where low and high values are expressed as one standard deviation less than or greater than the entire period mean

BCP/Belgorod	1988–2000	2001–2014
Low	0	10
Moderate	96	81
Elevated	4	9
BCP/Missouri	1980–1998	1999–2014
Low	17	12
Moderate	66	82
Elevated	17	6

result occurred in spite of the increased variability in warm season precipitation (e.g., NCA 2014). Examining the data (not shown) shows that some drier summers were associated with cooler temperatures (e.g., 2013, 2014), while other wetter summers (e.g., 2010, 2016) experienced the opposite conditions but all producing similar moisture index values.

The moisture index for subregions of the Belgorod region (not shown) indicates a reduction of the occurrence of optimal humidification regimes during the warm season from 38 to 21% in the southeast, 23 to 21% in the west, 38 to 29% in central, and 31 to 21% in the northeast parts of the study region.

BCP (Eq. 2) in the Belgorod region has also changed from 1.81 for the period 1988–2000 to 1.85 for the years 2001–2014. The corresponding values for Missouri were 1.81 for the 1980–1998 period versus 1.60 for the 1999–2014 period. A qualitative assessment of the regional bioclimatic potential for Belgorod during the two periods showed that during the first period, the BCP was characterized as moderate for 96% of cases, elevated for only 4% of cases, and there were no years with low potential. For the second period, the variability of this parameter increased as the percentage of both elevated and low potential conditions increased, resulting in a decrease of moderate regimes (Table 5). For the Missouri region, the BCP index showed a more dramatic decrease than the moisture index (Table 5). In the Missouri region, the breakdown of years corresponds to the phase of the PDO (e.g., Birk et al. 2010; Nunes et al. 2017). The decrease in the moisture index and BCP corresponds to the results of both these studies, which show that the Missouri region is drier during the negative phase of the PDO (1999–2014) than during the positive phase (1980–1998).

Table 6 breaks down the BCP for both regions using a finer bin width than Table 5. Note the decrease in the more favorable conditions represented by the middle three bins for the Belgorod region. There was little change in the character of excessive moisture, but a large increase in the character of arid conditions. This represents a flatter normal distribution with larger tails in the beginning of the twenty-first century as compared to the late twentieth century. This indicates a significant change in the unfavorable weather conditions significant at greater than the 99% confidence level using the chi-square test (e.g., Neter et al. 1988; or any elementary statistics text) for two distributions treating the earlier period as the expected distribution. This also correlates positively with the increase in anticyclonic weather regimes within the Belgorod region. Whether this change is due to a long-term climate trend or decadal variability in the atmosphere is unclear from this analysis. However, the study of Mokhov et al. (2012) showed this trend toward increased summer season anticyclonic

Table 6 The average regional indicators of BCP the methods of Sapozhnikova (1970) and expressing as a percentage

(a) Belgorod		
The moisture index	1988–2000	2001–2014
Very dry (%)	3.9	1.8
Dry (%)	19.1	35.7
Slightly arid (%)	28.8	35.7
Well-hydrated (%)	32.7	23.2
Heavy wet (%)	11.6	0
Excessive moist (%)	3.9	1.8
Waterlogged (%)	0	1.8
(b) Missouri		
BCP	1980–1998	1999–2014
Very dry ($< -1.5\sigma$) (%)	5.5	0.0
Dry (-1.5σ to -1.0σ) (%)	11.0	12.0
Slightly arid (-1.0σ to -0.5σ)	5.5	18.0
Well-hydrated (-0.5σ to $+0.5\sigma$) (%)	37.5	59.0
Heavy wet (0.5σ to 1.0σ) (%)	27.5	6.0
Excessive moist (1.0σ–1.5σ) (%)	0.0	6.0
Waterlogged ($> 1.5\sigma$) (%)	11.0	0.0

conditions continues into the mid-twenty-first century for some future climate scenarios.

For the Missouri region, Table 6 shows that for the earlier period, conditions were either well-hydrated or heavy wet. These encompassed 65% of the years in the early period. For the later period, the distribution was skewed toward the slightly arid conditions, this category and well-hydrated accounting for 77% of the later period years. The distributions for the Missouri region were also tested using the chi-square test and these were different at the 99% confidence level as well, confirming that this distribution indicated a drier, less variable climate in the latter period (negative PDO). Additionally, given that Eastern Pacific Blocking is associated with more moderate summer season conditions in the Missouri region (Lupo et al. 2008), the less variable conditions of the latter period may reflect the dramatic increase in the East Pacific blocking discussed earlier. The tendency toward moderate but drier conditions in the early twenty-first century has not resulted in decreases of agricultural yields for corn and soybeans in Missouri, as shown by the work of Henson et al. (2017). They showed continuous yield increases for this region since the mid-twentieth century likely due to technological improvements. However, studies such as the NCA (2014) show that increasing variability in precipitation will have a negative impact in the future due to higher temperature.

Interannual variability in HTC and BCP

Examining the interannual variability for the Belgorod region revealed that the HTC and BCP were highest during neutral years (Table 7), while values of these quantities were lowest during La Niña warm seasons. The lower HTC values for La Niña warm seasons were significant at the 95% confidence level. The means were tested using a Z-score test (e.g., Neter et al. 1988). The results are also consistent with those of Lupo et al. (2014) who demonstrated that some of the driest summer periods in this region are associated with a transition toward the El Niño phase and with more spring and summer blocking. In the Missouri region, Table 7 shows the ENSO variability for the HTC and BCP for the period 1980–2014. The results show that during warm seasons following the onset of El Niño in the previous year values are significantly lower for the HTC (at the 99% confidence level) and the BCP (at the 95% confidence level). Note that the ENSO neutral growing season HTC and BCP were highest, but consistent with the La Niña season values. However, since Newberry et al. (2016) and Henson et al. (2017) demonstrated that the direction of the transition during the warm season (e.g., from El Niño to neutral or La Niña in the fall and vice versa) in this region strongly correlates with summer temperatures and precipitation, the direction of the transition is tested here.

Table 7 Values of HTC and BCP for the (a) Belgorod and (b) Missouri regions, where an *, **, and *** indicates the mean is different from that of the total sample at the 90, 95, and 99% confidence level, respectively

(a) Belgorod		
ENSO	HTC	BCP
El Niño	1.05	1.83
Neutral	1.18	1.86
La Niña	0.99**	1.78
(b) Missouri		
ENSO	HTC	BCP
El Niño	1.59***	1.51**
Neutral	1.92	1.81
La Niña	1.80	1.69

During all transitions toward El Niño conditions in Missouri, the HTC and BCP were 1.90 and 1.66, respectively, while for the opposite transition (toward La Niña) the HTC and BCP were 1.58 and 1.51, respectively. The HTC transition result is significant at the 99% confidence level, while the BCP was statistically significant at the 95% confidence level. The same results were obtained for transitions toward El Niño in the Belgorod region. Henson et al. (2017) showed that corn and soybean yields were lower across Missouri for La Niña transitions, which is consistent with the HTC and BCP index result found here. The results in this section indicate that for both regions, both indexes capture interannual variability, but the HTC was superior in the Belgorod region. In the Missouri region while the BCP may have better accounted for variability related to the PDO and/or climate change. Lastly, time series analysis was performed similar to Henson et al. (2017) for the HTC, Cp, and BCP and the results were identical to the co-variance spectra shown in their work confirming ENSO variability.

Conclusions

Here, we studied the change and variability in indexes that combine daily mean temperature and precipitation from the last part of the twentieth century and the first part of the twenty-first century in the Belgorod region of Southwest Russia and the Missouri region in the Central USA. These changes are then studied within the context of summer season stationary anticyclones (and blocking) either for the region itself (Belgorod) or upstream of the region (Missouri). Also, the variability with respect to teleconnections such as ENSO and PDO are examined. Then the data were used to calculate the HTC and BCP indexes, which are indexes that combine daily mean temperature and precipitation into a value that represents the growing conditions for the warm season or vegetated part of the year. In the Belgorod region, this is the May to September period; while for the Missouri region, this is the April to October period.

Here, it was shown that the Belgorod region has observed statistically significant increases in temperature during the warm season, and these have led to an increase in the BCP within the Belgorod region and that overall is a positive for regional agriculture. But it should be noted that the growth of BCP values from 1.81 to 1.85 is insignificant and occurs against a background of a 10% reduction of the moisture index. This was supported by a weak decrease in the HTC over the region. This situation is less favorable for agricultural production, and it is reflected by the statistically significant increase in the interannual variability of the weather conditions associated with agricultural meteorological indicators used here. The overall trend is also associated with the more frequent occurrence of blocking over the region. Lastly, both the HTC and BCP capture interannual variability consistent with an earlier study (Lupo et al. 2014) in that a transition toward El Niño conditions are less favorable for agriculture. However, only the results for the HTC were statistically significant.

Within the Missouri region, the HTC showed no appreciable trend from 1980 to 2014, which reflected the lack of statistically significant trends in warm season temperature and precipitation over the same period. However, the BCP showed a trend toward a drier and less variable climate in the early part of the twenty-first century compared to that of the later twentieth century for the Missouri, in spite of increased variability in precipitation. This result is likely due to changes associated with the change in phase of the PDO as well as a change in the frequency of growing season blocking anticyclones over the Eastern Pacific. However, as of yet, agricultural yields in Missouri have continued to improve likely due to technology (Henson et al. 2017). Additionally, both indexes captured interannual variability as related to ENSO for the region.

According to the results of this research, it should be noted that the expected warming may create potential for growth in crop yields. For the effective adaptation of regional agricultural production to climate change, it is recommended that:

- integrated regional studies be conducted to assess the risks (vulnerabilities) in agricultural production due to adverse weather and climate factors,
- optimize the ratio of winter crops and spring crops to account for changes in the conditions of the autumn-winter period,
- increase the acreage of more thermophilic and higher yielding crops, or intensifying agricultural production in favorable regions, and
- the introduction of moisture saving technologies, selection of more resistant crops(varieties), the creation of insurance stocks of food to reduce losses from possible dependence on climate.

Finally, there is now an imperative to build statistical or dynamic models that would project one to two seasons ahead (e.g., Henson et al. 2017) or even longer in order that the agricultural community can better anticipate the likely conditions of upcoming warm or growing season(s). Then models can be constructed for use in anticipating regional agricultural productivity, and efforts to do this type of work have been accomplished in the natural resources (e.g., Klyashtorin and Lyubushin 2007) and agriculture (e.g., Lobell and Burke 2010; Henson et al. 2017) in recent years.

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References

Agayan GM, Mokhov II (1989) Quasistationary autumn regimes of the Northern Hemisphere atmosphere in FGGE. Izv Atmos Oc Phys 25: 1150–1156

Agroclimatic Resources of the Belgorod region, Leningrad (1972) Hydrometeorological service of the Central Chernozem regions, p. 92

Ahrens CD (2012) Meteorology today: an introduction to weather, climate, and the environment, Brooks-Cole, 10th edition

Ashabokov BM, Calow HM, Fedchenko LM, Stasenko DV (2012) Some problems and methods of agriculture adaptation to climate change. In the book: Regional effects of global climate change (causes, effects, predictions): proceedings of Intern. Scientific. conf. (Voronezh, 26–27 June 2012). Voronezh, Publishing house “Scientific book.” pp. 360–365

Birk K, Lupo AR, Guinan PE, Barbieri CE (2010) The interannual variability of Midwestern temperatures and precipitation as related to the ENSO and PDO. Atmósfera 23:95–128

Changnon SA, Winstanley D (1999). Long-term variations in seasonal weather conditions and their impacts on crop production and water resources in Illinois. Research Report No. 127. Department of Natural Resources. Illinois Water Survey. pp. 37

Chen D, Chen HW (2013) Using the Koeppen classification to quantify climate variation and change. An example for 1901–2010. Environmental Development 6:69–79. https://doi.org/10.1016/j.envdev.2013.03.007

Dawson NW, Guinan PE, Lupo AR (2010) A long-term study of tropical systems impacting Missouri. Transactions of the Missouri Academy of Science 44:29–41

Edgerton MD (2009) Increasing crop productivity to meet global needs for feed, food, and fuel. Plant Physiol 149(1):7–13. https://doi.org/10.1104/pp.108.130195

Enfield DB, Mestas-Nuñez AM (1999) Interannual-to-multidecadal climate variability and its relationship to global sea surface temperatures. In: Markgraf V (ed) Present and Past Inter-Hemispheric Climate Linkages in the Americas and their Societal Effects. Cambridge University Press, Cambridge

Gershunov A, Barnett TP (1998) Interdecadal modulation of ENSO teleconnections. Bull Amer Meteor Soc 79(12):2715–2725. https://doi.org/10.1175/1520-0477(1998)079<2715:IMOET>2.0.CO;2

Gordeev AV, Kleschenko AD, Chernyakov BA, Sirotenko OD (2006) Bioclimatic potential of Russia: theory and practice. Moscow: Partnership of scientific editions KMK.- p. 512

Gustokashina NN, Maksutova EV (2006) The tendencies of the climatic fridiy change in steppe and forest-steppe of the Baikal region. Geog Nat Res 4:76–81 [In Russian]

Henson CB, Lupo AR, Market PS, Guinan PE (2017) The impact of ENSO and PDO-related climate variability on regional Missouri crop yields. Int J Biometeorol 61(5):857–867. https://doi.org/10.1007/s00484-016-1263-3

Hu Q, Buyanovsky G (2003) Climate effects on corn yield in Missouri. J Appl Meteorol 42(11):1626–1635. https://doi.org/10.1175/1520-0450(2003)042<1626:CEOCYI>2.0.CO;2

Hu Q, Woodruff CM, Mudrick SE (1998) Interdecadal variations of annual precipitation in the Central United States. Bull Amer Meteorol Soc 79(2):221–230. https://doi.org/10.1175/1520-0477(1998)079<0221:IVOAPI>2.0.CO;2

Intergovernmental Panel on Climate Change (IPCC), Climate change 2013: The Physical Scientific Basis, in Contributions of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Intergovernmental Panel on Climate Change (IPCC), http://www.ipcc.ch.(2013)

Karl TR, Knight RW (1998) Secular trends of precipitation amount, frequency, and intensity in the United States. Bull. Amer. Meteor. Soc. 79(2):231–241. https://doi.org/10.1175/1520-0477(1998)079<0231:STOPAF>2.0.CO;2

Khromov SP, Petrosyants MA (2006) Meteorologia i Klimatologia. Publication of Moscow State University, Moscow

Klyashtorin LB, Lyubushin AA (2007) Cyclic climate changes and fish productivity. Science Export, Moscow, Russia pp. 230

Kolomeychenko BV (2007) Crop: A textbook for students. M: Agrobiznescentr.-552 p

Kononova NK (2009) Classification of the Northern Hemisphere circulation mechanisms by B. L. Dzerdzeevsky. edited by A. B. Shmakin, Russian Acad. Sciences. Institute of Geography. M.: Voentechinizdat 372 p

Lebedeva MG, Krymskaya OV, Lupo AR, Chendev YG, Petin AN, Solovyov AB (2016) Trends in summer season climate for Eastern Europe and southern Russia in the early 21st century. Adv Meteor, 2016, Article ID 5035086, pp. 10

Lebedeva MG, Solovyov AB, Tolstopyatova OS (2015) Agroclimatic zoning of the Belgorod region in the context of climate change. Scientific sheets of BelSU. No. 9 (206), 31: 160–167

Lebedeva MG, Krymskaya OV (2008) A manifestation of modern climate changes in the Belgorod region. Scientific sheets of BelSU. No. 3 (43):6: 188–196

Lobell DB, Burke MB (2010) On the use of statistical models to predict crop yield responses to climate change. Agric For Meteorol 150(11):1443–1452. https://doi.org/10.1016/j.agrformet.2010.07.008

Losev AP, Zhurina LL (2001) Agrometeorology. Kolos, Moscow 296 p

Lupo AR, Kelsey EP, Weitlich DK, Davis NA, Market PS (2008) Using the monthly classification of global SSTs and 500 hPa height anomalies to predict temperature and precipitation regimes one to two seasons in advance for the mid-Mississippi region. Nat Wea Dig 32(1):11–33

Lupo AR, Smith NB, Guinan PE, Chesser MD (2012a) The climatology of Missouri region dew points and the relationship to ENSO. Nat Wea Dig 36:81–91

Lupo AR, Mokhov II, Akperov MG, Chernokulsky AV, Athar H (2012b) A dynamic analysis of the role of the planetary and synoptic scale in the summer of 2010 blocking episodes over the European part of Russia, Adv. Met, 2012: 11p, Article ID 584257

Lupo AR, Mokhov II, Chendev YG, Lebedeva MG, Akperov MG, Hubbart JA (2014) Studying summer season drought in western Russia. Advances in Meteorology, Special Issue: Large Scale Atmospheric Science, 2014: 9 p, Article ID 942027

Matveev SM, Chendev YG, Lupo AR, Hubbart JA, Timashuk DA (2016) Climatic changes in the East-European forest-steppe and their effects on scotch pine annual rings increment. Pure Appl Geophys 174(1):427–443. https://doi.org/10.1007/s00024-016-1420-y

Mokhov II, Khon VC, Timazhev AV, Chernokulsky AV, Semenov VA (2014) Hydrological anomalies and trends in the Amur River basin due to climate changes. In: Extreme Floods in the Amur River Basin: Causes, Forecasts, and Recommendations, Roshydromet, Earth Climate Theory Studies, 81–121

Mokhov II, Akperov AG, Prokofyeva MA, Timazhev AV, Lupo AR, Le Treut HR (2012) Blockings in the Northern Hemisphere and Euro-Atlantic region: estimates of changes from reanalyses data and model simulations. Doklady, 449, 430–433

Mokhov II (2011). The anomalous summer of 2010 within the general context of climate change and the anomalies. Analysis of the anomalous weather over Russia during the Summer of 2010, 41–47

Mokhov II, Chernokulsky AV, Shkolnik IM (2006) Regional model assessments of fire risks under global climate changes. Doklady Earth Sci 411(9):1485–1488

National Climate Assessment (NCA) (2014). The National Climate Assessment Summarizes the impacts of climate change on the United States, Now and in the Future 2014. Available online: http://nca2014.globalchange.gov/

Neter J, Wasserman W, Whitmore GA (1988) Applied statistics, 3rd edn. MA. Allyn and Bacon, Boston 1006 pp

Newberry RG, Lupo AR, Jensen AD, Rodriges-Zalipynis RA (2016) An analysis of the spring-to-summer transition in the West Central Plains for application to long range forecasting. Atms Cli Sci 6: 375–393

Nunes MJ, Lupo AR, Lebedeva MG, Chendev YG, Solovyov AB (2017) The occurrence of extreme monthly temperatures and precipitation in two global regions. Papers Appl Geog 3(2):143–156. https://doi.org/10.1080/23754931.2017.1286253

Petin AN, Lebedeva MG, Krymskaya OV, Chendev YG, Kornilov AG, Lupo AR (2014) Regional manifestations of changes in atmospheric circulation in the central black earth region (by the example of Belgorod region). Adv Environ Bio 8(10):544–547

Reddy VR, Panchepsky YA (2000) Predicting crop yields under climate change conditions from monthly GCM weather projections. Environmental Modeling and Software 15:79–86

Sapozhnikova SA (1970) To clarify of agricultural land capability climate assessment, agroclimatic resources of natural zones of the USSR and their use. L:Gidrometeoizdat, 80–92

Selyaninov GT (1928) On agricultural climate valuation. Proc. Agric. Meteor. 20:165–177 [In Russian]

Shashko DI (1985) Agroclimatic Resources of the USSR. Leningrad: Gidrometeoroizdat. 248. Stock materials of the Federal service for Hydrometeorology and environmental monitoring for 1899–2014

Strashnaya AI, Maksimenkova TA, Chub OV (2011) Agrometeorological specifics of the 2010 drought in Russia in comparison with past droughts. Works of Russian Hydro-Meteorological Center 345: 171–188 [In Russian]

Tarankov VI (1991) Forest meteorology: textbook. Voronezh Pedagogical Institute Press, Voronezh (in Russian)

Wiedenmann JM, Lupo AR, Mokhov II, Tikhonova EA (2002) The climatology of blocking anticyclones for the Northern and Southern Hemispheres: block intensity as a diagnostic. J Clim 15(23):3459–3473. https://doi.org/10.1175/1520-0442(2002)015<3459:TCOBAF>2.0.CO;2

Wuebbles D, Meehl G, Hayhoe K, Karl T, Kunkel K, Santer B, Wehner M, Colle B, Fischer EM, Fu R, Goodman A, Janssen E, Kharin V, Lee H, Li W, Long LN, Olsen SC, Pan Z, Seth A, Sheffield J, Sun L (2014) CMIP5 climate model analysis: climate extremes in the United States. Bull. Amer. Meteor. Soc. 95:571–583. https://doi.org/10.1175/BAMS-D-12-00172.1

Zolotokrylin AN, Titkova TB (1998) The dependence of the climate anomalies in the growing season forest on the Russian plains on large-scale atmospheric circulation. Izv. Geog 5:121–128