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MODELING THE IMPACT OF CLIMATIC CHANGE ON REGIONAL ECOSYSTEMS

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PREFACE

For several years researchers at IIASA have been investigating that most crucial of interactions between man and the biosphere -- the interaction between climate and society.

In 1978, for example, a meeting was held on "Carbon Dioxide, Climate and Society". This meeting brought together experts from around the world to assess the state of knowledge on the prospects of climatic change resulting from increasing atmospheric injections of carbon dioxide and in particular to review work on this subject in the IIASA Energy Systems Program. In the same year, IIASA hosted the International Workshop on Climate Issues organized by the Climate Research Board of the US National Academy of Sciences and a preparatory meeting for the World Climate Conference organized primarily by the World Meteorological Organization (WMO) of the United Nations. In 1980, a Task Force meeting on the Nature of Climate and Society Research was convened to advance our knowledge of the relationship of climate to specific aspects of physical and social systems. More recently, in 1982, an international workshop on "Resource and Environmental Applications of Scenario Analysis" was organized. Now, a major 2-year project is being implemented with the support of the UN Environmental Programme. This project is investigating the impacts of short-term climatic variations and the likely long-term effects of CO_2-induced climatic changes on agricultural output at the sensitive margins of food grains and livestock production.[1]

As a part of this project, IIASA is also concerned with the effect of climate variations on ecosystem margins. One of the ecological models which is providing inputs to the project is that developed at the All-Union Institute for Systems Studies (VNIISI).[2] A full description (in Russian) of the model has just been completed, but

[1] For a description of the methodology behind this project, see Parry and Carter (1983), Assessing impacts of climatic change in marginal areas: the search for an appropriate methodology, IIASA Working Paper, WP-83-77.

[2] A sensitivity study of this model is reported in Watts (1984), Predicting changes in crop yield due to CO_2-induced climatic change – some cautionary comments, IIASA Working Paper, WP-84-15.

will probably not be available in English for some months. The brief English description (Kroutko *et al.*, 1982) does not define all the terms employed by the authors in the present paper; and to do so in this text has not always proven possible. As a result, readers will on occasion be given a tantalizing glimpse of the results of some model runs without having a full explanation of their meaning. I ask for their indulgence, but wish to emphasize that, while realizing these shortcomings, we nevertheless believe it is valuable to report this work in progress. That being said, the authors emphasize that the results reported here are preliminary.

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Leader
Climate Impacts Project

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MODELING THE IMPACT OF CLIMATIC CHANGE ON REGIONAL ECOSYSTEMS

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Climate is one of the most important environmental considerations in understanding ecosystems and human activities. Historical climatic changes on Earth have significantly altered its flora and fauna. For example, two million years ago the Neogene subtropical vegetation in the middle latitudes was replaced by Pleistocene continental glaciers which had moved to 48° N in Europe. Simultaneously, a decrease in sea level of more than one hundred meters relative to the present sea level drastically changed continent and ocean configurations.

More recently, and as seen over the shorter term (i.e. the last 100 years), climatic changes occur on a more modest scale. For example, the fluctuation of the mean annual surface air temperature in the Northern Hemisphere has not exceeded ± 0.5° C over the last one hundred years. However, such seemingly small fluctuations can have a major impact on the natural and human environment. For example, total crop production for approximately the same planted area in the USSR was 140 million tons in 1975 and 223 million tons in 1976 (MSD, 1977). Most was probably directly or indirectly (i.e. via disease and pests) the result of different weather conditions. For the USA, Lepper *et al.* (1974) have estimated that corn production would decrease by about 11% for each 1° C increase in average maximum temperatures over the combined summer months.

Similar impacts might be expected for natural ecosystems. Considering the locations of present day environmental zones it becomes obvious that there can exist a broad spectrum of ecosystems for a relatively narrow climatic range. The biome type gradually changes from forests to semi-deserts as we progress from areas with mean annual temperatures of 3° C towards those with corresponding values of 8° C (Whittaker, 1970). The increasing influence of human activity on climatic variability and change makes the investigation of the natural and agricultural ecosystems' responses to these changes an urgent task. The aim of this paper is to investigate some of these responses with the use of an ecological model for selected zones in the European USSR.

CLIMATIC CHANGES CAUSED BY NATURAL AND ANTHROPOGENIC FACTORS

Figure 1 shows a time series of mean annual surface air temperature in the Northern Hemisphere for the last hundred years. This time series has been analyzed by numerous scientists, among them Vinnikov and Groisman (1979), who have argued that this series can be considered a combination of *stochastic* and *deterministic* variables. The stochastic component results from the instability of oceanic and atmospheric circulation. Annual averaging of the series values significantly reduces the stochastic component's contribution to the deviation from the mean of the Hemisphere's temperature. As the time period becomes shorter and the regions become smaller, the role of the stochastic component becomes increasingly significant.

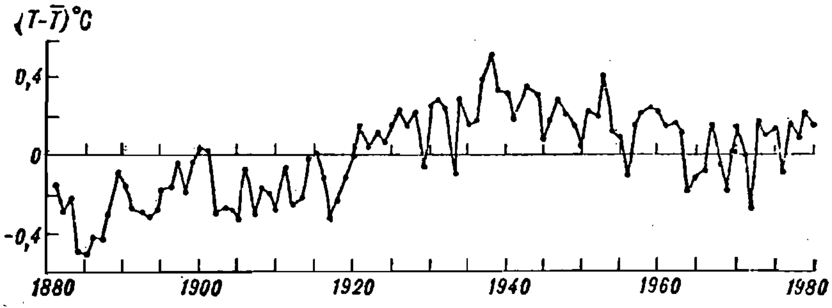


Figure 1. A time series of mean annual surface air temperature in the extra-equatorial region (17.5°-87.5° N) of the Northern Hemisphere for the last one hundred years (Sov-Amer, 1982).

The deterministic component is conditioned by changes in atmospheric transparency and in the atmospheric CO_2 content. Changes in atmospheric transparency are mainly caused by changes in the amount of stratospheric aerosol resulting from volcanic activity. Figure 2 depicts the fluctuations of atmospheric transparency for the last hundred years. According to estimates made by Budyko et al. (1981) the probability for five-year running mean hemispheric deviations exceeding 0.25° C caused by natural factors (including those other than atmospheric transparency) is negligible.

Increasing atmospheric CO_2 content is primarily the result of many different anthropogenic activities such as fossil fuel combustion (being the major contributor, *vide* Sov-Amer, 1982), deforestation, and land use change. The scientific measurements of atmospheric CO_2 concentration between 1958 and 1979 show an increase from 315 ppm to 336 ppm (Machta, 1979). According to the most recent estimates (Sov-Amer, 1982), the CO_2 concentration one hundred years ago was about 290 ppm. Vinnikov and Groisman (1982) analyzed Bryson and Goodman's

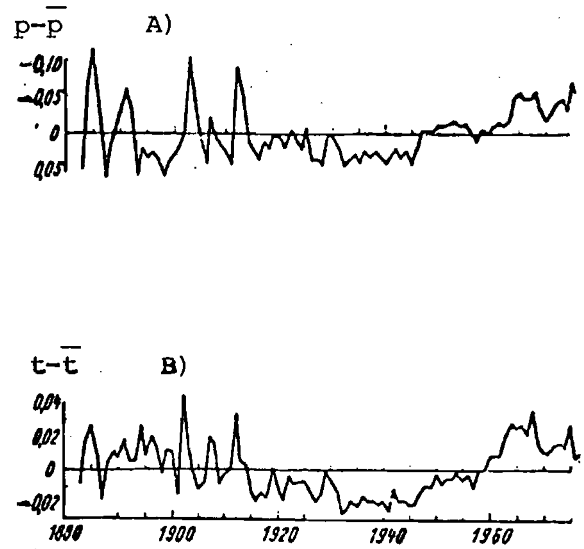


Figure 2. A comparison of two time series of atmospheric transparency (p) and turbidity (t) for the last one hundred years. From Vinnikov and Groisman (1982), after
a) Pivovarova (1976) for atmospheric transparency (p)
b) Bryson and Goodman (1980) for atmospheric turbidity (t).

(1980) and Pivovarova's (1976) data regarding changes in atmospheric transparency. They have identified a response of the Northern Hemisphere's surface air temperature to variations in atmospheric transparency and in atmospheric CO_2 content. Their analysis suggests that the increase in atmospheric CO_2 over the last one hundred years has already resulted in an increase of the Hemisphere's mean annual surface air temperature of 0.4-0.6° C. Their analysis also disproved (by the F-criteria with the probability exceeding 99%) the hypothesis which states that changes in CO_2 concentration do not bring about changes in the Hemisphere's mean annual surface air temperature. In this paper we will examine the ecological impact of climatic change due only to CO_2 increase since this seems to be the dominant factor of climate change.*

*Global warming would probably be more intensive if trace gases of anthropogenic origin (ozone in the troposphere, CH_4, N_2O, etc.) were taken into consideration (Ramanathan, 1975; Hameed et al., 1980).

THE RATE OF CO_2 PRODUCTION AND CO_2 CONCENTRATION IN THE ATMOSPHERE

A forecast of CO_2 concentration in the atmosphere is based on an energy growth production scenario and a carbon cycle model. One of the better known of these scenarios is IIASA's Energy Systems Program Scenario (IIASA, 1981). According to this scenario, carbon dioxide emission will increase from 7 - 8 x 10^{15}gc/y to 10 - 17 x 10^{15}gc/y between the years 2000 and 2030. At present, approximately 50% of produced CO_2 remains in the atmosphere (Sov-Amer, 1982).**

Carbon cycle modeling has been undertaken by numerous scientists during the past few years (see, for example, Broecker et al., 1980; Byutner et al., 1981). The general conclusion of these studies has been that approximately 60% of all industrial CO_2 emitted will remain in the atmosphere for the next 100 years.

Niehaus (IIASA, 1981) computed that IIASA's CO_2 Emission's Scenario would result in a CO_2 concentration between 365 and 380 ppm in the year 2000 and between 430 and 550 ppm (Figure 3) in the year 2030, with high and low estimates corresponding to IIASA's high and low energy scenarios.

ESTIMATES OF THE SENSITIVITY OF MODELS TO CO_2 INCREASES

It is well known that an increase in atmospheric CO_2 concentration will increase the amount of the long-wave radiation absorbed by the atmosphere. The troposphere becomes warmer but, in order to maintain a radiative equilibrium, the stratosphere cools. This phenomenon has been simulated, using climate models which range in detail from one-dimensional latitude or vertical structure models to more complex general circulation models. The results of these simulations have suggested that the mean annual surface air temperature for the globe could increase in the order of 2-3° C with a doubling of CO_2 (Sov-Amer, 1982).

**2.124 x 10^{15}g of carbon is equivalent to 1 ppm CO_2 concentration in the atmosphere.

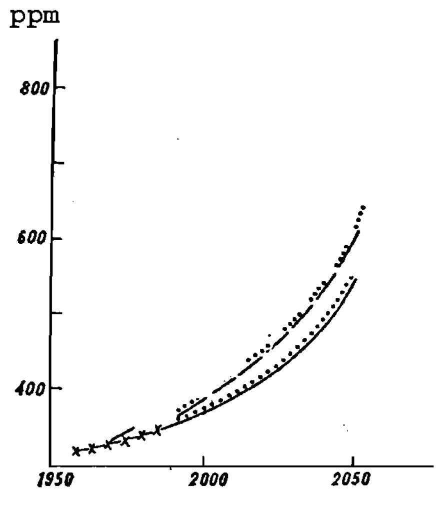


Figure 3. CO_2 concentration for the IIASA high and low energy scenarios (From Sov-Amer (1982), after IIASA (1981)).

Let T_c be a function of the global temperature equilibrium corresponding to the given concentration of atmospheric CO_2. Results of simulations show that T_c is approximately proportional to the logarithm of concentration for a considerable range of CO_2 concentration (Sov-Amer, 1982). This can be stated as follows:

$$T_c - T_o = \delta T_c \log_2(n(t)/n_o) \qquad (1)$$

where n(t) and n_o are the present day and preindustrial concentrations of CO_2, respectively, T_o is the preindustrial mean annual global temperature, and δT_c is the increase of the equilibrium temperature for a doubling concentration of CO_2 relative to preindustrial levels. Later in this paper we will use this formula to estimate T_c.

Three-dimensional dynamic models can realistically describe present climate. They incorporate the main physical processes which might induce a global warming such as decrease of atmospheric transparency to long-wave radiation, a connection between the temperature and the water vapor content of the atmosphere, decrease in albedo at high latitudes due to ice melting and dependence of cloud cover on water vapor concentration in the atmosphere. Many climatologists believe that further model improvements will not affect the qualitative character of the final results (e.g., Sov-Amer, 1982). The numerical results can be compared with independent results obtained using empirical methods based on paleoclimatic and current climatic data.

The empirical methods give an estimate for δT_c of about 2-3.5° C (Budyko et al., 1983) which is in agreement with model computations.

THERMAL INERTIA AND THE DELAY OF THE GLOBAL WARMING

At present one of the most disputed questions in climate research concerns the extent of the lag time of global warming associated with the climate system's thermal inertia. The interactions between the atmosphere and the ocean would probably delay any warming caused by the increase of CO_2 concentration. This inertia is connected to the heat capacity of the upper quasi-homogeneous ocean layer and to the processes of this layer's interaction with the deeper oceanic layers. The inertia assessments derived from numerical climatic models (Hunt and Wells, 1979) satisfactorily correspond to the empirical data of modern climatic changes (Budyko, 1980; Oliver, 1976), suggesting a time delay for the response of mean annual surface air temperature of approximately 10 years.

However, present uncertainties surrounding oceanic heat exchange relationships may lead to an increase in the modeled time delay, and this important problem demands more detailed consideration (Carbon Dioxide Assessment Committee, 1982). Nonetheless, if we accept the given scenario of the increase in atmospheric CO_2 (Figure 3), and if we assume that the dependence of the mean annual global temperature increase related to the increased concentration of CO_2 satisfies equation (1) which has $\delta T_c \approx 3^\circ C$ and also accept that the time delay due to thermal inertia is about 10 years, we arrive at the scenarios of global temperature increases given in Table 1.

Table 1. Global temperature change in response to projected increases in atmospheric CO_2 for IIASA high and low scenarios.

Years	2000	2010	2020	2030
	temperature change $\delta T(^\circ C)$			
High Scenario	.9	1.2	1.6	2.2
Low Scenario	.8	1.0	1.2	1.4

EMPIRICAL ESTIMATES OF REGIONAL CLIMATIC CHANGE

To evaluate the ecological consequences of these hypothesized climatic changes, we need a regional estimate of the changes in various climatic parameters. Similar evaluations can, in principle, be obtained using a detailed three-dimensional dynamic model. However, because of the impractical demands on computer time required to achieve an adequate spatial resolution, estimates of temperature change for different geographic regions are considerably less precise than estimates of the global thermal regime.

Alternatively, the quantitative information about local climatic changes which accompany global scale climatic changes might also be obtained by undertaking statistical assessments of the empirical data about climatic changes during the period of instrumental meteorological observations as well as statistical assessments of available paleoclimatic data.

Vinnikov and Groisman (1979) derived a relatively simple statistical model connecting global and local climatic variables:

$$T_i(t)=\alpha_i T(t)+\beta_i+\varepsilon_i(t) \tag{2}$$

where t is the time, i is a number of local climatic characteristics, T(t) is the evaluation of a mean annual air temperature within the extra-equatorial part of the Northern Hemisphere (17.5 - 87.5° N. Lat.), $T_i(t)$ is an evaluation of local climatic characteristics (not only temperature), $\varepsilon_i(t)$ is a random error comprising the error of estimating the variable of y_i , i.e. (T_i-y_i) as well as the independent on T(t) of the component y_i ; α_i is a dimensionless parameter; and β is the regular error. The parameter α and its associated confidence intervals have been estimated by Vinnikov and Groisman (1979) using the "instrumental variable" method for Northern Hemisphere mean annual zonal air temperature (Table 2).

Table 2. Estimates and 95% confidence intervals of parameter α required to evaluate the empirical model of the change in Northern Hemisphere zonal air temperature (Eq. 2). Source: Vinnikov and Groisman (1979).

	Latitude (degree)													
	85	80	75	70	65	60	55	50	45	40	35	30	25	20
α	2.1	2.5	2.4	2.3	1.9	1.1	1.1	1.0	1.0	0.8	0.8	0.6	0.5	0.4
Λ	3.5	3.7	3.2	2.9	2.4	1.6	1.4	1.4	1.3	1.0	1.0	0.9	0.7	0.6
V	0.8	1.2	1.6	1.7	1.4	0.6	0.7	0.7	0.7	0.6	0.6	0.5	0.3	0.2

Groisman (1981) used the same method for studying the changes in precipitation regimes for 39 different regions in the USSR (Figure 4), the regions being identified according to the relationship between the regional mean annual precipitation and the mean annual surface temperature of the Northern Hemisphere (extra-equatorial part) (Table 3). These calculations are based on data for the past century which, as previously stated, have been characterized by an approximate 15%

change in CO_2 concentration, and mean annual temperature fluctuations within a range of ± 0.5° C.

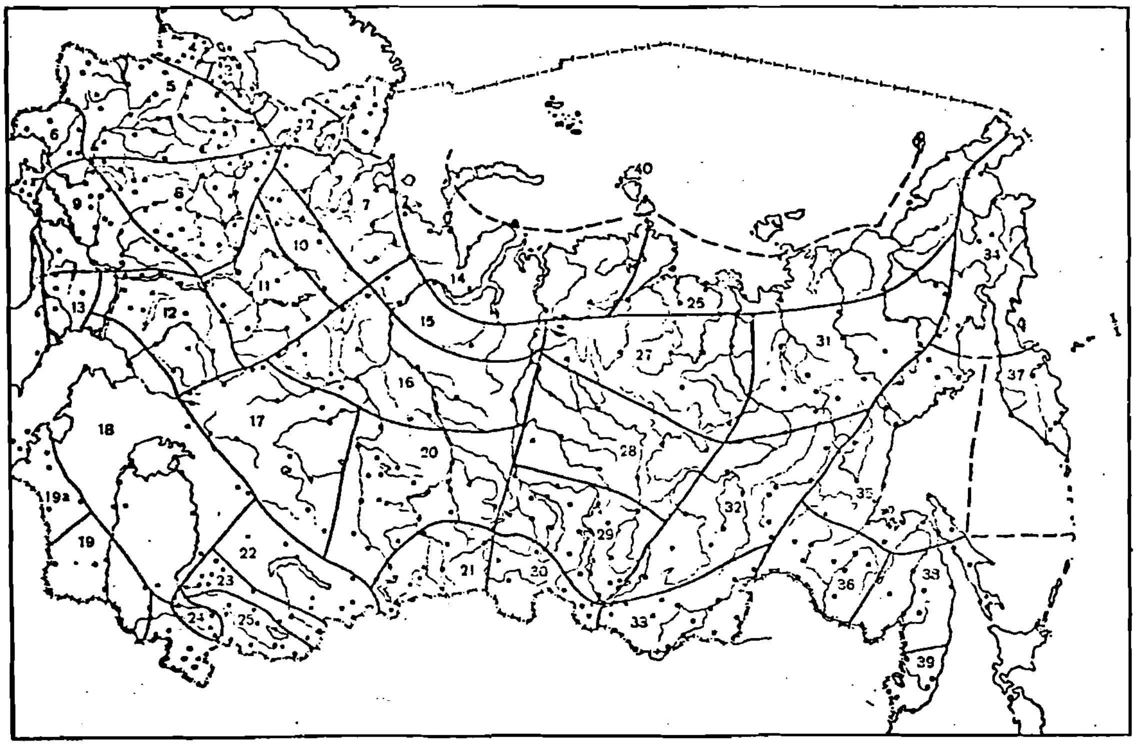


Figure 4. Regions where the relationship between precipitation and the Hemisphere's temperature has been studied (Groisman, 1981).

Table 3. The parameter of linear relationship between regional precipitation and global temperature.

Region Number	Normal Precipitation (mm/year)	α (%/0,1°C)	Region Number	Normal Precipitation (mm/year)	α (%/0,1°C)
1	450	-1.9	16	500	1.5*
2	550	0.7	17	280	-2.7*
3	570	-0.4	18	150	-1.6
4	620	-1.1	19	160	1.0
5	600	-1.6*	20	420	1.2
6	480	2.5*	21	440	2.5*
7	510	1.7	22	230	1.7**
8	540	-0.5	23	390	1.8**
9	180	0.1	29	410	1.6*
10	550	-0.6	33	390	2.0*
11	560	0.3	36	570	2.6*
12	340	-0.6	38	720	0.4
13	460	-1.7	39	640	1.6

*90% confidence interval does not contain the zero point.
**estimates of low accuracy.

A comparison of empirical and theoretical estimates of the mean annual zonal air temperature for the Northern Hemisphere for a doubling of the CO_2 content has been made by Vinnikov and Groisman (1982) (Figure 5). A similar comparison for the mean annual zonal amount of precipitation was made by Budyko et al. (1983) (Figure 6). That these two results are close gives us a chance to use empirical estimates for a wider range of CO_2 concentrations as compared to the range for which they were originally obtained.

Such an extrapolation, however, must be done within reasonable boundaries. For example, the use of empirical estimates associated with the quadrupling of the CO_2 concentration results in the disappearance of the seasonal temperature cycle in the high latitudes.

We assume that the empirical estimates can be considered the basis for regional climatic forecasts, if the average global temperature increases by 1-1.5° C. According to the global warming scenario shown in Table 1, it is possible to use these estimates for the purpose of ecological modeling for the time horizon up to 2010-2020.

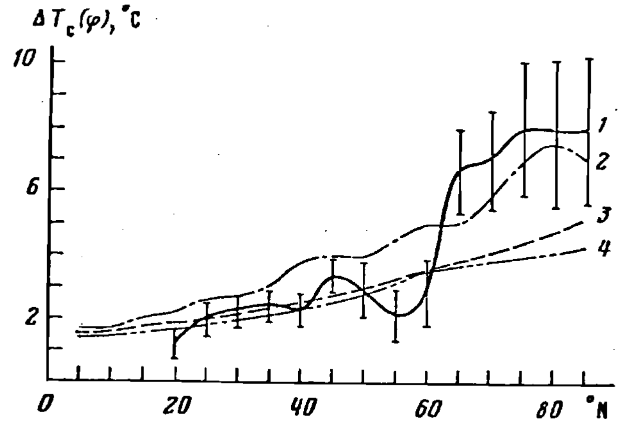


Figure 5. Mean annual zonal air temperature changes for the Northern Hemisphere due to doubling of CO_2 concentration (after Vinnikov and Groisman, 1982).
1) empirical estimates (Vinnikov and Groisman, 1982).
2) numerical computation (Manabe and Wetherald, 1980).
3) numerical computation (Wetherald and Manabe, 1981).
4) numerical computation (Manabe and Stouffer, 1980).

We can also use paleodata for estimating local climatic changes due to the twofold or greater increase of CO_2 concentration estimated to occur by 2030-2050. Budyko et al. (1978) used pliocene climatic information that appears to correspond to the above mentioned global warming (although it is not certain that the pliocene warming was caused by a similar phenomenon). The pliocene climatic optimum is of interest because the position of continents then was similar to that today. Budyko used the paleoclimatic map of Sinitsyn (1967) for extra-tropical latitudes in Eurasia and North America. Sinitsyn's data are characterized by a twofold increase in the CO_2 concentration for the late pliocene. Taking carbon sedimentation rates to be valid indicators of atmospheric CO_2 (Monin and Shishkov, 1980), Budyko and Ronov (1979) estimated the CO_2 concentration for that period from the values of

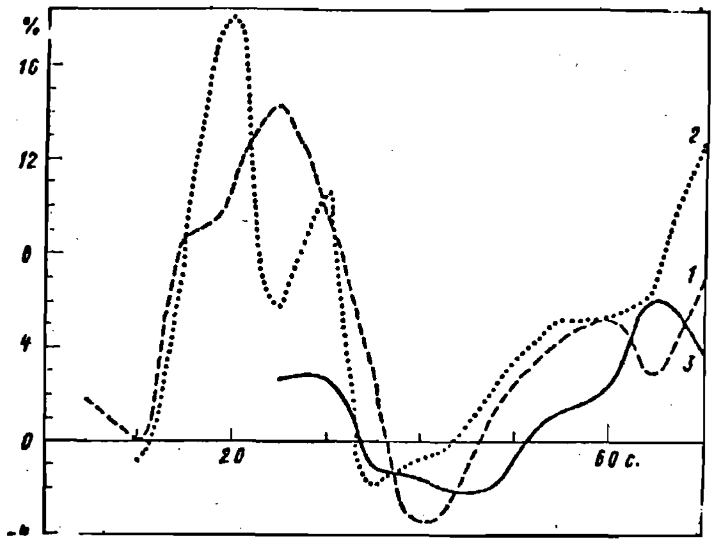


Figure 6. The relative change of mean zonal precipitation at continents due to CO_2-produced 1° C warming of the Northern Hemisphere (after Budyko et al., 1983).
1) numerical computations (Manabe and Wetherald, 1980).
2) empirical estimates (Budyko et al., 1983).
3) paleoclimatic data (Sov-Amer, 1982).

carbonate sedimentation rates to be 550 ppm. Figures 7 to 9 show the differences in air temperatures between the pliocene and the present as well as the difference in the annual total amount of precipitation for the European part of the USSR. The combining of empirical and paleoclimatic estimates gives us the opportunity to develop scenarios of regional climatic changes up to the year 2030.

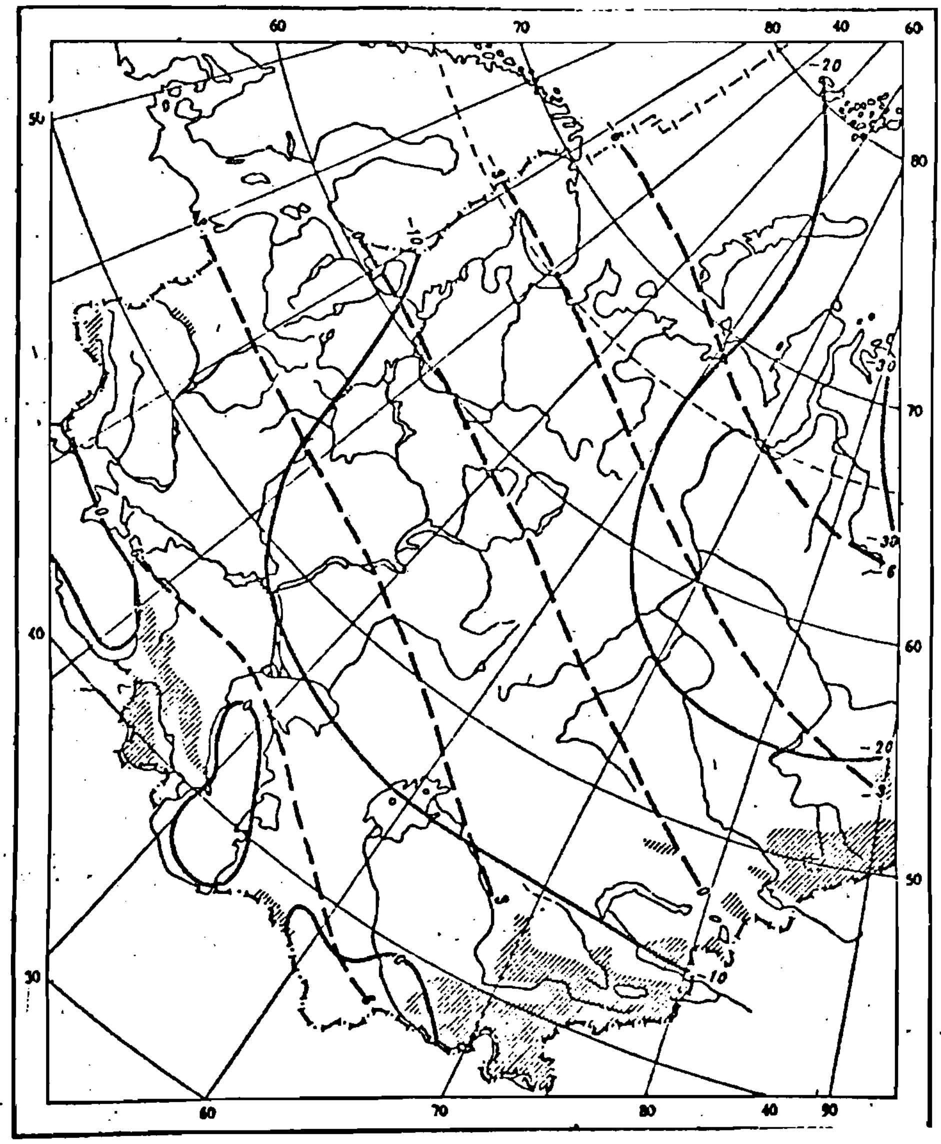


Figure 7. Mean monthly temperature. January.
[Solid lines are present-day isotherms, dashed lines are isotherms under the CO_2 scenario for the year 2030 (after Budyko et al., 1978).]

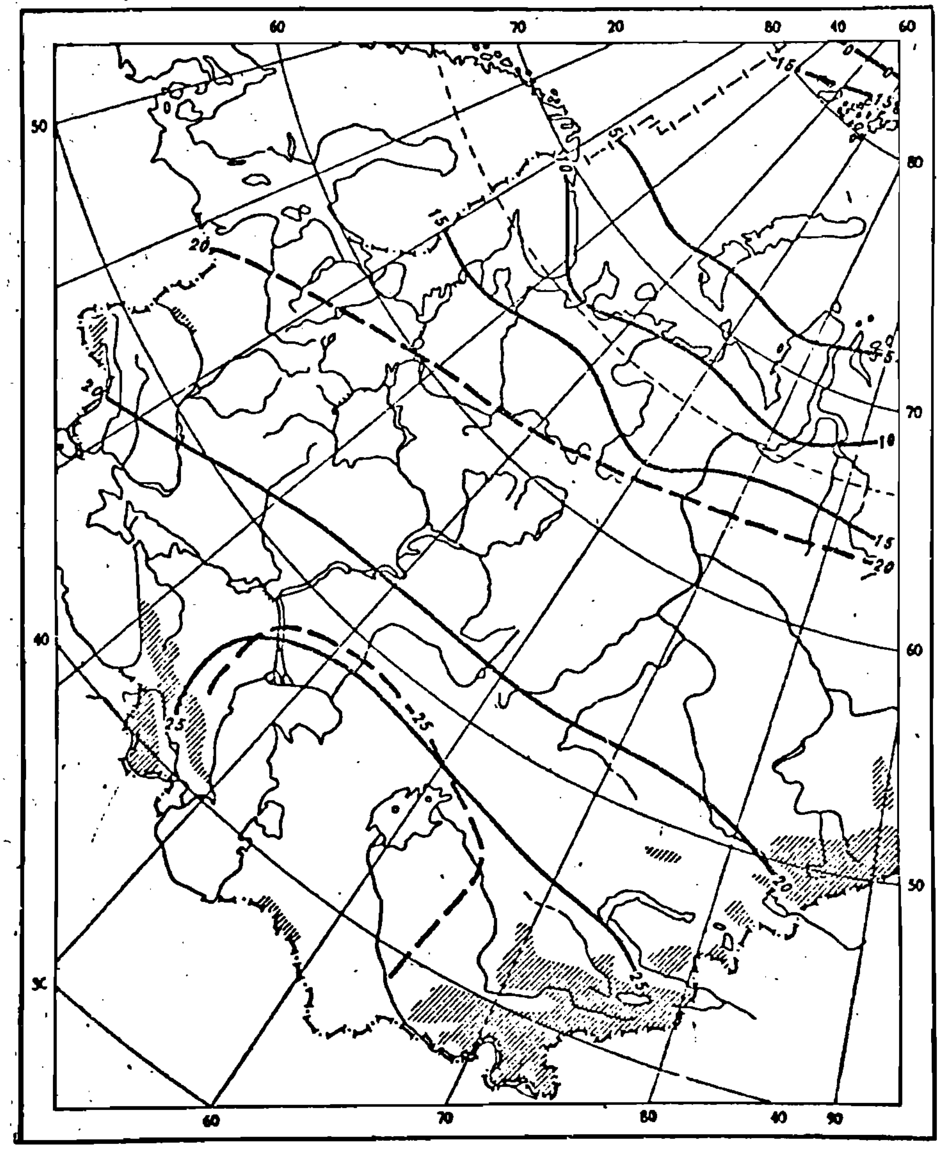


Figure 8. Mean monthly temperature. July.
[Solid lines are present-day isotherms, dashed lines are isotherms under the CO_2 scenario for the year 2030 (after Budyko et al., 1978).]

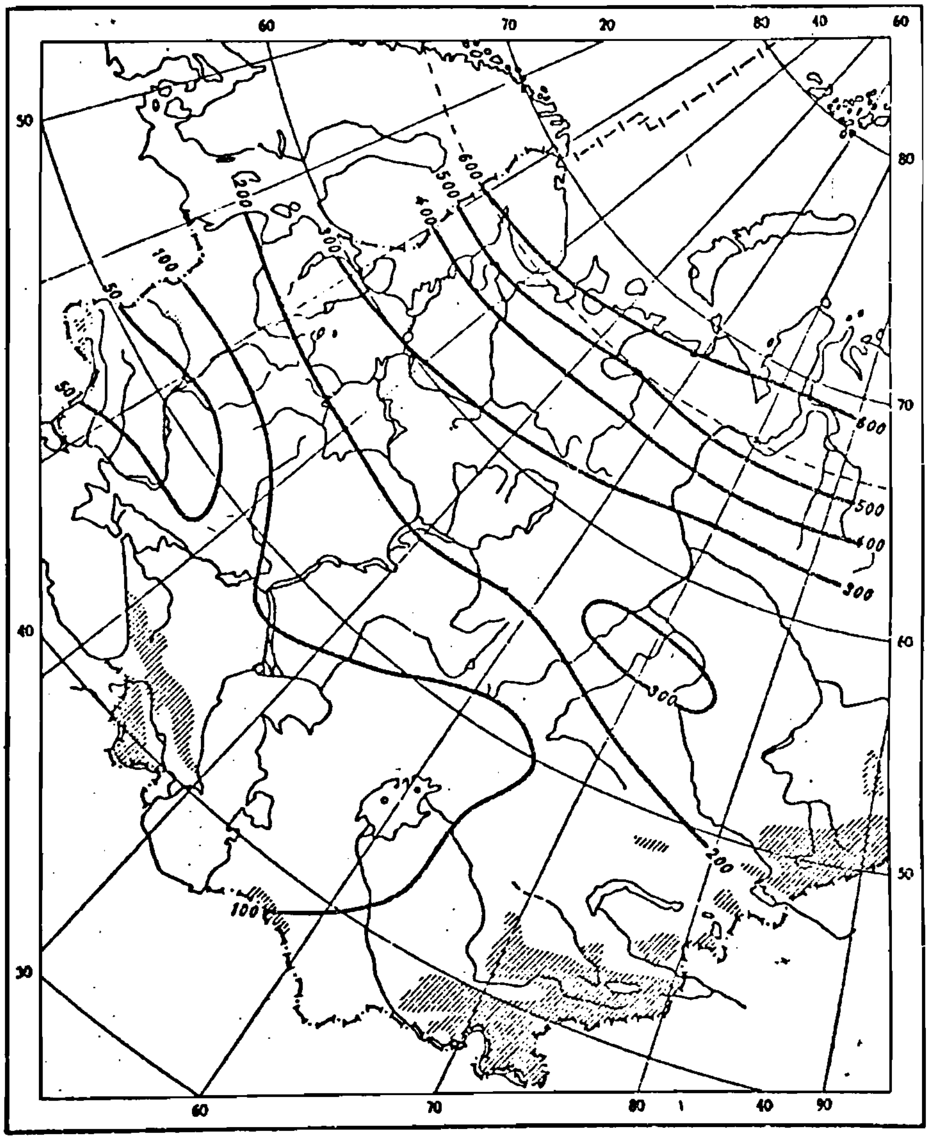


Figure 9. Mean annual precipitations predicted for 2030 (after Budyko et al., 1978).

ECOLOGICAL MODELING

The forest-tundra in the northern part of the USSR (region 7 in Figure 4), the mixed forest in the central part of the European region of the USSR (region 8), and the Northern Khazakhstan steppe (region 17) have been chosen for the modeling of dynamic environmental factors. The ecological model used for modeling was developed in the All-Union Institute for Systems Studies (Moscow). The model is outlined in Krutko et al. (1982), with a full description in Pegov et al. (1983 - forthcoming). Taking into consideration the empirical and paleoclimatic assessments for these regions (see Pegov et al., 1983), it is feasible to develop regional scenarios based on changes at the regional level in the values of the mean annual temperature and precipitation that might correspond to the high and low scenarios of global temperature changes (Table 4).

Table 4.

	Region N7		Region N8		Region N17	
	ΔT°	Changing of precipitation (mm/year)	ΔT°	Changing of precipitation (mm/year)	ΔA	Changing of precipitation (mm/year)
2000 YEARS						
High Scenario	1.7	76	1.0	-24	0.9	-67
Low Scenario	1.5	69	0.9	-22	0.8	-60
2010 YEARS						
High Scenario	2.3	102	1.3	-32	1.2	-90
Low Scenario	1.9	87	1.1	-27	1.0	-76
2020 YEARS						
High Scenario	3.0	138	1.8	-43	1.6	-120
Low Scenario	2.3	102	1.3	-32	1.2	-90
2030 YEARS						
High Scenario	$\approx$8.0 *	100*	$\approx$5.0 *	-200*	3.0*	-150*
Low Scenario	2.7	122	1.5	-38	1.4	-100

*Paleoclimatic data.

Preliminary results from these numerical experiments suggest the following:

1) The qualitative behavior of the changes in the main environmental components for low and high estimates of potential warming are similar.

2) The specific character of the regions determines the direction of environmental changes.

3) The amount of warming within the specific limitations on temperature and precipitation (as determined by the scenario) influences only the rate of the environmental changes. Thus, we shall consider simultaneously the environmental changes for both climatic scenarios in each region.

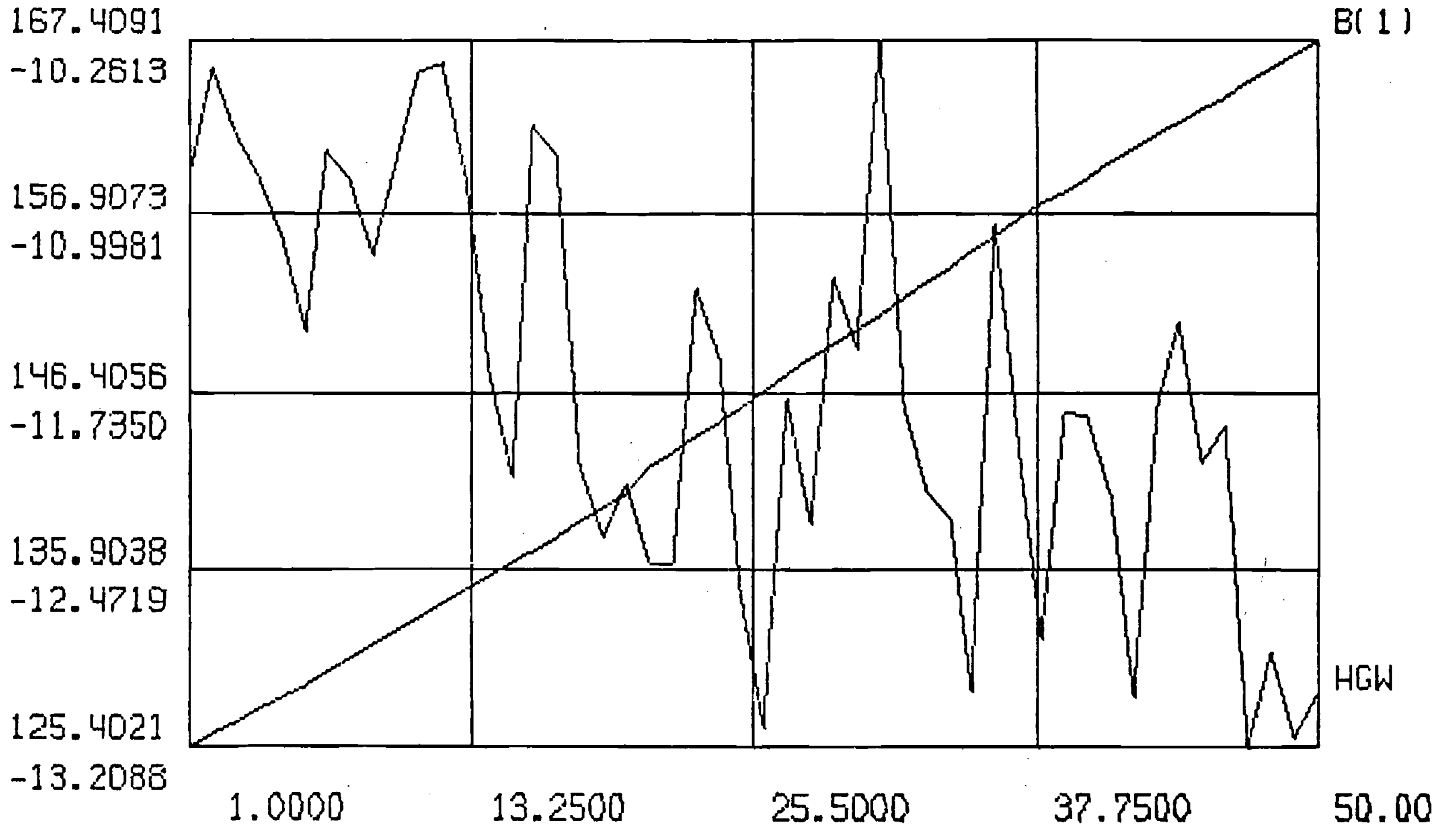
THE FOREST-TUNDRA REGION OF THE NORTHERN PART OF THE USSR

According to the low scenario, warming is accompanied by an increase in precipitation. The biomass of natural ecosystems increases from 120 to 160-170 tons/hectare. The soil index (a measure of soil fertility ranging from 1 to 20) increases slightly up to approximately 10 units. In spite of the increase in precipitation, the increase in stream flow will be greater than the increase in ground water level. Because of this phenomenon, the creation of swamps in the area decreases, and the ground water level declines. In summary, the main consequences of potential warming are:

1) Replacement of ecosystems of the forest-tundra by the Northern taiga ecosystems.

2) An increase of the biomass of ecosystems, and

3) A decrease in the ground water levels (Figure 10).



YEARS

Figure 10. The forest-tundra region (low scenario).
B(1) is the biomass of natural ecosystems (in tons/hectare).
HGW is the ground water level (in meters).

THE MIXED FORESTS OF THE CENTRAL PART OF THE EUROPEAN TERRITORY OF THE USSR

According to the low scenario, decreased precipitation is associated with a warming (Table 4). Mixed forests are replaced by broad-leaf forest. The biomass of natural ecosystems increases from about 200-230 tons/hectare to about 300-325 tons/hectare. The soil index is raised from 7 to 10 units which is similar to a replacement of turf-podzol soils by grey forest soils. Streamflow decreases and ground water levels sink in the order of 1.5-2 meters. Agricultural conditions also improve. The soil index increases from 4 to 4.6 units (Figure 11). The average minimum yield for cereal crops (i.e. without technological inputs, under natural conditions) increases from 900 to 1200 kg/hectare (Figure 12).

THE NORTHERN KHAZAKHSTAN STEPPE

The warming in this low scenario is accompanied by a decrease in precipitation (Table 4). The natural ecosystem biomass decreases from 18 to 10 tons/hectare. The soil index decreases from 17 to 15 units, corresponding to the replacement of the steppe by the dry steppe ecosystem. Agricultural conditions worsen but the soil index of agricultural ecosystems falls only slightly (Figure 13). The reduced moisture results in the fall of minimum yields from 1300 to 1100 kg per hectare. Streamflow falls from 50 to 10 mm/year, thus substantially affecting the potential for irrigation (Figure 14).

CONCLUSIONS

The scenarios presented here suggest that CO_2-induced warming is likely to be accompanied by marked shifts of ecosystem boundaries and marked changes in agricultural potential in the European part of the Soviet Union. It should be emphasized, however, that these are preliminary results. Further work is necessary to enable more extensive analysis.

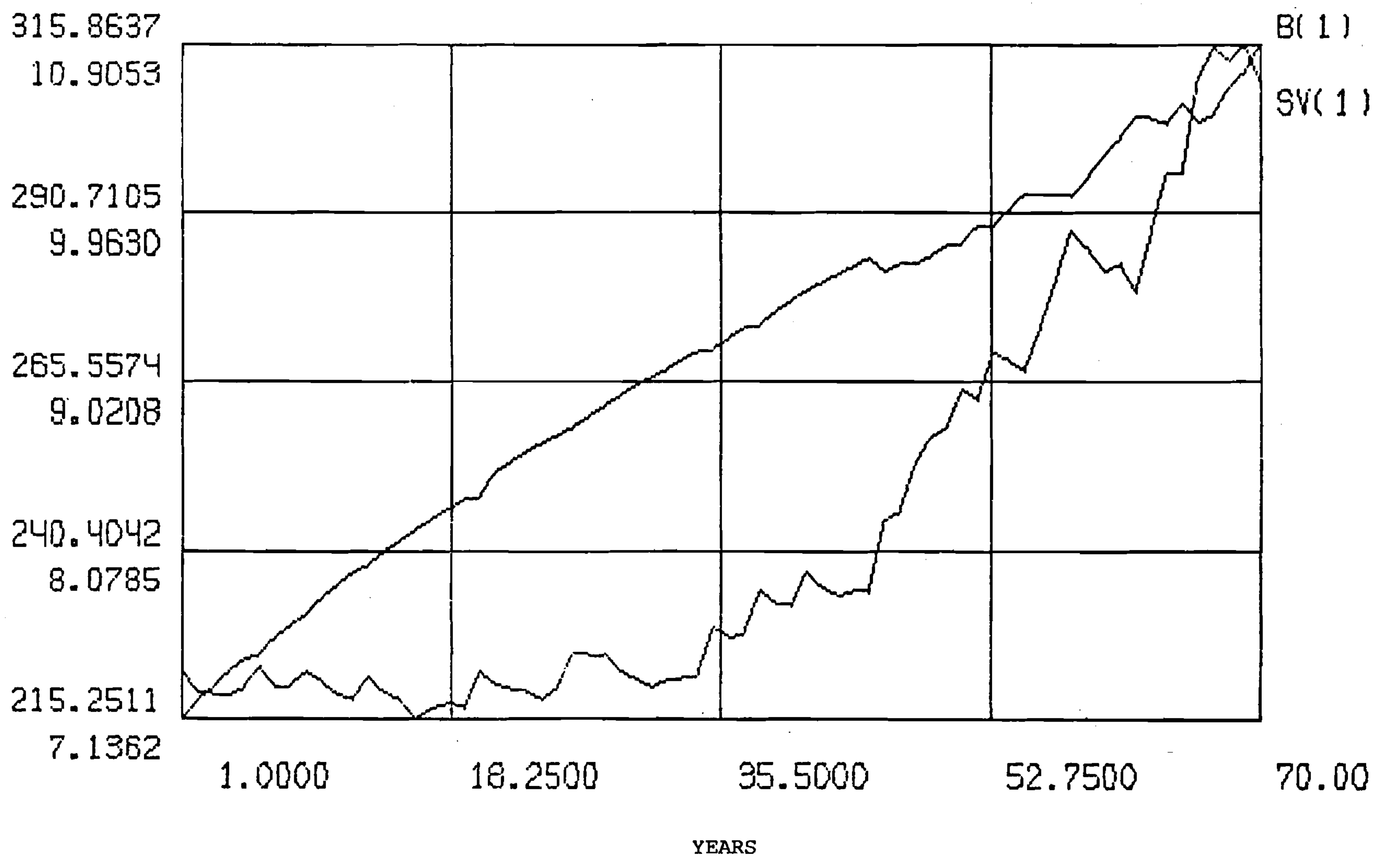


Figure 11. The mixed forest region (low scenario).
B(1) is the biomass of natural ecosystems (in tons/hectare).
SV(1) is the soil index of natural ecosystems.

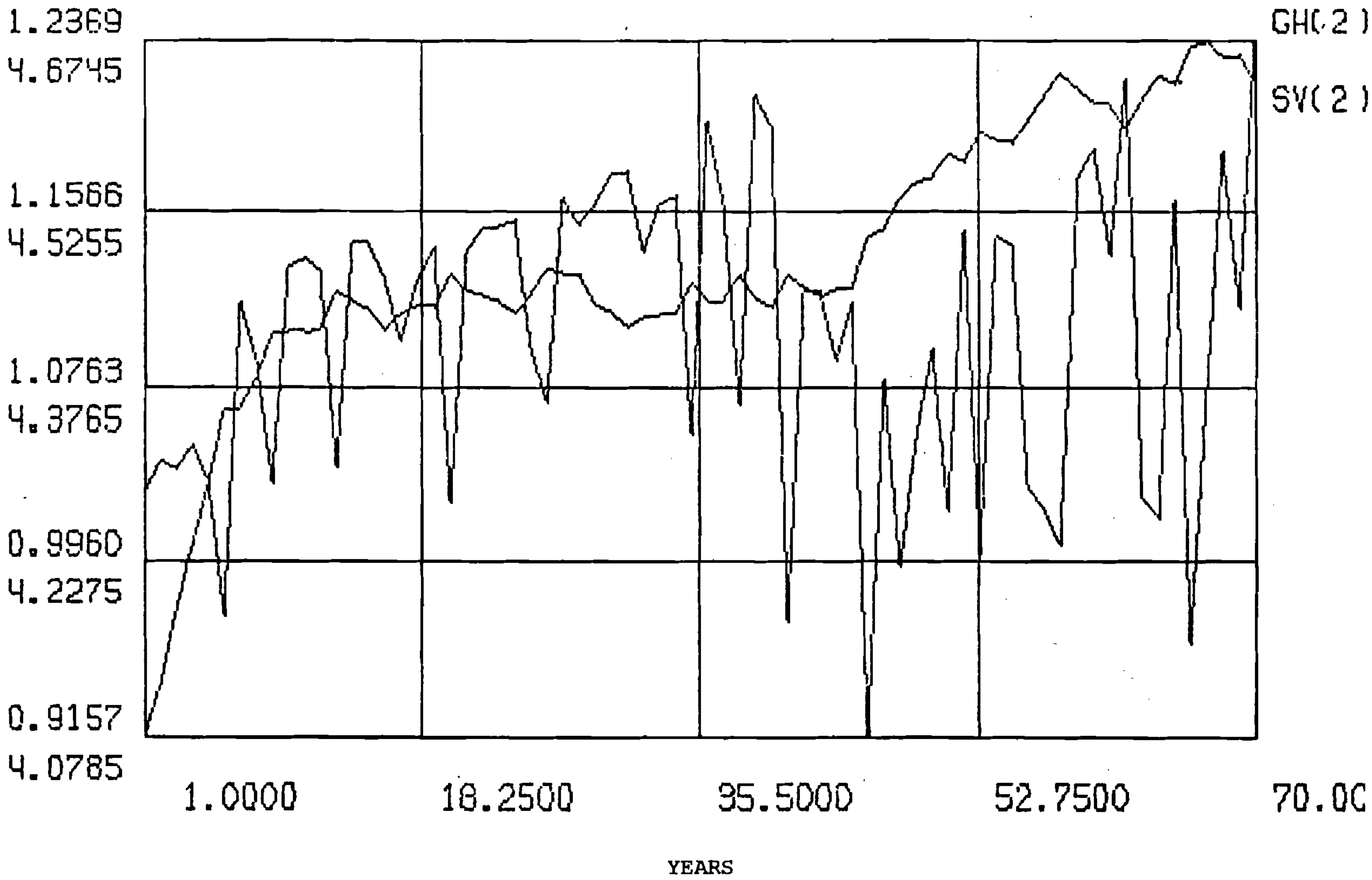


Figure 12. The mixed forest region (low scenario).
GH(2) is the crop yield under natural conditions (in 100 kg/hectare).
SV(2) is the soil index of agricultural ecosystems.

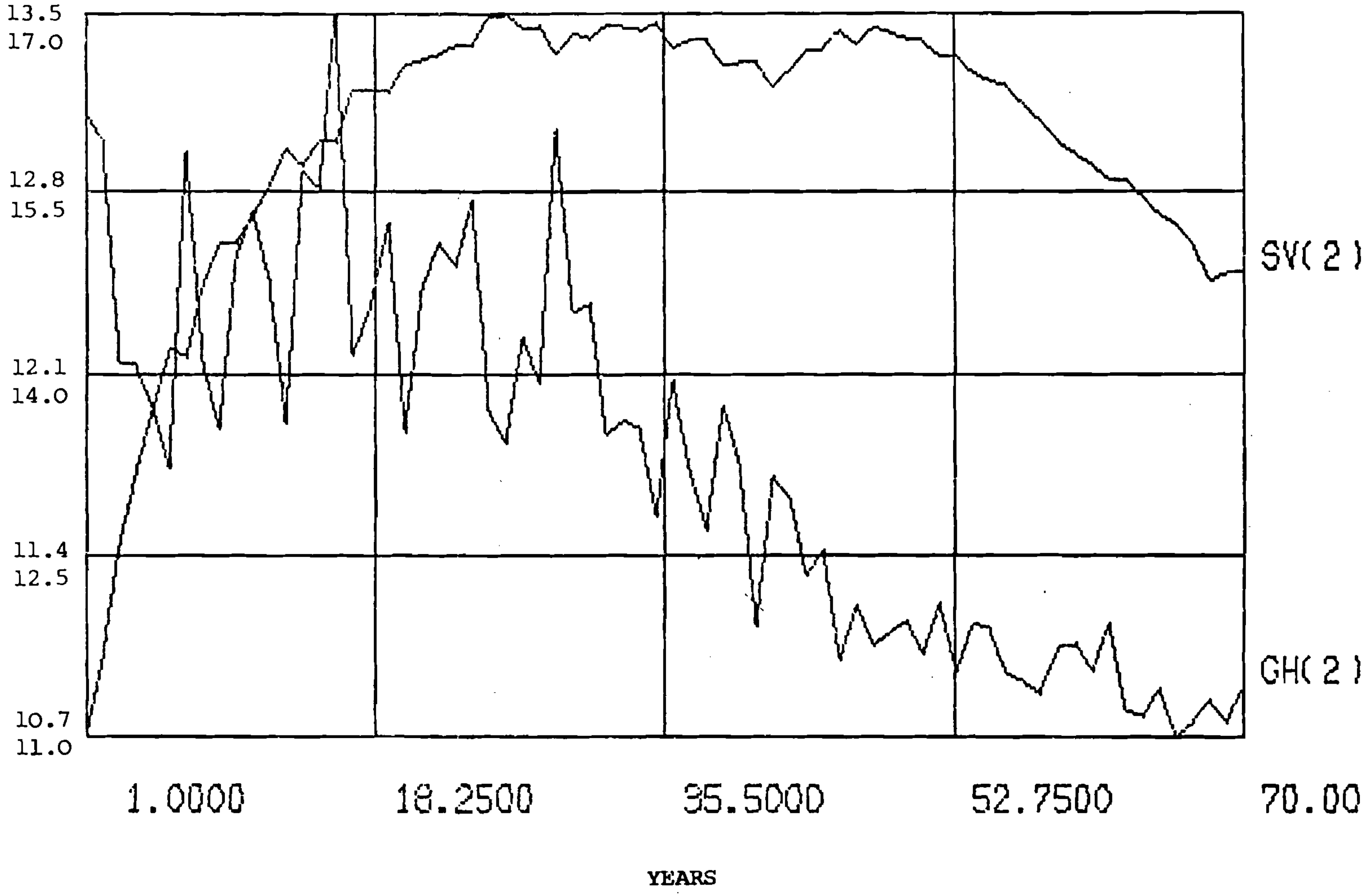


Figure 13. The Northern Khazakhstan Steppe (low scenario).
GH(2) is the minimal crop production of agricultural ecosystems (in 100 kg/hectare)
SV(2) is the soil index of agricultural ecosystems.

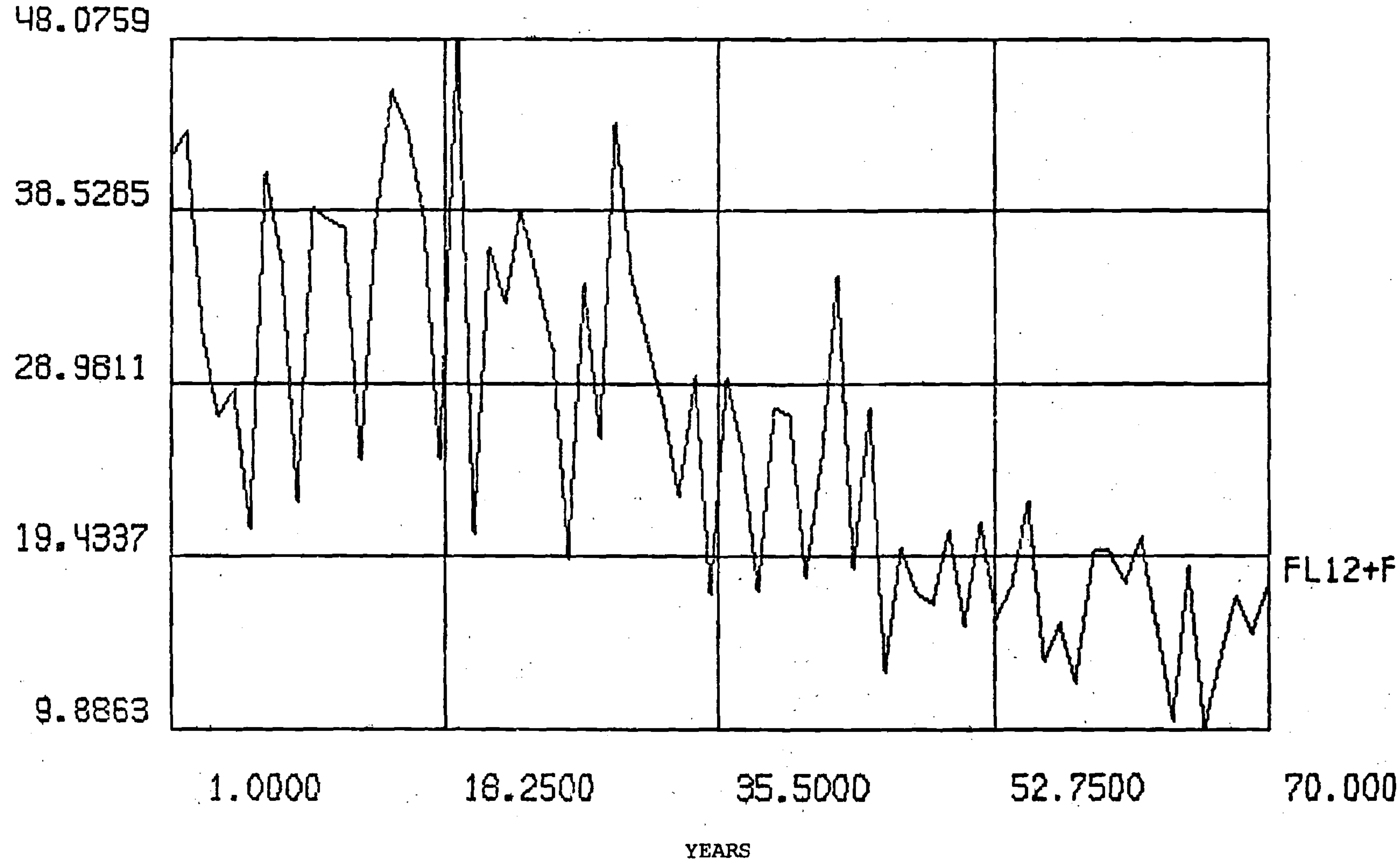


Figure 14. Streamflow (mm/year) in the Northern Khazakhstan Steppe (low scenario).

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