Changes in Drought and Bioproductivity Regimes in Land Ecosystems in Regions of Northern Eurasia Based on Calculations Using a Global Climatic Model with Carbon Cycle

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Estimates of possible changes in climatic regimes and biospheric effects in regions of Northern Eurasia, from subtropical to subpolar latitudes, in the 21st century were obtained on the basis of calculations using a global climatic model with carbon cycle [1–3] and taking into account anthropogenic influence [4–6]. Emphasis is given to the analysis of changes in regimes of drought and bioproductivity in land ecosystems at mid-latitudes, with a comparison of variations in the East European (EER) and West European (WER) regions.

The results of calculations using the global climatic general atmospheric and oceanic circulation model (CGCM) with carbon cycle IPSL-CM2 [1–3] were used in the analysis. Anthropogenic emission of carbon dioxide into the atmosphere based on observations in 1860–1990 and the SRES98-A2 scenario for 1991–2100 [7] was specified in the numerical calculations using the CGCM with IPSL-CM2. The IPSL-CM2 cycle includes the model of the general circulation of the atmosphere LMD-5.3, the model of the general circulation of the ocean with ice block OPA-ice, and the OASIS interface block. The carbon cycle model includes the SLAVE block for the continental part and the IPSL-OCGM1 block for the oceanic part based on the HAMOC3 biochemical scheme.

The inclusion of interaction with the carbon cycle into the global climatic model [1, 2] fosters its sensitivity to increases in the carbon dioxide content in the atmosphere. This indicates the corresponding positive feedback.

Along with the account for the complete interaction of the climatic model with blocks of the carbon cycle (version I), we also analyzed the results of numerical calculations (with the exception of interaction between model blocks) to estimate the role of different factors and feedbacks [3]. In particular, we analyzed the changes occurring under the condition of increasing anthropogenic emission of carbon dioxide into the atmosphere (version II). In this case, variation in the carbon dioxide content in the atmosphere affects the rate of photosynthesis and, consequently, the vegetation cover of land without the influence of climate changes on this process. At the same time, the climatic regime remains at the level of the preindustrial state (i.e., without anthropogenic influence).

During the warm period of the year, the drought regimes are characterized by anomalies in the temperature and hydrological regimes, in particular, by positive anomalies of surface temperature $\delta T > (\delta T)_{cr}$ and negative anomalies of precipitation $\delta P < -(\delta P)_{cr}$ in the analysis of atmospheric (meteorological) droughts. The data of meteorological observations and results of reanalysis were used for testing the model results. In particular, we used monthly mean data [8] for the variations of surface temperature $\delta T$ and precipitation $\delta P$ during the growth of vegetation in May–July for mid-latitude regions of the Northern Hemisphere, EER, and West Asian region (WAR) for the period of 1891–2002, with the drought index $D$ characterizing the spreading of anomalous regimes with $\delta T > (\delta T)_{cr}$ and $\delta P > (\delta P)_{cr}$. In this case, we also determined the critical values of $(\delta T)_{cr}$ and $(\delta P)_{cr}$ from the corresponding root-mean-square deviations and varied them.

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Analysis of the results of numerical calculations shows that the IPSL-CM2 CGCM adequately describes the joint dynamics of regional variations in the near-surface temperature $T$, precipitation $P$, and characteristics of droughts in May–July as compared to the data of observations described in [8] for 1891–1995. In particular, data of observations for the EER based on the corresponding linear regression indicate that the parameter of the sensitivity of precipitation $P$ to variations in $T$ is estimated as $\frac{d(P/P_C)}{dT} = -0.07(\pm 0.01) \text{ K}^{-1}$ (root-mean-square deviations are given in parentheses) [4, 9]. Model calculations for the EER (46.1°–53.2° N, 39.4°–50.6° E) yielded a similar estimate: $\frac{d(P/P_C)}{dT} = -0.06(\pm 0.01) \text{ K}^{-1}$ [4, 9]. Both the data of observations and model calculations testify to a decrease in precipitation with an increase in positive anomalies of surface temperature in May–July in the EER over the last more than one hundred years.

The corresponding estimates of the sensitivity of the drought index $D$ to variations in surface temperature in the EER also demonstrate a good quantitative correlation: $\frac{dD}{dT} = 10.7(\pm 2.3) \text{ % K}^{-1}$ (at the correlation coefficient equal to $r = 0.82$) according to the data of observations, and $\frac{dD}{dT} = 9.5(\pm 2.3) \text{ % K}^{-1}$ ($r = 0.80$) according to the model calculations. In the EER, this corresponds to an increase in the spreading of drought regimes approximately by $10\%$ if the surface temperature anomaly increases by $1 \text{ K}$. Similar trends were also noted in the WAR, but the agreement between the model results and data of observations in this region is worse than in the European region (see also [4, 9]).

The results of model calculations indicate that the probability of the spreading of spring–summer droughts in mid-latitudes of the WER and WAR in the 21st century is higher relative to the 20th century [4]. In the 21st century, the corresponding drought index $D$ also increases for the WER. It is noteworthy that spring–summer climatic regimes in the WER and EER are significantly different, and the critical anomalies of temperature and precipitation should differ, in general. It is significant that the temperature sensitivity of $D$ increases in the study regions in the 21st century as compared to the 20th century. The general trends of the increasing temperature sensitivity of $D$ in the EER and WER are accompanied by different trends of variations in the corresponding indices of droughts with weaker conditions, i.e., only for temperature anomalies $D_T = D(\delta T)$ and only for anomalies of precipitation $D_P = D(\delta P)$. In the EER, a significant increase in the temperature sensitivity of $D_T$ is noted in the 21st century. In the WER, a significant decrease in the temperature sensitivity of $D_T$ is combined with a significant decrease in the temperature sensitivity of $D_P$.

To what extent can climate changes, including anomalies of temperature and hydrological regimes, influence carbon exchange and the bioproductivity of land ecosystems, in particular, the vegetation cover and potential for agricultural production in the North European regions? The rate of CO$_2$ transformation into organic matter by photosynthesizing vegetation is characterized by the general primary production of ecosystems. The intensity of CO$_2$ absorption from the atmosphere during photosynthesis (intensity of exchange between the atmosphere and continental biota) is characterized by net primary production (NPP). The rate of biomass deposition or net ecosystem production (NEP) is determined by the difference between NPP and heterotrophic respiration $R_H$: $\text{NEP} = \text{NPP} – R_H$ [10].

Interannual variations in NPP and NEP for the growth season (May–July) in the EER based on calculations using the IPSL-CM2 CGCM [6] are shown in Fig. 1a. The values of NPP and NEP obtained from calculations in version I using the complete model with account for all feedbacks (thin solid curves) and for version II (thin dashed lines) were normalized by their mean values in May–July for the 30-yr period from 1961 to 1990. Heavy curves denote the corresponding 30-yr running mean values of NPP and NEP. In the 21st century, a general increase in NPP and NEP along with the increase in their variability is manifested under the condition of very strong interannual variability, especially for NEP. The general increase in NPP and NEP in version I is smaller than in version II. According to the model calculation, the general increase in NPP and NEP in the EER is related to the intensification of photosynthesis with an increase in the CO$_2$ content in the atmosphere. Anthropogenic variations of climate lead to a significant decrease in NPP and NEP, especially in NEP.

The corresponding variations in normalized values of NPP and NEP obtained from calculations for the WER (46.1°– 53.2° N, 0°– 11.2° E) [6] are shown in Fig. 1b. Similarly to the EER, a general increase in NPP and NEP is manifested in the 21st century along with an increase in their variability under the condition of strong interannual variability, in particular, of NEP. The variability of normalized values of NPP is notably smaller in the WER than in the EER. It is noteworthy that the mean values of NPP in the WER are notably greater than in the EER. The difference between mean values of NEP in the WER and EER is not so large as for NPP. A general increase in NEP obtained from numerical calculations using the complete model (with account for all feedbacks, version I) is generally smaller than in version II. The differences between two numerical calculations for NPP in the WER are small: in the complete version I, the values of NPP are slightly greater than in version II. According to the obtained
results, the general increase in NPP in the WER is appreciably related to the increase of CO$_2$ content in the atmosphere, while anthropogenic changes of the climate lead only to a weak additional increase in NPP. As to the net production of ecosystems, anthropogenic climate changes in the WER lead to a significant drop in the increase of NEP.

Thus, according to the calculations, the general increase in the values of NPP and NEP in the 21st century in the WER and EER is considerably related to the intensification of photosynthesis under the condition of increasing contents of CO$_2$ in the atmosphere. However, anthropogenic climate changes in both European regions lead to a significant drop in the increase of biomass deposition (NEP). Anthropogenic climate changes lead to different variations in the intensity of CO$_2$ absorption from the atmosphere during photosynthesis (NPP) in different regions: the mean rate of NPP

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**Fig. 1.** Variations in the normalized values of NPP and NEP for (a) EER and (b) WER in May–July based on calculations using the IPSL-CM2 CGCM at an increase in the anthropogenic emission of CO$_2$ according to the SRES-A2 scenario with account for all feedbacks (version I, thin solid curves) and without anthropogenic climate changes (version II, thin dashed curves). The values are normalized by their mean values in May–July for a 30-yr period from 1961 to 1990. Thick curves show the corresponding 30-yr running mean values for NPP and NEP.
growth decreases notably in the EER and slightly increases in the WER. It is important that the general increase in NPP and NEP (in the EER and WER) is accompanied by an increase in their variability. The greatest relative variability was found for NEP, especially in the EER.

Analysis of the correlation of the characteristics of carbon exchange and bioproductivity of land ecosystems with the drought regimes based on model calculations revealed a notable decrease in NPP in the EER in the 20th century as a response to an increase in the drought index $D$ [5]. At the same time, no notable correlation between NPP and $D$ was found in the EER for the 21st century. This can be interpreted as a decrease in the influence of meteorological (atmospheric) droughts on the intensity of exchange between the atmosphere and continental biota in the 21st century at an increase of the CO$_2$ content in the atmosphere.

Figure 2 shows the correlation coefficients between NPP versus (a) precipitation $P$ and (b) moisture content in the soil $W$ in May–July in the EER based on the calculations using the IPSL-CM2 CGCM for different
According to Fig. 2, the general weakening of the correlation between NPP and \( P \) in the model is accompanied by a general intensification of the correlation between NPP and \( W \) during the period of vegetation growth in the 19th–21st centuries. Similar effects were also recorded in the WER. The results of calculations suggest the variation in the relative influence of the atmospheric (meteorological) and soil droughts on the intensity of exchange between the atmosphere and continental biota, as well as on the formation of agricultural droughts, in particular. It is noteworthy that significant long-term variations appear in the characteristics of the correlation of NPP with \( P \) and \( W \) against the background of the general trends mentioned above. In particular, an opposite trend is observed from the end of the 20th century and in the first half of the 21st century: the NPP shows an increase in correlation with \( P \) and decrease in correlation with \( W \).

In general, calculations based on the climatic model with the carbon cycle indicate that the bioproductivity of land ecosystems in the analyzed mid-latitudes of Eurasia increases with the increase of anthropogenic emission. This is related to the increase in biospheric productivity with the increase of \( \text{CO}_2 \) content in the atmosphere, despite the unfavorable changes in the regional climate and the intensification of the drought regime. Model results indicate changes in the type of regional droughts in the presence of global warming. As compared to the model estimates in [11] for variations in the bioproductivity of vegetation cover in the regions of North Eurasia caused by anthropogenic changes, the calculations presented here take into account the feedbacks in the model blocks of the carbon cycle and climate. Our model takes into account not only the anthropogenic influence on the climatic regime (including the biosphere), but also the influence of biospheric changes on climatic characteristics.

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