Trends in regional climate change and field crop productivity in Orenburg steppe region of Russia

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Abstract. Over the past four decades, climate in Orenburg region changed towards a significant increase in average annual air temperature from 4.5 °C to 6.2 °C and a significant decrease in the annual precipitation from 380 to 320 mm. For winter and early grain crops, these changes led to a sharp decrease in the productivity of crops about 2 times compared to the maximum values in the early 90s. Sunflower and sorghum cereals being the most thermophilic and drought-resistant crops adapted to the changed climate conditions better than other crops. The relationships that we have established between the temperature anomaly in the lower troposphere of the Northern Hemisphere and crop productivity can be used in models for long-term forecasting of weather changes and the productivity of field crops in Orenburg region.

1. Introduction

As registered by leading climatologists of the world [1-5], a rather long period of time, more than 4 decades, has passed since the beginning of intensive climate change (approximately in the mid-1980s). The most intensive processes of change occur in the temperate latitudes of the Northern hemisphere, where Orenburg region of the Russian Federation is located [3-5]. It is known that the average annual air temperature in the central steppe part of Orenburg region over the last century has increased by 2.8-3.0 °C, which is about 4 times higher than the increase in global temperature as a whole on the planet over the same period [6].

The results of observations of scientists of various specialties [7-11]: climatologists, hydro-meteorologists, astrophysicists show that an increase in the energy content of the planet’s climatic system leads to inhomogeneous changes in atmospheric processes in different regions. This is primarily due to the inhomogeneity of the underlying surface relief, changes in solar activity, albedo of the planet's surface over time, atmospheric circulation, characteristics of sea currents, etc.

In the areas of insufficient and unstable moisture in the Russian Federation (Astrakhan, Orenburg, Volgograd regions, Kalmykia), on the contrary, the frequency of droughts during the growing season of plants and their intensity increased.

2. Problem statement

In recent years, works [12-24] have been published, confirming the telecommunication links of global climatic changes with productivity of agricultural crops in small regions.
In this regard, we have set the goal of identifying trends in climate change in the northern hemisphere of the planet and in the Orenburg region, their relationship, to determine the factors that determine the yield of agricultural crops.

3. Material and method
Research objects - long-term time series:

- the average grain yield of winter rye, barley, spring wheat, millet and sunflower in Orenburg district of the Orenburg region (1979-2020);
- weather conditions: average annual air temperature and annual precipitation in Orenburg (1891-2020) according to the data of the Orenburg Center for Hydrometeorology and Environmental Monitoring - a branch of the Federal State Budgetary Institution “Volga Department of Hydrometeorology and Environmental Monitoring”;
- air temperature anomalies in the lower troposphere in the Northern Hemisphere of the planet Earth over land and ocean.

The construction of trends in plant productivity and climatic factors was carried out using the method of weighted weights with a moving averaging phase equal to 22 years in the author's program Prognostic v. 4.1.

Diagrams of variables and correlations were studied using the Statistica v. 6.1.

4. Results discussion
In the period from 1979 to 2020 there was an intensive increase in the average annual air temperature in Orenburg region.

Since the mid-90s, the average annual air temperature has risen from 4.7°C to 6.2°C following the trend, the growth amounted to 1.5°C or 32% from the initial level by 2015. Catastrophic changes on a global planetary scale are considered to be an increase in temperature at and above 1.5°C. Until the early 2000s, the rise in temperature was accompanied by the amount of precipitation ranged from 350 to 380 mm. However, at the beginning of the third millennium, a further increase in temperature over 5.6°C along the trend led to a sharp decrease in the average annual amount of precipitation from 380 to 320 mm (falling branch on the graph.

An increase in temperature with a simultaneous deterioration in the moisture supply of crops led to a significant decrease in the productivity of traditional grain crops in the steppe regions of the Orenburg region (figure 1).

Figure 1. Yield trends of grain crops and sunflower in the central zone of the Orenburg region (1979-2020).
Winter crops were the most productive, spring wheat is the least. However, the reaction of winter rye to changes in climatic conditions differed from that of early spring crops. In the early period of warming, accompanied by an increase in the average annual precipitation, the yield of winter rye increased from 1.5 to 2.0 t ha$^{-1}$ along the trend line. It is likely that milder winters created better conditions for overwintering and plant survival. In the subsequent period, there was a linear decline in the yield of winter rye to the current level of 1.1 tons. Spring crops: barley and wheat throughout the observation period (1979-2020) reacted to climate change unequivocally - a linear decrease in productivity: from 1.4 to 0.8 for barley, from 1.2 to 0.6-0.7 t ha$^{-1}$ for wheat.

Millet and sunflower being more heat-loving and drought-resistant crops reacted differently to changes in climatic conditions. The outlined decline in millet productivity over the past two decades has stopped and showed stable results at the level of 0.8 t ha$^{-1}$, it is higher than the trend level for spring wheat and is approaching the level of barley productivity in recent years.

This phenomenon, against the background of climatic changes, contributed to a significant increase in the productivity of sunflower seeds in Orenburg region. Over the past 20 years, the yield of sunflower has increased from 0.5 to 1.0 t ha$^{-1}$, i.e. 2 times according to trend. To date, the most drought-resistant and heat-resistant sunflower culture, taking into account the high purchase prices for seeds, has become the leading crop in crop production, ensuring the profitability of the entire crop production industry not only in Orenburg region, but also in other steppe regions of Russia. In Orenburg region, the sown area of sunflower approached 1.0 million hectares.

Taking into account the inertia of the development of temporary trends, it can be assumed with a high degree of probability that in the next 5 years, winter crops will have an advantage in productivity: rye and wheat, sunflower, as well as a group of sorghum crops such as millet, sorghum, Sudanese grass.

We have reliably established that the processes of weather and climate change in the region are closely related to temperature changes in the Northern Hemisphere of the planet (figure 2).

![Figure 2. Relationship between the mean annual air temperature in Orenburg and September temperature anomaly over the land of the Northern Hemisphere.](image-url)

Over a long observation period (1979-2020), a fairly high correlation relationship $r = 0.635$ was established between September air temperature anomaly over the land of the Northern Hemisphere and the average annual air temperature in Orenburg. If we follow the development of the surface air temperature anomaly over the land of the Northern Hemisphere, then its growth is obvious in the form of a linear trend (figure 3).
Figure 3. Dynamics of September temperature anomaly over the land of the Northern Hemisphere (1979-2020).

We have established a high inverse relationship $r = -0.63$ between anomaly temperature of January in the lower troposphere over the ocean of the Northern Hemisphere and the yield of spring barley in the central zone of Orenburg region (figure 4).

![Graph showing the relationship between temperature anomaly and barley yield](image)

**Figure 4.** Relationship between the yield of barley in Orenburg district of Orenburg region and anomaly temperature of January of lower troposphere over the ocean of the Northern Hemisphere.

The relationship is significant and linear; the anomaly growth contributes to a decrease in the productivity of the main grain crops.

At present, the anomaly temperature has a tendency to linear growth (figure 5), which suggests a further decrease in the productivity of early grain crops in the steppe zone of Orenburg region.
5. Conclusion
The processes of changes in weather conditions and climate in Orenburg region over the past four decades are closely associated with an intense temperature increase in lower layers of the troposphere over the land and ocean of the Northern Hemisphere of the planet.

Climate in Orenburg region changed towards a significant increase in average annual air temperature from 4.5 °C to 6.2 °C and a significant decrease in the annual precipitation from 380 to 320 mm in the central zone of the Orenburg region. For winter and early grain crops, these changes led to a sharp decrease in the productivity of crops about 2 times compared to the maximum values in the early 90s.

Sunflower and sorghum cereals being the most thermophilic and drought-resistant crops adapted to the changed climate conditions better than other crops.

The relationships that we have established between the temperature anomaly in the lower troposphere of the Northern Hemisphere and crop productivity can be used in models for long-term forecasting of weather changes and the productivity of field crops in Orenburg region.

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