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RESEARCH ARTICLE

Phytocoenotic and Soil Signs of Current Global Warming on the Boreal Ecotone of the East-European Plain

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Abstract: The current global warming, which has been going on since the mid-70s of the last century, has been confirmed by numerous factual observations. A decrease in edaphic moisture should inevitably cause the replacement of forest-steppe vegetation by northern steppe vegetation, and the latter by dry steppe vegetation. At the same time, dark-gray forest soils and ordinary chernozems still remain in the position of northern relics during this short period. However, due to the increased humification of organic matter, the predominant type of humus changes from humate-fulvate to fulvate-humate. The successional trend in boreal phytocoenoses includes the replacement of oak and/or pine by spruce, with a decrease in forest density, as well as the nemoralization of the ground cover. On the Main Landscape Boundary of the Russian Plain, a three-dimensional local phytocoenotic ecotone is developing to a certain extent, with the strengthening of the boreal vegetation type in the tree layer and sub-boreal types in the undergrowth and ground cover. The increase in the range of inter-annual fluctuations in temperatures and precipitation over the last century indicates a clear increase in climate extremes. The frequency of extreme weather increases – abnormally cold and abnormally warm, as well as excessively humid and extremely dry. All this contributes to the development of steppe ecosystems and has an extremely unfavorable effect on the state of oak groves, causing waves of their mass drying out even at the northern borders of their habitats. In general, on the territory of the Eastern European sub-continent, the "savannization" of mesophilic broad-leaved forests should begin, with their merging with a mosaic complex of sparse forests, meadows and steppes of the typical forest-steppe.

Keywords: modern global warming, boreal & nemoral phytocenoses/soils successional trends, 3D phytocenotic ecotone, increasing climate extremes, oak forest drying

1 Introduction

The ecological safety of large territories and the reproduction of biotic resources depend significantly on the state of zonal types of ecosystems, and, first of all, on two competing plant formations: forest and grassy. For regions with intense competition, the problem of preserving forest resources becomes especially urgent in the conditions of a changing climate. In this regard, the territory of the main catchment area of the Volga basin is very indicative. It is part of the so-called transcontinental boreal ecotone [1] – a system of first-order zonal boundaries dividing the boreal belt (mainly taiga) and the subboreal (forest-steppe and steppe). In this relatively narrow transition zone, fundamental changes in the structure and functioning of natural ecosystems of the zonal type occur [2], caused by the most important climatic boundary – the transition of the heat and moisture ratio through 1.

One of the most dynamic natural processes on the planetary scale are changes in the global climate caused by changed chemical composition of atmosphere, with the corresponding demonstration of greenhouse effect. Global geosystem monitoring is most up-to-date and actually realizable on the scale of individual ecological regions. This strategic direction is reflected in the "International Geosphere-Biosphere Program" [3], which provides for the development of scenarios for the near future of the biosphere Natural processes and events on the regional hierarchic level are characterized by the greatest diversity and high discreteness, therefore the regional response of global climatic changes inevitably takes the form of multiple reactions of vegetation, soils and landscapes as a whole to background climatic signals.

This report presents some results of the author's and other researches's observations and assessments of phytocenotic and soil features of the response of forest ecosystems of the Volga basin to hydrothermal signals of modern global warming.

2 Main features of the climatic trend

Global warming began, according to earlier estimates [4], in the mid-1980s. Now its onset is attributed to the period 1970–1975, which is confirmed by the results of averaging meteorological observations of the global network of 3288 ground stations – T3288 [5]. Since that time, the increase in the average annual surface temperature has been quite stable, and its 11-year moving averages give a clearly expressed linear trend (Figure 1). This trend is most pronounced in the Northern Hemisphere – at a rate of about 0.88 ^{0}C/10 years. At the same time, on the European continent the rate of annual temperature increase averages 0.498 ^{0}C/10 years, and in the summer season reaches 0.531 ^{0}C/10 years. The year 2023 turned out to be the warmest in the entire history of global meteorological observations, starting from 1850. Its average temperature was 1.48 ^{0}C higher than the temperature of the pre-industrial period [5].

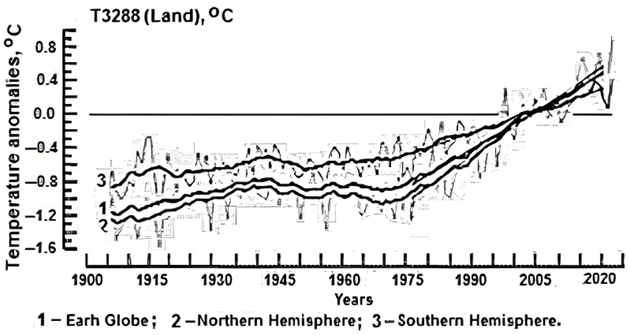

Figure 1 Time series of mean annual surface temperature anomalies, averaged to T3288 (land). The data and the technique of special averaging of the IGCE were used [5].

The results of climate time series analysis show that the mean annual value of temperature increase on the continents in the 20th century was within 0.7–1.6^{o} [6]. As early as in 1980, of the Northern hemisphere the mean July temperature at the 55–60^{o} N changed by 0.4–0.5^{o} relative to the normal value for 1891–1979 [7]. In the past 100 years, the mean annual air temperature on the territory of European Russia, including the Volga River basin, has increased by 0.9–1.1^{o} on average [8, 9]. After the known "Arctic warming" of the 30–40s followed by the wave of cooling in the 50–60s (see Figure 1), a new stable tendency of global climate warming has manifested itself since the early 70s of the 20th century [10, 11] and has been continued up to now.

In the taiga and forest steppe regions of the neighboring West Siberian Plain, the rate of total annual warming observed at meteorological stations in the last third of the 20th century was 0.04–0.08 ^{o}C/yr, while the increase in the mean surface temperature after 1900 in the Altai-Sayan region, Central Europe, Central America, and other regions of the world was no less than 0.6–0.8^{o}C, according to geothermal data [12]. The mean annual temperature had been rising at a rate of 0.02–0.08 ^{o}C/yr along the whole network of forest-steppe and steppe regions of southern Siberia during the 60-year period of meteorological observations (1938–1998), intensifying general aridization of exogenous processes under the conditions of unstable fluctuations of atmospheric precipitation [13].

Thus, the global character of warming in the last century is undoubted, and it is a fluctuating and accelerating process. , For example, during 1995-1999 deviation of the mean annual temperature from the 20-year norm of "pre-industrial period" (1886–1905) on the European territory of Russia was 0.7–0.8^{o} to 1.9^{o}C [8]. Paleo-botanic data for the Russian Plain [14, 15] also demonstrate that the sub-Atlantic cold and humid trend has become slightly weaker and even tends to change for the thermo-arid one.

Assuming that the warming started in the 20th century is for the most part and even predominantly anthropogenic and caused by the increasing emission of technogenic "greenhouse" gases into the atmosphere, it should not be forgotten that it coincided with the beginning of a "conservatively stable", according to [16], warm and dry phase of the latest 1800-1900-yr climatic rhythm and, therefore, may be a result of positive interference of the anthropogenic and natural factors of climate changes.

Atmospheric humidification could be characterized by negative interference: a general increase in precipitation should be expected under global anthropogenic warming [17], whereas in the modern phase of natural super-century climatic rhythm the temperature rise must be accompanied by general, though slower, aridization of the climate. Both factors, neutralizing each other, are able to significantly weaken the modern century-long trend of atmospheric humidification. Indeed, based on the factual data [8, 18], annual precipitation on the territory of the Volga River basin, like in European Russia as a whole, has hardly changed in the past 100 years (there was only a very weak and statistically unreliable tendency to increase). Nevertheless, in the last third of the 20th century there was still a marked increase in precipitation. Such was, e.g., the 24-year period of 1967–1990, when annual precipitation on the European territory of Russia increased by 30% [19].

3 General changes in soil-plant cover

The important question now arises of whether there are any signs of modern aridization and steppification of the boreal and nemoral forests and what forms of phytocoenotic structures and soil characteristics they assume.

The current century-long warming on the territory of the Volga River basin could not but cause, first and foremost, the northward expansion of areals of grass steppe (*i.e.*, the most dynamic) ecosystems. Experiments with the mathematical models of biosphere processes show [20] that forest ecosystems can much more efficiently neutralize the thermal signal compared to herbaceous ecosystems under the conditions of increased temperature or atmospheric CO_2, which induce simultaneous increase in both primary bio-productivity and the rate of decomposition of dead organic matter. Herbaceous ecosystem proves to be more sensitive to natural and/or anthropogenic climate changes. This difference manifests itself already in the first decades and is maintained throughout several centuries, suggesting the first-priority response of exactly grass steppe but not forest ecosystems to stable climate changes.

As we have already shown [1], the stored summer soil moisture, which is the main hydrothermal factor directly influencing vegetation and soils, almost equally depends on variations of both the mean July temperature and annual precipitation. It means that the thermal and pluvial signals are rather interchangeable and can exert the same ecological effect. Consequently, the general warming that occurred in the 20^{th} century must have influenced the state of zonal geo(eco)systems even in the absence of any substantial changes in precipitation. According to our estimates based on the empirical data and statistical information analysis [21], the increase of the mean July air temperature in the south of the forest steppe zone of the Volga River basin by 0.5°, *i.e.*, by half of the total annual warming in the 20th century, is equivalent to a 30-mm increment of annual evaporation capacity. The latter causes a decrease in summer productive moisture reserves in the 0–50 cm soil layer of herbaceous ecosystems by 5–7 mm, which is equivalent to reduction of annual precipitation by more than 50 mm. We have established that the taxonomic (average-weighed) norm of annual precipitation is 507–509 mm for the southern forest steppe (both East-European and By-Ural) and 438 mm for the northern trans-Volga steppe. Hence, it may be supposed that the above decrease in edaphic humidification must inevitably cause replacement of forest steppe plants by northern steppe vegetation and replacement of the latter by dry steppe plants. At the same time, dark-gray forest soils and common chernozems have no time for significant changes during this short period and remain in the state of northern relicts (Table 1).

These soil relicts could emerge in a comparatively short period of time (within a century or even several decades), because they were determined by active northward transgression of grass steppe ecosystems (especially grasslands), what should cause [22] intensive stand breakup and suppression of forest reproduction.

The described situation seems to be typical not only of the south of the middle belt of the Russian Plain. In the low- and middle-mountain regions of the South Ural, Krashennikov (1951) [23] already in the mid 30s of the 20th century found under the canopy of broad-leaved and even fir-spruce forests the "originally alien" xerophilic herbaceous species from the larch-pine-birch forest steppe of the foothills of South Ural, which he characterized as a heritage of cold-arid "ancient Pleistocene forest steppe". In their turn, forest steppe communities proved to be a field of transgression of dry-steppe elements being parts of the rocky North Caucasus steppes. West Siberia is also characterized by modern expansion of meadow steppe on forest and of semi-desert on meadow steppe [24].

The incremental warming of the 20th century also affected some properties of soil-moment,

Table 1 Distribution of ecological niches of plant formation groups of the forest-steppe and steppe zones of the Volga River basin by soil groups

Soils		Vegetation				
		Typical forest-steppe		Southern forest-steppe		Northern steppe
		A	B	C	D	E
Broadleaf forests	GFlight			•↑		
	GFown	•				
	GFdark	•	•		•↑	
Typical an southern forest-steppe	Chpod	×	•	•		•↑
	Chmed	•	×	•	•	
Northern steppe	Chtyp		•		•	
	Chordin				×↓	×
Southern steppe	Chsouth		•↓	×↓	×↓	×↓

Note: The symbol "×" denotes an ecological optimum, and the symbol "•" denotes a "fuzzy" part of the niche. The symbol "↓" indicates that this soil group is a southern relict in relation to the plant formation, and the symbol "↑ " denotes a northern relict. Formation groups: A – forb-grass pine forests with steppe shrubs; B — meadow steppes and steppe meadows in combination with oak forests; C – rich forb-feather-grass steppes of the Black Sea type; D – the same Trans-Volga-Kazakhstan; E – Trans-Volga fescue-feather-grass steppes in combination with wormwood on solonetz. For the designations of soil groups, see the Note to Table 2.

according to [25], particularly the fractional composition of humus in horizon A_1. In contrast to vegetation, soil underwent these changes not in the southern but in the northern area of the boreal ecotone: in mixed forests and, to a lesser extent, in the south and middle taiga. The dominant values of the humic to fulvic acid ratio (C_{ha}:C_{fa}) in these soils (1.00–1.50) proved to be slightly above their zonal norm (0.75–1.25). This shift was especially considerable in sod-podzol and transitional podzol/brown forest soils of pine and complex spruce forests of the Middle Kama region, where the predominant humus type changed from humate/fulvate to fulvate/humate (Table 2).

Table 2 Areas of dominance of humus types by the ratio of C_{HA}: C_{FA} in various soil groups of the Volga River basin and its surroundings

Humus type	Correlation CHA:CFA	Soil groups													
		northern and middle taiga		southern taiga and mixed forests				broadleaf forests			typical an south forest-steppe		northern steppe		southernsteppe
		Podzol (P)		Soddy-podzol (SP)				Gray forest (GF)			Chernozem (Ch)				
		gum	own	gley	small	ferru	2gum	light	own	dark	podz	med	typ	ordin	south
Humate-Fulvate	0.50–0.75	⊗	⊗												
	0.75–1.00	•		⊗	○	⊙	⊙	○							
Fulvate-Humate	1.00–1.25		•		×		○	⊗	⊙		•	•			
	1.25–1.50			•		×		×	⊗	⊗					
	1.50–1.75				•	•	×			○	⊗	○			⊗
Humate	1.75–2.00										⊗	⊙	•	•	⊙
	2.00–2.25											×	⊗	⊙	
	2.25–2.50												⊙	⊗	

Note: The signs ⊗, ⊙ and ○ indicate the zonal norm of the C_{HA}: C_{FA} ratio in the A1 horizon for a given soil group. according to previous studies [26, 28–30]. Podzol soil groups: ***gum*** – illuvial-iron and illuvial-humus podzols and peat and podzolic-gley; ***own*** – properly podzolic soils (finely. shallowly and deeply podzolized). Soddy-podzol soil groups: ***gley*** – soddy-podzolic gley. shallowly podzolized; ***small*** – the same. finely podzolized; ***ferru*** – soddy-polzolic illuvial-iron; ***2hum*** – soddy-podzolic with a second humus horizon, clarified and residually carbonate. Gray forest soil groups: ***light*** – light gray forest; ***own*** – gray forest; ***dark*** – dark gray forest. Chernozem soil groups: ***podz*** – podzolized and leached chernozems; ***med*** – meadow chernozems and meadow-chernozem leached soils; ***typ*** – typical and non-carbonate chernozems; ***ordin*** – ordinary chernozems; ***south*** – southern chernozems and carbonate and dark chestnut soils. Additional ecological dominant in each vector-column of niche are defined by symbol ×, and "fuzzy' links of the niche – by symbol •. The remaining designations are the same as in Table 1.

The predominance of humic acids over fulvic acids is also observed to increase in the light-gray forest soils of oak-lime forests and in the leached chernozems of typical forest steppe (both coniferous and broadleaf). Such a noticeable increase in the depth of organic matter humification in these soils was due not only to the temperature increase but even more to the respective extension of the period of biological activity of soils. As is known [26], close dependence of the C_{ha}:C_{fa} ratio on the latter factor is one of the main biogeochemical "rules" of humus formation.

Certain phytocoenotic changes are also observed in boreal forests. Stationary geobotanic studies on the territory of Moscow region in the subtaiga zone during a 20 –25 year period [27] have shown the following regularities of the succession trend: (1) substitution of spruce for pine and/or oak, with the loss of aspen and general decrease in the degree of forest density, for the stands and (2) nemoralization of herbage, with reduction of the number of boreal species, for the ground cover. The former process may be ascribed to the increase in atmospheric humidification in the preceding centuries (the heritage of super-century climate fluctuations [21], while the latter seems to be caused by the modern temperature increase (first of all during the vegetation period) and, consequently, demonstrates an example of one of the initial phytocoenotic responses to global warming.

This example shows the obvious signs of enhanced contrast of the vertical component of three-dimensional local phytocoenotic ecotone: reinforcement of the positions of boreal-type vegetation in the arboreal layer and sub-boreal vegetation in the ground cover. Such mutually antothetical transgression of boreal and subboreal species in the mixed forest zone (boreal along the upper bio-horizons in the north and sub-boreal along the lower horizons in the south) seems to be a result of the two climatic trends of different frequency: super-century of 1800–1900 years [16] and century-long of 80–90 years, respectively.

Thus, the modern century-long thermal signal has had a well-defined effect both on the structure of herbaceous communities (not only in steppe and forest steppe but also in forest zones) and on the properties of soil-moment (mainly in boreal forests being most sensitive to temperature changes).

4 Phytocoenotic changes at the Main landscape Border of the Russian Plain

Let us refer to the results of geobotanic studies in Nizhegorodskoye Povolzhye [25, 31]. As is shown in Kharitonychev (1978) [32], this territory is characterized by the most marked natural latitudinal-zonal ecotonization of the entire Russian Plain: high diversity of natural zones of the boreal and subboreal belts and considerable closeness of zonal-subzonal boundaries to each other. Figure 2 shows the meridian profile of vertical structure of the phytocoenotic environment encompassing the northern part of the By-Volga Upland and the southern area of low-lying Vetluga/trans-Volga region, *i.e.*, the parts of territories on both sides of the Main Landscape Border of the Russian Plain, according to the terminology of Mil'kov (1981) [33]. The profile characterizes the distribution of three zonal types of vegetation: taiga, nemoral forest, and steppe. As we can see, the above types regularly replace each other not only in horizontal direction (from south to north) but also vertically: from the upper biogeocoenotic horizons, in terms of Byallovich (1960) [34], to the lower ones. It is a result of sequential wedging from below of more southern into more northern type, resulting in appearance of a kind of superzonal stratification of phytocoenoses in the south taiga subzone, in the mixed-forest zone, and in the nemoral sub-zone.

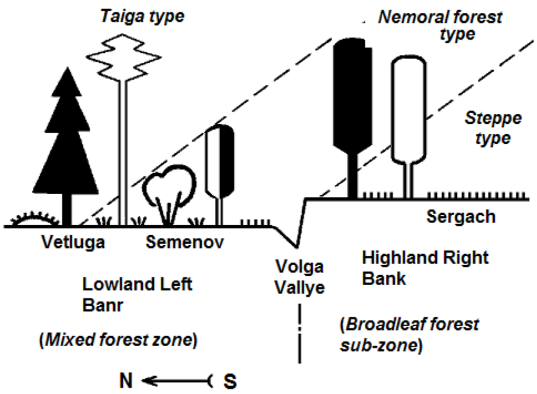

Figure 2 Three-dimensional phytogeographic ecotone on the Main Landscape Boundary of the Russian Plain (within the Nizhny Novgorod Volga region).

According to the descriptions made in the 40–50s of the 20th century by Stankov (1951) [25], the upper tree layer of well-drained watershed complex fir-spruce (coniferous) forests of the Povetluzhye is referred to the boreal (taiga) type of natural environment. At the same time, oak-forest elements (lime, maple, hazel, honeysuckle, buckthorn, etc.) are widespread in the second layer and in the undergrowth. The ground cover also acquires much of the nemoral-forest appearance, where the boreal species of dwarf shrub and herbs (mountain cranberry, ferns, shamrock (oxalis), Lithuanian mannagrass, etc.) grow nearby the widespread nemoral species (hair-like sedge, woodruff, glague (*Aegopodium*), asarabacca (*coltsfoot*), high aconite, etc.).

Stankov believes that such vertical structure of ramens results from the struggle between plant groups dramatically different in the zonal respect, their thrusting into each other. Southern elements are also widespread in the herbaceous layer of pine forests of trans-Volga subtaiga. Such are, for example, lily-of-the-valley pine forests [31].

In turn, representatives of typical forest steppe intrude into the zone of broad-leaved forests from the south; they have already "forced" the Volga river valley and spread over the lower reaches of Kerzhenets and Vetluga. As a result, oak and pine forests of the By-Volga Upland have acquired multi-layeredness and species abundance (diversity), with evident steppification of the lower biogeocoenotic horizons in the southern belt of the sub-zone [31]. The undergrowth often contains steppe shrubs (Russian broom (*Chamaecyticus ruthenicus*), dyer's-broom (*alleluia*), and creeping (*juniper*) and the ground cover contains forest steppe and steppe grasses (vetch, Corydalis marsch-alliana, narrow-leaved lungwort, Mediterranean chrysanthemum, cinquefoil, mountain sedge (*Carex scopulorum*), geranium, etc.). Broad transgression of steppe plants resulted in appearance of big "islands" of typical forest steppe in the broadleaf forest sub-zone (such as, e.g., Arzamas and Sergach forest steppes).

The described phytocoenological profile having the appearance of puff pastry is one more example of three-dimensional biogeographical ecotone, which has come into existence due to transgression of only grass/shrub forest layers under the influence of the modern climatic trend. The ecotone has been formed as a result of penetration of steppe plant elements into broad-leaved forests along the lower bio-horizons and, in turn, penetration of representatives of the nemoral flora into mixed forests and even south taiga. Such unidirectional wedging of horizons causes strong mobility of their lateral boundaries [34], thereby initiating reorganization of the vertical phytocoenotic structures over vast areas.

The above example characterizes the initial stage of structural trans-formations of natural ecosystems under the influence of thermo-arid climatic trend, and this period seems to have been completed on the territory of the Volga River basin. As has been said above, soil-forming processes underwent the respective changes as well.

5 Phytoecological effect of enhanced non-stationarity of the climate

We should also note the considerable enhancement of interseasonal climatic contrasts and the higher recurrence of extreme hydrothermal conditions during the past 100 years. Statistical analysis of time series showed [18] a general tendency to greater abnormality of the temperature field, which developed on the territory of the European part of Russia, West Siberia and Kazakhstan during 1891–1961 and has been especially noticeable since the 20s of the 20th century. The materials presented in Zolotokrylin (1988) [35] also showed an increase in the amplitude of interannual fluctuations of summer temperatures and precipitation on the territory of European Russia during 1891–1980 (quasi-biennial oscillation with a period of 15–20 years), indicating unambiguously increasing climatic extremity. The winter regime of typical and southern forest steppe of the Russian Plain has also undergone noticeable changes. In the last quarter of the 20th century, the recurrence of winters with little and unstable snow increased here from 28% to 40% [36].

Thus, there was intensification of the climatic imbalance of the territory providing development of exactly steppe ecosystems [37] and having an extremely unfavorable effect on the state of oak forests not only near the southern boundaries of the area of their distribution but, as it seems, over the whole areal, as indicated by Morozov (1926) [38]. The latter is confirmed by the widely known facts about the waves of large-scale drying of oak forests on the Russian Plain building up throughout the 20th century [39], which is associated first of all with the higher recurrence of strong draughts in the spring-summer period. The extreme values of thermal conditions of May in 90% cases cause abnormalities in the course of oak growth even near the northern boundaries of its areal [40].

Numerous materials of different authors [41,42] show that the large-scale oak drying observed since early 40 s of the 20th century, with the maximum intensity in the 50-60 s, has been altogether noninfectious. The fungal diseases of oak finally resulting in stands drying and dying is a secondary event. Their main causes are changes in the state of ecotopes induced by external climatic fluctuations; therefore, the still continuing large-scale drying of oak forests noted, e.g., in the Middle Povolzhye [39], is quite probably the phytocoenotic feature of the modern global climate changes.

The mechanism of such connection is as follows: oak and lime at the periphery of their areals are very sensitive to the extreme states of the atmosphere: oak to the winters with strong frost and little snow, especially in the initial period of winter [43], and lime to dry and hot summer [44]. In forest steppe, oak also suffers a lot from draughts. Late frosts are also important; arboreal species become more sensitive to them under general warming [38]. At the same time, one of the paramount phenomenal indicators of global climatic changes of the 20th century is considered to be the increase in its high-frequency instability, the growth in the amplitude of temperature fluctuations and atmospheric humidification from one year to another, with the higher frequency of occurrence of extreme weathers: abnormally cold and abnormally warm, as well as excessively humid and extremely dry [6]. In particular, rather stable 10–30-year cycles of the pronounced climatic fluctuations with abnormalities of the mean annual air temperature of 2° and more have been revealed for the territory of steppe, forest-steppe and mixed-forest zones of the Russian Plain beginning from the 20s of the 20th century [45]. There have also been regularly repeating (approximately every two decades) 7–8-year periods of quasi-biennial oscillation with the outbreaks of regional climate extremity [46]. The trend of intensified climate aridity in the warm period of the year was most significant, first of all due to abnormally hot summer seasons. For example, the June and July air temperatures in 1981, 1988, 1991, and 1998 regularly increased up to 36-39^o in the Central-Chernozem region and up to 42^o in the Lower Povolzhye [8], exceeding the long-term temperature maximums for these regions. As is known [47], strong draught sets in when the mean temperature goes beyond the long-term norm by 3–4^o.

The first cause of intensification of climatic aridity and extremity in the Volga River basin may be considered, according to the data [18,48], the considerable general increase in recurrence of the eastern (E) form of atmospheric circulation (by the Vangengeim–Dzerdzeevsky–Girs classification) during 1899–1997 with maintenance of rather high frequency of meridian (C) circulation and reduced recurrence of western (W) circulation. According to other data [7], in 1890–1980 there was a considerable increase in the total recurrence of E + C forms of atmospheric circulation and the weakening of W form. Somehow or other, the main features of such synoptic situation are: (1) continuous alternation of warm and humid air inflows from the Mediterranean resulting in abundant rains and snowfalls in the fall-winter-spring period, with deep intrusions of dry and cold Arctic air [48] causing light frosts, and (2) the inflow of abnormally warm and dry air from the intra-continental regions of Eurasia, causing early snow thawing in winter and prolonged strong draughts in summer. At the same time, the activation of meridian circulation increases winter snowiness, while the lower zonal circulation increases summer atmospheric aridity [46].

The winter temperature conditions of the 20th century altogether resembled the time of medieval climatic optimum (XII century) but with higher recurrence of extremely cold but not warm winters, while the abnormally cold winters were characterized by both little and much snow. Summer seasons were the coldest on average throughout the past 800 years. Nevertheless, every 10 years there were up to three extremely warm summer seasons, and the recurrence of extremely humid and extremely arid spring-summer periods was approximately equal [46].

The described peculiarities of climate of the middle area of the Russian Plain in the 20th century should have had a very unfavorable effect on the state of oak forests and promoted northward expansion of steppe phytocoenoses, first of all along the prominent, driest elements of meso-relief. Vegetation of exactly eluvial and transeluvial locations is a primary indicator of background climatic changes. This tendency is apparently bound to be maintained in the nearest future, because a new significant increase of the mean annual air temperature is predicted by 2005–2010 [45].

6 Conclusions

Our data show that the modern global warming is to a certain extent reflected in the structural and functional changes in natural ecosystems on the south of the boreal belt and in the region of its transition to the sub-boreal belt. These changes are determined by a rather stable thermo-arid bioclimatic trend, which started to develop as early as in the last century and is being predicted for the whole first half of the 21st century. Under such conditions, transgressive development of mixed-forest phytocoenoses should be expected in future on the main catchment area of the Volga River basin not only in the south of the boreal belt but also in its “typicality core”: the middle taiga. Even for the nearest decades, one should assume also certain “savannization” of mesophilic broad-leaved forests and their joining with the total mosaic complex of light forests, meadows and steppes of typical forest steppe. We also anticipate further transformation of complete canopy of mixed and even coniferous forests into light-forest park-type stands disconnected by the sites of meadow-steppe communities (the analogs of modern glades). The latter, as is known, are formed in the course of long-term human influence on coniferous forests, *i.e.*, are a consequence of anthropogenic aridization of forest lands. Finally, one can speak with confidence about the enhancement of mobility of geobotanic areals and instability of zonal boundaries.

Conflicts of Interest

The author declares no conflict of interest.

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