Global carbon cycle

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This review is devoted to the problem of global carbon cycle. It analyzes the state of the art in understanding the processes responsible for formation of the global carbon cycle; a particular attention is paid to the need of taking into account the dynamics of various global biogeochemical cycles and climate. The latest estimates for components of the carbon cycle, including contributions due to anthropogenic impact, are presented. In particular, it is shown that the anthropogenically caused increase of the CO_2 concentration in the atmosphere can hardly be prevented by the increase of compensating natural processes. The urgency of further development of "integral" methods of numerical simulation (system approach) for obtaining reliable estimates of future evolution of the carbon cycle is emphasized.

Introduction

In the study of global biogeochemical cycles of various elements as stability indicators of the biosphere evolution and, in particular, interaction between the biosphere and atmosphere, the carbon cycle undoubtedly occupies the central place by a number of reasons, but especially in the context of climate change due to intensification of the greenhouse effect caused by human activity.[1–82] The high degree of closure of the natural global carbon cycle reflects the almost ideally balanced system of numerous feedbacks determining formation of the natural cycle due to biospheric dynamics.[1–4]

However, for the last 200 years, the anthropogenic impact on the global carbon cycle manifested itself in the increasing degree. The consequence of this impact is the decrease in the closure by about an order of magnitude, and this decrease is an indicator of the global ecological disaster imminent to the world.[1,53,54]

Realization of possible consequences of the anthropogenic impact on the carbon cycle for forthcoming decades gains the essential importance for prognostic estimation and planning of the further development of economy, trade, power engineering, and technologies, as well as for provision of the ecological safety for next generations.[1,29]

Of special concern is the continuing increase of the carbon dioxide concentration in the atmosphere. Falkowski et al.[31] rightly noted that the current demand for power, presence of sufficiently large stocks of fossil fuel, absence of strategies of using alternative energy sources, and continuing growth of population determine the inevitable further increase of the CO_2 concentration in the 21st century (see also Refs. 5 and 6). It is important, however, that the growth of the CO_2 concentration is determined not only by its anthropogenic emissions, but (mostly) by complex interactions of biogeochemical and climatological processes responsible for formation of the carbon cycle. Analysis of paleoinformation plays an important role in understanding of such processes.[4,6,9,10]

1. Atmospheric emissions of CO_2

From the beginning of the first direct measurements of the CO_2 concentration in the atmosphere (Keeling, Observatory Mauna Loa, the Hawaii), the global network of stations for daily observations has been created. This network covers both the Northern and Southern hemispheres.[42] As a result, we have now long series of measurements on the CO_2 concentration with high time resolution. The analysis of the data on the Northern Hemisphere revealed the annual trend of the CO_2 concentration superimposed on the trend of the concentration growth. Interannual and interdecadal variations are also clearly seen.

Calculations of the frequency spectrum from the data on the time series detected several important peculiarities in variability of the CO_2 concentration that are not directly pronounced in the time series. The frequency spectrum clearly demonstrates the presence of maxima that correspond to the periods equal to 6.2, 1.0, and 0.5 years.

As is well-known, the annual behavior of the CO_2 concentration is caused by seasonal changes in productivity of photosynthesis on land. The phase analysis suggested that the minimum of the CO_2

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concentration coincides with the maximum of photosynthesis in the Northern Hemisphere, but with some hysteresis. The minimum of the CO_2 concentration is shifted by about 85 days with respect to the maximum of insolation. The origin of the cycle with the period of 6.2 years was earlier explained by nonlinear interaction between the annual behavior and atmospheric tides near the pole. The half-year cycle that is present in spectra of most climatic parameters is the deviation of the annual behavior from a simple sinusoid. If the annual "signal" is mostly sinusoidal, then the probable cause of the annual periodicity of CO_2 may be cyclic variations of productivity of the sea phytoplankton due to variations in insolation. The three periodicities mentioned above explain 99% of the CO_2 concentration variability obtained after filtering-out of the long-term trend.

Fossil fuel burning, cement industry, and deforestation since the preindustrial period have emitted such amounts of carbon dioxide that by now its concentration in the atmosphere increased from 280 to 360 ppm (Ref. 32). Earlier some attempts were undertaken to analyze the observational data on the CO_2 concentration together with the results of numerical simulation of 3D transport in the atmosphere in order to reveal the distribution of sources and sinks of CO_2 over the globe.

That approach was based on selection of such an optimal set of sources and sinks that provided reliable reconstruction of the observed distribution of the CO_2 concentration based on general circulation models (GCM) of the atmosphere. However, the results obtained in such a way occurred to be insufficiently adequate. Therefore, Fan et al.[32] reconstructed the distribution of CO_2 sources and sinks from observations of the CO_2 concentration for the period 1988–1992 and results of numerical simulation of atmospheric transport with the use of the SKYHI model developed in the Geophysical Fluid Dynamics Laboratory (USA). The computations have shown that the use of a reconstruction model without regularization led to unrealistically high CO_2 fluxes in the tropics. The application of three different techniques has demonstrated that they all provided minimization of unrealistic CO_2 fluxes in the tropics.

The estimates of CO_2 fluxes for regions of the Northern Hemisphere turned to be the least sensitive to measurement errors and the choice of regularization parameters. Therefore, observations in these regions restrict the results of reconstruction in the best way. Application of regularization increases the reliability of results relating to the tropics and oceans of the Southern Hemisphere, where observational data are most fragmentary.

The results obtained in Ref. 32 allow the conclusion that a great amount of CO_2 is assimilated on land in the mid-latitudes of the North America and in Boreal Europe. The oceanic sink in the Northern Hemisphere is mostly caused by the contribution of the Northern Atlantics in the mid-latitudes. The oceanic sink in the Southern Hemisphere mostly falls on the mid-latitudes, and a small contribution of the latitudes to the south of 54°S is present as well. To refine the obtained estimates, additional observations of the CO_2 concentration and isotopic relations for CO_2 and O_2 are needed, especially, in the tropics and Southern Hemisphere.

Although we have now a global network for measurements of the near-surface concentration of carbon dioxide and its isotopic species, the global budget of CO_2 is still to be studied. This is due to the fact that the problem of taking into account the effect on the field of the CO_2 concentration of anthropogenic emissions due to fossil fuel burning and, to a lesser degree, land-use, is very difficult.[80]

In 1995 the global emissions of CO_2 due to fuel burning (including the contributions of plumes of natural gas burning and cement production) achieved 6.4 Gt carbon (GtC) a year, whereas in 1950 they were only 1.6 GtC/year. It is still unclear how the growing concentration of CO_2 may affect the climate.

Although the causes of that growth were generally assumed anthropogenic and assigned to increasing human activity (first of all, power generation and consumption), it was shown that since 1980 natural factors contributed more significantly than the increasing level of fuel burning. Recent research has led to the conclusion that carbon fluxes are significantly affected by possible changes in physiology of ecosystems connected, in particular, with the effect of "fertilization" (intensification of photosynthesis under conditions of the increased CO_2 concentration).

To obtain more reliable information on the global field of the CO_2 concentration in the free troposphere of the Southern Pacific region, in August–October 1996 Vay et al.[79] have conducted precision airborne (NASA DC–8 and P3–B instrumented aircraft) measurements of the CO_2 concentration within the framework of the PEM–Tropics Program (the obtained data cover the altitudes from 0.1 to 12 km).

Analysis of the observations has shown that the field of the CO_2 concentration in the Southern Hemisphere is determined by the dominant effect of inter-hemisphere transport with the significant influence of regional processes. Comparison of the observed concentrations of CO_2 and other minor gases has suggested that the level of the CO_2 concentration is mostly caused by the contribution of continental sources. Large-scale plumes of increased CO_2 mixing ratios due to biomass burning were found above remote regions of the Pacific Ocean within the low and middle troposphere.

In Ref. 79, sources of CO_2 were revealed in the latitude belt 15°N–15°S from the data of ground-based observations and in the latitude belt 8°N–8.5°S (with

the zone of the increased CO_2 concentration from 6.5°N to 1°S) – from the airborne data for the lower troposphere. These observations suggest that in the oceanic region of the Southern Hemisphere there exists a sink of CO_2 to the south of 15°S with two clearly separated zones having the annual behaviors of the concentration opposite in phases. The obtained data are important for checking the models of the global carbon cycle.

Potosnak et al.[64] have analyzed data of hourly observations of the CO_2 concentration and flux at the height of 30 m. The data were obtained from spring 1994 to late 1996 with the equipment installed on a tower in Harvard Forest (Petersham, Massachusetts, USA, 42°32′ N, 72°11′ W). The CO_2 concentration was measured with Dasibi gas-correlation IR sensors.

In the time series of observations, the contributions of the following components were separated: regional burning sources (mostly, motor cars), local exchange between the plant cover and the atmosphere, monthly mean biotic exchange (with allowance for modulation of such exchange by the diurnal behavior of the atmospheric boundary layer (ABL)), and regional background concentration of CO or C_2H_2.

The results from Ref. 64 were compared with the similar data obtained for Cold Bay (Alaska). Processing of the observations showed that the contribution of burning products to the measured concentration of CO_2 under conditions of Harvard Forest was 4–5 ppm in winter and 2–3 ppm in summer. The presence of regional biotic emissions causes the growth of the daily mean CO_2 concentration by 4–6 ppm in winter, whereas in summer it increases further by 1–2 ppm due to correlation of the biotic cycle of assimilation and emission of CO_2 with the height in the ABL. The minimum mean afternoon values of the concentration in summer were 10 ppm lower than in Cold Bay. The observations under discussion indicate that the regional representativeness of local data on CO_2 can be evaluated only provided that simultaneous observations characterizing contributions of various factors into the concentration change are present.

Lafleur[56] discussed the results obtained with the use of the correlation technique for measuring the CO_2 exchange between the atmosphere and subarctic boreal forest ecosystem situated near the northern forest border not far from Churchill (Manitoba, Canada, 58°45′ N, 94°04′ W) in the vegetation period of 1997. Observations of components of the heat balance of the surface, air temperature, and precipitation showed that the observational conditions in 1997 were close to the mean climatic ones. The daily mean Bowen ratio was 1.16 ± 0.12 (1σ), and evaporation was (1.8 ± 0.19) mm. Closure of the heat balance turned out to be 0.92 ± 0.036.

Analysis of the observations revealed the correlation ($r^2 = 0.51$) between the half-hour values of net ecosystem exchange (NEE) for CO_2 and photosynthetically active radiation. However, the correlation between ecosystem respiration at night and the temperature of air and soil occurred to be weak. The strongest correlation ($r^2 = 0.20$) with the air temperature was observed inside the plant cover at night. The annual variability of daily values of NEE was revealed (with maximum assimilation of CO_2 in late July) equal to 6.2 g $CO_2/(m^2 \cdot day)$. The daily mean value of NEE representing the assimilation of CO_2 was 1.72 g $CO_2/(m^2 \cdot day)$. The estimates of the NEE values, accumulated for the 90-day period of observations, were within 86–151 g CO_2/m^2. The measured CO_2 fluxes turned to be far lower than for sites situated in the central and southern parts of boreal forests and only slightly higher than those observed in tundra.

In-depth understanding of the carbon distribution between its reservoirs in the atmosphere, terrestrial biosphere, and ocean is of key importance for adequately predicting the future change of the CO_2 concentration in the atmosphere at different scenarios of CO_2 emissions due to fossil fuel burning. One of the most poorly studied aspects of this problem is interannual variability of assimilation of atmospheric anthropogenic CO_2 by the terrestrial biosphere and ocean.

According to the available estimates, assimilation of CO_2 by the ocean varies widely. In this connection, Lee et al.[58] obtained new estimates of the interannual variability of the globally mean atmosphere–ocean exchange depending on the observed wind field and the partial pressure (P_{CO_2}) in the oceanic water and the near-water atmosphere. The values of P_{CO_2} for the oceanic waters were obtained from the data on interannual anomalies of the ocean surface temperature with allowance made for the regional variability and annual behavior of the temperature dependence of P_{CO_2}. It was assumed that the variations of the ocean surface temperature reflect the P_{CO_2} variations in the oceanic water due to thermodynamic and biological processes, as well as mixing in the ocean.

The calculated interannual variability of the CO_2 assimilation by the ocean was about 0.4 GtC/year (within the error of 2σ). It turned out to be far below the value obtained earlier from the measurements of the CO_2 concentration in the atmosphere. It follows herefrom that the most variable component of the global carbon cycle is accumulation (or emission) of carbon by the terrestrial biosphere. The satellite information on phytoplankton fields, ocean surface temperature, and wind fields will help to refine these estimates in future.

Data on fluxes of isotopic species of carbon dioxide and water vapor are of great importance for adequate understanding of the carbon cycle. Two biological processes have a controlling effect on ^{18}O as a marker of carbon dioxide in the atmosphere: (1) low

rate of the CO_2 diffusion from soil as a product of respiration of roots and soil microbes that does not allow the isotopic equilibrium relative to soil water to be achieved; (2) reverse diffusion to the atmosphere of those portion of CO_2, which was not used in the process of photosynthesis in leaves, but achieved isotopic equilibrium relative to leaf water due to enzyme of carbonic anhydraza.

Evaporation from inner surfaces of leaves causes significant enrichment of water in leaves (and, consequently, CO_2) with ^{18}O isotope relative to the soil water. The biosphere affects also the content of the ^{13}C in atmospheric CO_2. The discrimination of heavier ^{13}C due to photosynthesis causes enrichment of the atmosphere with this isotope as compared to leaves.

Since CO_2 connected with the processes of photosynthesis and respiration is characterized by various isotopic compositions, the components due to photosynthesis and respiration can be distinguished in the CO_2 flux.

Inasmuch as the efficiency of the ordinary gradient or fluctuation techniques occurred to be low in flux measurements, the methods of relaxed eddy accumulation (REA) has been developed. Bowling et al.[16] proposed the improved version of this method called hyperbolic relaxed eddy accumulation (HREA). In August 1996 the fluxes of $^{13}C^{16}O_2$ and $^{12}C^{18}O_2$ were measured above deciduous forest canopy in the eastern part of Tennessee State. These measurements imitated the use of the new HREA technique. Field tests demonstrated higher efficiency of the HREA technique as compared to the REA and the possibility of determining the isotopic composition of carbon dioxide from the data of gradient measurements.

Analysis of measurements of the concentration and isotopic composition ($\delta^{13}C$) of carbon dioxide in the atmosphere allows estimate contributions to the carbon cycle of such factors as CO_2 emissions due to fossil fuel burning and distribution of their assimilation between terrestrial plants and the ocean. In the context of this problem, the coordinated research program of studying the isotopic composition of atmospheric carbon dioxide and other trace gases was started in Australia.[8] Phase II of this program was aimed at studying the regularities in the space (for example, interhemispheric) and time (for example, interannual) variability of $\delta^{13}C$ (based on the data of the global observation network) with the measurement error no higher than 0.01‰.

In Ref. 8, measurements from various points were intercompared in order to evaluate the consistency and errors of the obtained results. Samples of clear air from Cape Grim (41°S) and the South Pole (90°S) were analyzed and then processed by three research groups from Australia and the USA. Comparison of the results showed some discrepancies that restricted the measurement accuracy needed to obtain reliable information on the carbon cycle. These discrepancies can be minimized by using unified standards for calibration of observations.

Reference 76 discusses the results of monthly mass-spectrometric measurements of the concentration and isotopic composition ($\delta^{13}C$) of carbon dioxide in Bucharest in 1991–1996. Since the measured values of $\delta^{13}C$ do not reflect the actual atmospheric values (because of some peculiarities of the applied measurement technique), the changes in the concentration $\Delta^{14}C$ are considered. The annually mean concentration $\Delta^{14}C$ in Bucharest varied within 124–143‰.

Contrary to expectations, this level of concentration kept almost unchanged during the period of observations from 1992 to 1995. The amplitude of variation of the monthly mean values of $\Delta^{14}C$ in 1991–1996 was 232‰. The annual behavior turned out to be both stronger (in 1995) and weaker (in 1994) than the mean value. Comparison of observations in different countries revealed the closeness of the amplitude of the annual behavior of the ^{14}C concentration in Bucharest and Krakow and coincidence in phase with data for Wellington. According to the data of long-term observations, the maximum of concentration falls on April, and the minimum occurs in August–September.

Florkowski et al.[34] compared the measurements of the concentration and isotopic composition of carbon in carbon dioxide and methane under conditions of the strongly polluted atmosphere of Krakow and a remote mountainous region of the station Kasprovy Vyerch. The obtained data were used to estimate the contribution of anthropogenic sources to regional budgets of these greenhouse gases. The consequence of the urban atmosphere pollution was a wide difference between the concentrations of CO_2 and CH_4 measured at these two sites. The calculated mean isotopic composition for methane in Krakow was $\delta^{13}C = -54‰$; it turned out to be close to the measured value $\delta^{13}C = -54.3‰$. The main anthropogenic source of atmospheric methane in Krakow was assumed to be gas leakage from the gas pipeline network. In the case of CO_2, three sources should be taken into account: soil, biosphere, and anthropogenic emissions. To distinguish these components quantitatively, it would be useful to obtain the data on $\delta^{13}C$.

Measurements of the atmospheric concentrations of CO_2 and O_2 and the isotopic ratios $^{13}C/^{12}C$ and $^{18}O/^{16}O$ in the composition of CO_2 are rather important as indicators of various factors determining the global carbon cycle. Although among these parameters the ratio $^{18}O/^{16}O$ is most poorly studied, it is of great interest as a factor controlled by isotopic ratios of CO_2 fluxes between the atmosphere, plant cover, soil, and ocean. The $^{18}O/^{16}O$ ratio in the composition of atmospheric CO_2 reflects the values of this ratio in water contained in the reservoirs mentioned above, including the soil. The soil water is characterized by

the lowest values of $^{18}O/^{16}O$ as compared to other reservoirs, but it has a tendency to some increase of the ^{18}O concentration near the surface, wherefrom water is evaporated. Therefore, the isotopic ratio for oxygen in the CO_2 flux from the soil to the atmosphere depends on kinetics of isotopic exchange between the soil water and the soil. Stern et al.[75] considered the results of field measurements and numerical simulation, wherefrom it follows that the rate coefficient of the isotopic oxygen exchange between the soil water and CO_2 is, on the average, 10^{-4}–10^{-3} s^{-1}. The corresponding value for the CO_2 flux from the soil to the atmosphere depends not only on the net flux due to soil respiration, but also on the amount of atmospheric CO_2 that enters the soil and experiences isotopic exchange with the soil water followed by reverse diffusion into the atmosphere.

The allowance for these regularities of CO_2 exchange between the soil and the atmosphere is important for estimating the contribution of the soil component to the global budget of atmospheric $CO^{18}O$, especially, for soils characterized by low respiration rate.

It is undoubted now that fossil fuel burning and other human activities affect seriously the global carbon cycle. Besides the data on the CO_2 concentration in the atmosphere, other characteristics are of great importance for understanding the formation (sources and sinks) of the carbon cycle. These characteristics include, in particular, the concentration ratio $^{13}C/^{12}C$ that strongly depends on the processes of photosynthesis, but is not subject to the influence of the ocean/atmosphere gas exchange.

Since terrestrial plants assimilate mainly the lighter isotope ^{12}C, the ratio $^{13}C/^{12}C$ in the composition of atmospheric CO_2 can serve as the marker of CO_2 assimilation by terrestrial plants. Although this "sign" is very weak and can be recorded only in ultra-precision mass-spectrometric measurements of the isotopic composition of CO_2, this problem can be solved. The best source of information on the latitudinal distribution of CO_2 fluxes caused by the ocean and the land is observations of the meridional gradient of the ^{13}C concentration.

The most interesting result in this case is the fact that at early 1990, when the rate of the CO_2 concentration growth in the atmosphere decreased to one third with respect to its normal level, the terrestrial ecosystems of the Northern Hemisphere served as a significant sink of anthropogenic CO_2 (Refs. 11 and 24). Because the long-term trend and interannual fluctuations of the ^{13}C concentration at every monitoring station were close to the detection limit by the data of mass-spectrometric measurements, even very small systematic errors of isotopic measurements could lead to wide differences in estimates of assimilation of anthropogenic CO_2 by the land and ocean.

Variations of O_2/Ar depending on the processes of photosynthesis, respiration, and biomass and fossil fuel burning (these variations are observed with mass-spectrometric instrumentation) are directly connected with formation of the global carbon cycle.[24] In the both hemispheres, the annual trend of O_2/N_2 in the atmosphere is rather well pronounced. This is due to the fact that bioproductivity of the ocean, as well as mixing and upwelling of water masses with the decreased concentration of oxygen and the ocean/atmosphere gas exchange affect the chemical composition of the atmosphere. The $^{18}O/^{16}O$ concentration ratio in atmospheric CO_2 can serve as some indicator of carbon assimilation by land biota in the process of photosynthesis and emission in the process of respiration. The $^{18}O/^{16}O$ ratio in CO_2 is indirectly controlled by the value of $^{18}O/^{16}O$ in the water of biosphere, and this determines the relations between the carbon and water cycles. The presence of the negative meridional gradient of $^{18}O/^{16}O$ in the atmosphere is interpreted as a fingerprint of CO_2 emissions due to respiration.

As was already mentioned above, analysis of paleodata is of great importance for understanding the regularities of formation of the carbon cycle.[9,59] Thus, for example, the isotopic composition of carbon ($\delta^{13}C$) in paleosols is characterized by the property of integration and recording of the relative contributions of plants of the types C_3($\delta^{13}C \cong -27‰$) and C_4($\delta^{13}C \cong -13‰$) into formation of the net productivity of plant communities in the past.[15] Since both the geographic distribution and relative productivity of C_4 plants have strong positive correlation with temperature, the values of $\delta^{13}C$ for organic carbon of paleosol must reflect the long-term dynamics of the plant cover and changes of paleoclimate. To better understanding of the dynamics of correlation "plant cover – climate" in the Great Plains (USA) in the Late Quaternary, Boutton et al.[15] have analyzed the variability of $\delta^{13}C$ of organic carbon in the paleosol samples taken from the northern and southern parts of the region (samples were dated by the radiocarbon ^{14}C dating technique).

A presence of significant "grass" component of the type C_4 occurred to be characteristic of the entire Late Quaternary in both sites, what points to the fact that they were occupied predominantly by grass or open savannas. In the southern part of the Great Plains, the variations of $\delta^{13}C$ and relative productivity of C_4 plants correlated with climate changes stipulated by income of melting water to the Gulf of Mexico in the period of 15 000–9 000 years to present time. The relative productivity of C_4 plants was maximum in the Holocene (5 000–2 000 years to present time). The northern part of the Great Plains was characterized by minimum values of $\delta^{13}C$ and relative productivity in the Late Pleistocene and early Holocene that reflected the conditions of cold climate.

After 11 000 years to present time $\delta^{13}C$ and the productivity began to increase quickly and achieved their maximum in the period 7 000–2 000 years to present time. This indicates that at that time the climate became warm. The considered data on variations of $\delta^{13}C$ and the relative productivity of C_4 plants in the Late Quaternary agree well with similar results obtained earlier. The mentioned regularities are of great interest for studying biogeochemical cycles and verifying results of numerical simulation of paleoclimate.

Gasse and Lin [36] have analyzed the results of isotope analysis of lacustrine sedimentary rock from the viewpoint of such data significance for understanding the reaction of continental ecosystems to great climatic changes in the past. The corresponding results are illustrated by the example of the African tropics and subtropics, and the particular attention is paid to analysis of (1) isotopes in plant remains and (2) oxygen isotopes in carbonates contained in lakes fed by subsoil waters. The isotope composition of plant remains in lacustrine bottom sedimentary rock rich in organics can serve as an important source of information on the distribution of biomes and the carbon cycle in the past.

In this connection, Ref. 36 discusses the main factors determining the concentration ratio $^{13}C/^{12}C$ in organic matter of peat and lacustrine sedimentary rock. In Africa in the last Ice Age the concentration of ^{13}C in peat and lacustrine sedimentary rock decreased significantly (>10‰) in the both hemispheres. Comparison with other indirect paleoclimatic (especially, palinological) data and with changes in the CO_2 concentration points to the fact that the latter were the main factors controlling the distribution of biomass in the tropics, rather than availability of water resources. The carbonate-rich sedimentary rock of lakes fed by subsoil water bears the information allowing reconstruction of the climatic conditions that determined the status of the lakes.

Reconstruction of climate parameters (for example, humidity) is possible with the use of the salt balance equation, except for the relations that determine water and isotope content in the sedimentary rock. The information on the income of water from subsoil waters is also needed. The application of such a technique was illustrated in Ref. 36, which considered the processes in a small Holocene lake in the northern Sahara. Archives of lacustrine isotope data contain rich information for reconstruction of changes in the paleoclimate, and in many cases the interpretation of isotope data can be complemented by consideration of other indirect indicators of the paleoclimate dynamics.

By the inversion method with the use of a box model of the ocean, Grand and Alverson [59] have shown that the decrease of the atmospheric CO_2 concentration in Ice Ages can be explained by variations in a series of factors manifesting themselves in the oceans of the Southern Hemisphere, such as weakening of deep-water ventilation, decrease of the ocean–atmosphere gas exchange, intensification of a "biological pump," as well as impacts of the decrease in the global ocean surface temperature.

Analysis of the concentration ratio of oxygen isotopes ($\delta^{18}O$) in air bubbles of ice grains as an indirect indicator of the air temperature revealed abrupt climatic changes in the last Ice Age. These changes were called the Dansgaard-Oeschger events (DOE). Thus, for example, in Greenland the fast near-surface air temperature changes took place for several decades. Those changes achieved several degrees and were followed by slow cooling and resetting completely ice-age conditions. The occurrence of DOE was supported (except for one case) by the data of analysis of soil samples from the Northern Atlantics. On the other hand, results of numerical simulation of the global ocean circulation suggested that the income of fresh waters to the ocean due to "emissions" to the ocean and iceberg melting could change significantly the process of formation of North Atlantic Deep Water (NADW).

In this connection, the influence of changes in the deep-water circulation and marine biochemical processes on the CO_2 concentration in the atmosphere is an open question. Analysis of the CO_2 concentration measured in air bubbles of Greenland ice cores revealed variations from ~200 ppmv in the periods of cold phases up to roughly 250 ppmv in warming periods connected with Dansgaard-Oeschger events. Analysis of Antarctic ice cores did not confirm the existence of the CO_2 content variations with such amplitude. Therefore, it was assumed that the high CO_2 concentration in the Greenland cores (in warming periods) does not reflect the actual increase of the CO_2 concentration, but is caused by the acid-carbonate reaction or oxidation of the organic matter of cores (the influence of these processes under Antarctic conditions is less significant).

To compare abrupt climate changes judged from the data on Greenland cores with the global trends of the CO_2 concentration determined by the Antarctic data (that are more reliable), the observations in Greenland and Antarctica should be synchronized. Stauffer et al.[74a] demonstrated the possibility of such synchronization for the last Ice Age with the use of the measurements on the methane content in the Greenland and Antarctic ice. This synchronization allowed the conclusion that in the period of the Dansgaard-Oeschger events the CO_2 concentration varied only slightly (<10 ppmv). However, during the Heinrich iceberg-discharge events in the Northern Atlantics the CO_2 concentration in the atmosphere varied significantly (~20 ppmv), especially during those

events, which started simultaneously with long-lasting Dansgaard-Oeschger events.

On the whole, the problem of correlation between climate changes and the globally mean CO_2 concentration is far from clearness. To understand the paleodynamics of the carbon cycle, further precision measurements of $\delta^{18}O$ and the CO_2 concentration are needed, as well as the synchronized data on indirect indicators of the climate. Such data are also important for understanding possible climate changes in the future.

2. Carbon monoxide

Carbon monoxide is an important trace gas with the annual cycle about $2.3 \cdot 10^{15}$ g. In remote regions of the Southern Hemisphere, the CO concentration varies from 40 to 65 nmol/mol. In the Northern Hemisphere, where more powerful sources of carbon monoxide exist, it varies (under conditions of nonpolluted environment) from 90 to 200 nmol/mol. The main mechanism of CO removal from the atmosphere is its oxidation *in situ* through the reaction

$$CO + OH \rightarrow CO_2 + H;$$

only a part of H atoms take part repeatedly in formation of OH. Roughly a half of atmospheric hydroxyl is involved in this reaction, and, thus, carbon monoxide affects very strongly such short-living oxidant as OH. In spite of CO, some other trace gases (CH_4, DMS, HCFC, hydrocarbons, etc.) are oxidized via hydroxyl.

Interacting with OH, carbon monoxide can affect indirectly the concentrations of other trace gases, including such greenhouse gas as methane. All this determines the urgency of studies of the carbon monoxide budget, although this problem is very complicated by a number of reasons (Table 1). First, carbon monoxide has short lifetime: up to several weeks in the tropics and up to several months in high latitudes in winter). Second, CO has numerous sources (one of them is latitude-dependent oxidation of methane by hydroxyl, and another is biomass burning). A high contrast in the CO content is observed between the hemispheres due to impacts of transport, industry, and local sources. A significant source of CO in the tropics is oxidation of biogenic non-methane hydrocarbons (NMHC) that plays an important part in middle and high latitudes as well. The data of Table 1 characterize the components of the global budget of carbon monoxide.[17]

In connection with strong uncertainty of data on the CO budget, Brenninkmeijer and Rockmann[17] discussed the capabilities of using the data of isotopic measurements with application of the mass-spectrometric technique to estimate the budget components. Most promising data on $\delta^{13}C$ were obtained for CO samples from the lower stratosphere in high latitudes of the Southern Hemisphere in the period of formation of an ozone hole, when free Cl atoms react with CH_4 and CO with the isotope ^{13}C ($\delta^{13}C \cong$ $\cong -120‰$) is generated.

Table 1. Global budget of carbon monoxide

Source		Sink	
Industry	300–550	Reaction with OH	1400–2600
Biomass burning	300–700	Assimilation by soil	250–640
Biogenic sources	60–160	Atmospheric income	~100
World Ocean	20–200		
Methane oxidation	400–1000		
Oxidation of NMHC	200–600		
Total	1800–2700	Total	2100–3000

If the variations of $\delta^{13}C$ are most pronounced in the Southern Hemisphere, then the Northern Hemisphere is characterized by significant variability of $\delta^{18}O$. The value of $\delta^{18}O$ in carbon monoxide produced in high-temperature internal combustion processes is close to the value of $\delta^{18}O$ for atmospheric oxygen, but significantly higher than $\delta^{18}O$ for all other sources of CO. Thus, carbon monoxides produced by motor cars, industry, and heating systems are isotopically very close, and high values of $\delta^{18}O$ correspond, as a rule, to the high CO concentration due to anthropogenic sources.

In the winter period, the high-latitude troposphere of the Northern Hemisphere is gradually filled with CO from high-temperature combustion sources. This fact is reflected, for example, by measurements of $\delta^{18}O$ on Spitsbergen. In spring and summer natural sources becomes significant, but the reaction with hydroxyl causes some decrease of the CO concentration. Understanding of causes of $\delta^{18}O$ variability is complicated by lack of data on the content of $\delta^{18}O$ in CH_4. For almost all oxygenic compounds $\delta^{17}O = 0.52\delta^{18}O$, i.e., variations of $\delta^{18}O$ and $\delta^{17}O$ are correlated. Although the isotopic modification ^{14}CO is very rare (5 molecule/cm^3 in the Southern Hemisphere in summer and 25 molecule/cm^3 in the Northern Hemisphere in winter), nevertheless it is interesting as an indicator of the OH content.

The main sources of CO are both of natural and anthropogenic origin. Natural carbon monoxide is mostly formed due to oxidation of methane and other hydrocarbons. The anthropogenic sources of CO are fossil fuel burning (largely in the Northern Hemisphere) and biomass burning in the tropics. The chemical lifetime of carbon monoxide varies from 0.1 year in the tropics to roughly one year in the polar regions in winter. Such the variability causes wide variations of the long-range transport of CO. This determines the particular role of spaceborne

observational tools in obtaining the information on the global distribution of carbon monoxide.

That is why the MAPS experiment was conducted within the framework of the Shuttle research program in the period from November 1981 to October 1984. The experiment was aimed at remote sensing of pollution of the global atmosphere.[67] The success of this experiment gave rise to its continuation for two 10-day periods in April and October 1994 with the use of the improved MAPS equipment. The equipment included a radiometer directed at nadir with a gas filter. The radiometer operated at the wavelength of 4.67 μm within the ground absorption band of carbon monoxide. It was based on the use of the principle of selective modulation. The measured signal was formed as a difference between signals having passed through gas cells, one of which was filled with the gas under study (carbon monoxide), and another was empty or filled with some non-absorbing gas. Analysis of the obtained results has shown that the error of reconstruction of the carbon monoxide content in the atmosphere does not exceed 10%.

In the periods of flights of the Shuttle Endeavor in April 2–19 and October 30–11 of 1994, the content of carbon monoxide in the atmosphere was measured with the MAPS remote sensing equipment.[25] In April this equipment operated for 211 h (cloudless conditions were observed in 161619 s of 736471 s of Earth sighting in nadir). The corresponding values for October were 256 h (192004 and 821502 s). For 10 days simultaneous surface (at 30 points in the latitude belt from 70°N to 67°S) and aircraft (five instrumented aircrafts of three countries) measurements were performed.

Analysis revealed a close agreement (discrepancy no more than ±10%) between spaceborne and airborne measurements. Latitudinal and longitudinal cross sections plotted based on these data illustrate a pronounced annual variability of the CO content that reflects the specific geographical situation and variations in the intensity of the CO sources and sinks. Thus, for example, in April the maximum value of the CO concentration averaged over the entire atmospheric altitude was about 120 ppbv. This maximum occurred in the Northern Hemisphere with the gradual decrease of the concentration (down to 45–60 ppbv) in the direction to middle and high latitudes of the Southern Hemisphere.

The distribution of carbon monoxide changed drastically in October, and this change was accompanied by alternation of the sign of the meridional concentration gradient as compared to April. In October, the maximum values of the CO concentration (higher than 135 ppbv) localized in the tropic belt extending over the central part of South America, southern Africa, southern India, Indonesia, and northern Australia. In this region, astronauts of the Shuttle STS-68 recorded a great number of intense fires connected with biomass burning. The variability of the global content of carbon monoxide in the troposphere was characterized not only by the pronounced annual variation, but also by pronounced interannual variations caused by complex interactions of CO sources and sinks, global atmospheric circulation, and chemical processes.

Fuluvegi et al.[33] simulated numerically the global field of the CO concentration in the troposphere over North America, Europe, and Atlantics in order to reconstruct the data of remote sensing obtained within the framework of the MAPS experiment in April 1994 on the CO concentration measurements with the instrumentation installed aboard the Shuttle. They used the Multiscale Air Quality Simulation Platform (MAQSIP) for calculation of the long-range transport of a trace gas. The model was based on the mesoscale model developed in the Pennsylvania State University and the National Center for Atmospheric Research (USA).

The distribution of the ground-based sources of CO emissions due to fossil fuel and biomass burning, characteristics of the processes of oxidation of non-methane hydrocarbons, oceans, and soils were borrowed from the data of the corresponding inventory made in Belgium.

The discrepancy between the calculated CO concentration averaged over the entire atmospheric altitude (about 38 ppb) and the observed value (60 ppb) reflects the significant influence of ground-based sources of CO on the time scale about a week. On the whole, comparison of the calculated fields of the CO concentration with the observed ones demonstrates a good qualitative agreement on different space and time scales.

In this connection, Ref. 33 discusses the possible reasons for the discrepancies mentioned above and shows that calculations ignoring convection due to cumulus overestimate the CO concentration at the lower levels of the model, but underestimate it at the upper levels. Allowance for the diurnal variations of emissions is important when calculating instantaneous local concentrations; however, it does not play a significant part when calculating averaged values. The causes of model imperfection include too simplified boundary and initial conditions, neglect of methane oxidation, insufficient adequacy of setting carbon monoxide emissions, as well as gaps in observations because of cloudiness.

3. Carbon cycle

The results considered above clearly illustrate the interactivity of the problems of climate change and carbon cycle dynamics. Now we consider in more detail the problem that has attracted considerable interest in recent years in connection with approval of the new Global Carbon Project (GCP) within the framework of the International Geosphere-Biosphere Programme (IGBP). The main objectives of this project are:

1. Discussion of the available information on the global carbon cycle;

2. Development of the International Global Carbon Program.

To understand the regularities of the global carbon cycle, one needs reliable information on the main sources and sinks of carbon. As Scholes[72] noted, the terrestrial sources are determined by three main factors.

3.1. Differences in the functional dependence of ecosystem sensitivity to temperature and carbon dioxide concentration

Assimilation of CO_2 by terrestrial ecosystems is determined as the difference between carbon assimilation due to photosynthesis and carbon loss due to respiration. Photosynthesis is characterized by instantaneous reaction to the growth of the CO_2 concentration in the atmosphere. This reaction can be approximated by the empiric equation:

$$C_{\text{assim}}(y) = C_{\text{assim}}(x)[1 + \beta \ln(y/x)],$$

where $C_{\text{assim}}(y/x)$ is the rate of assimilation at the CO_2 concentration equal to y/x (in ppm), and the constant β depends on the conditions of water and nutrients supply. According to the data of laboratory experiments, it roughly equals 0.4, but under actual conditions of dryness and deficit of nutrients it may be less than 0.2. The model of the global carbon cycle that served as a basis for the estimates, used in the Reports of the Expert Group of the UN Framework Convention on Climate Change, takes into account the effect of fertilization due to the increase in the CO_2 concentration, but ignores the effect of respiration.[72] The consequence of such an approach is the erroneous prognosis of the infinite increase in the considered CO_2 sink with the increase in the CO_2 concentration.

The respiration process that also should be taken into account does not react to the growth of the CO_2 concentration directly, but only through temperature, which is affected by the concentration of CO_2 and other greenhouse gases. Such an indirect effect manifests itself as a lag of about several decades. If the dynamics of carbon sink is considered on the time scales about a century, it becomes clear that at a certain stage of growth of the CO_2 concentration some saturation of the carbon sink (C_{sink}) will take place followed by its decrease. Estimates have shown that in the near future C_{sink} will reach its maximum (if the CO_2 concentration stabilizes near 600 ppm) and then decrease. Finally, such conditions will occur that the effect of respiration will surpass the contribution of photosynthesis and the carbon sink will transform into its source.

3.2. Time lags in the interactive atmosphere/ocean system

If the rising concentration of CO_2 causes almost instant stimulation of photosynthesis, then its effect on the climate manifests itself only several decades later because of the giant thermal inertia of the ocean. Therefore, after stabilization of the CO_2 concentration (just this is an objective of the UN Framework Convention on Climate Change) the temperature will increase during several centuries.

3.3. Slowness of carbon cycle in biospheric reservoir

Carbon is stored in the terrestrial biosphere in two forms: as a biomass, largely, forests (about one third) and as carbon in the soil (about two thirds). Both these forms include subreservoirs with the different time constants of the cycle (some of them are very large). This determines the variability of the carbon sink. Thus, for example, if the increase of the CO_2 concentration intensifies growth of forest, this means a presence of a sink. The forest lifetime is one or two centuries, and then follows the wood expenditure and CO_2 emission into the atmosphere due to heterotrophic respiration.

According to the approximate global model of the continental component of the carbon cycle, the global terrestrial carbon sink is now about 2 GtC/year (in the period 1991–1997 about 6.2 GtC/year in the form of CO_2 was emitted to the atmosphere due to fossil fuel burning, and the CO_2 content in the atmosphere increased only by 2.8 GtC/year (Ref. 12)). However, this estimate has been obtained using the nearly maximum value of the sink, which must decrease for several following decades (already now the terrestrial biosphere in the tropics is mainly a source of carbon because of transformation of forests into pastures).

Estimates of the contributions of the terrestrial biosphere and oceans to carbon assimilation are of critical importance for research into the global carbon cycle. Battle et al.[12] used two approaches to obtain such estimates. One approach is connected with the use of long-time-average (to exclude the influence of ocean biodynamics) measurements of the rate of the O_2 concentration change in the atmosphere with allowance made for the O_2/N_2 ratio in the atmosphere as its indicator. If fossil fuel burning decreases O_2/N_2, then assimilation of CO_2 by the ocean does not affect O_2/N_2. This allows the data on O_2/N_2 variations to be used as an indicator of terrestrial storage of carbon. Another approach consists in analysis of the isotopic composition of atmospheric CO_2 described by $\delta^{13}C$, which was considered above. In this case, assimilation of CO_2 by the ocean also does not change $\delta^{13}C$, whereas on the land $\delta^{13}C$ changes. Therefore, the change of $\delta^{13}C$ proves to be a reliable indicator of terrestrial carbon storage at global averaging of the data.

Results of processing the measurements on variations of the O_2 concentration for the period 1991–1997 contrast with the data for the 1980s, when the terrestrial biosphere was nearly neutral. The consistent

data on both O_2 and $\delta^{13}C$ revealed significant interannual variability of the carbon storage. Ocean was a powerful sink of CO_2 until 1995, which then began to weaken. The dynamics of CO_2 assimilation by the terrestrial biosphere turned to be more variable.

Kheshgi et al.[51] developed the global model of the carbon cycle that allowed one to estimate the contributions of emissions from fossil fuel burning and land-use, as well as assimilation of carbon by the ocean and terrestrial biosphere. It follows from their estimates that the oceanic sink of carbon in the 1980s was (17 ± 7) GtC (the continental sink was calculated as a residual term of the carbon balance). The estimates of CO_2 emissions into the atmosphere for the period 1765–1980 due to changes in fossil fuel burning and land-use gave the values of (158.54 ± 18.40) and (110.48 ± 70.13) GtC, respectively, whereas for the period 1980–1990 these values were (55.17 ± 4.72) and (9.31 ± 8.55) GtC.

The most acute aspect of the problem of the global carbon cycle is the so-called "missing sink" characterizing some absence of balance in the calculated cycle. Schindler[70] noted that about 30 years ago geochemists thought that carbon assimilation by ocean could explain the absence of balance between anthropogenic emissions of CO_2 (at that time they were believed to be almost completely due to fossil fuel burning) and measurements on the CO_2 concentration in the atmosphere. The large amplitude of the annual variability of the CO_2 concentration was considered as a consequence of the terrestrial biosphere dynamics. The results obtained in the 1970–1980s demonstrated those conclusions to be incorrect. In 1990 it was shown that the annual carbon influx to the ocean was less than $0.5 \cdot 10^{15}$ g C/year, i.e., only about a quarter of the flux needed to close the global carbon budget (see also Ref. 1).

Nadelhoffer et al.[61] demonstrated clearly that the missing sink could be explained by neither the ocean contribution nor carbon assimilation by boreal forests of the Northern Hemisphere. The last hypothesis was most popular and motivated by the observed growth in the amplitude of the annual variability of the atmospheric CO_2 concentration. The increase of the CO_2 influx to the atmosphere was explained by biomass burning, but rising CO_2 emissions were more or less balanced by growing assimilation. It was assumed that the increase of the carbon assimilation by forests was caused by its growing concentration in the atmosphere or by intensified fertilization due to the increased content of nitrogen whose atmospheric emissions more than doubled for the last century (more than $0.5 \cdot 10^{12}$ g nitrogen was deposited annually on the global forest).

According to the data for Europe, carbon assimilation by forests increased by about 25% for the period of growth of the nitrogen concentration. Calculations show that the increase in the forest productivity due to the fertilization stimulated by nitrogen can explain the missing carbon sink. Nadelhoffer et al.[61] demonstrated, however, that nitrogen did not at all stimulate carbon assimilation by forests even at those places, where such processes could be most probable. This was concluded based on the data of 18 field experiments with nine forest areas in Europe and North America. In these experiments, some amount of ^{15}N was added and its propagation was traced in different forest areas. On the average, only about 20% of the added ^{15}N were held by plant tissues. Estimates of the maximum contribution to the missing sink gave the value of only $0.25 \cdot 10^{15}$ g C/year.

The missing sink can be explained in different ways[61]: (1) the carbon influx to the ocean is underestimated; (2) boreal forests in the Northern Hemisphere, whose development in the past was favored by nitrogen, reached now the level of saturation with nitrogen; (3) other ecosystems (especially, wetlands) contribute significantly to the CO_2 assimilation; (4) development of northern forests is stimulated by climate warming. It is quite probable that the missing sink is determined by the total contribution of minor factors (the available estimates of sinks less than $0.5 \cdot 10^{15}$ g C/year cannot, however, be considered as reliable). Thus, the nature of the missing sink is still an open question.

As mentioned above, the adequate understanding of the global carbon cycle dynamics can be achieved only based on its interactive analysis with allowance for climate changes. Therefore, Craig et al.[26] simulated numerically the dynamics of the CO_2 cycle using the interactive model. The model is a combination of the 3D spectral (T42) 18-level community climate model (CCM) developed in the National Center for Atmospheric Research (USA) on the 2.8° latitude × 2.8° longitude grid and the 1D land surface model (LSM). It reconstructs "mechanically" the parameterized carbon cycle on land accounting for the CO_2 assimilation in the process of photosynthesis (primary productivity) and CO_2 emissions due to microbe aspiration. Interactivity in the CCM–LSM system is realized at every time step (20 min), including independent processes of photosynthesis and respiration with regard to advection in the atmosphere. Radiative fluxes and characteristics are calculated with the time step of 12 h.

An important peculiarity of the CCM–LSM model is that this model, unlike the earlier similar ones, does not balance artificially the annual values of CO_2 losses for respiration and assimilation through photosynthesis at every point of the spatial grid. This provides, for the first time, a possibility of computing the annual variations of the CO_2 concentration and exchange, taking into account the interactivity of the CO_2 cycle and climate. Integration is performed for the period of 10 years at a given temperature field of the ocean surface.

Analysis of computed monthly mean values showed (in comparison with the available observations) that the CCM–LSM model satisfactorily reconstructs many observed peculiarities of the space-time variability of the climate and carbon cycle, but some significant discrepancies take place. Thus, for example, inadequacy in computation of the precipitation, which is excessive in some regions, has a negative effect on the numerical simulation of the climate in the tropics. The latter circumstance especially concerns the Indian monsoon and related drought and high temperature conditions, which cause an appearance of intense sources of CO_2 near 20°N, determining anomalous CO_2 emission (about 7 GtC/year). As the consequences of such anomaly cannot be recorded by the existing network of measurement of the CO_2 concentration, inadequacy of such a network becomes clear.

The model overestimates the amplitude of the annual variability of the carbon dioxide exchange in the tropics. This gives rise to the equatorial maximum in the CO_2 concentration that exceeds the observed maximum by an order of magnitude. Overestimation of the amplitude may be connected with neglect of the fact that tree roots penetrate deep in the soil and extract water even in the dry season thus favoring assimilation of carbon.

In the extratropical latitude zone, the excess in summer temperatures in the USA region leads to unrealistically high CO_2 emissions to the atmosphere. Computations overestimate the amplitude of the annual variability of the CO_2 concentration at all observational stations situated to the north of 45°N. The summer vertical gradient of the CO_2 concentration turns to be larger in the Northern Hemisphere and opposite in sign as compared to the observations, because the model overestimates the CO_2 assimilation in summer in the middle and high latitudes. This leads to unrealistic annual sink of CO_2 to the north of 35°N (about 6 GtC/year). Such a sink is mainly responsible for formation of the annually mean interhemisphere gradient of the CO_2 concentration equal to −5 ppm, whereas, based on the models with balanced (at every point) CO_2 fluxes, this gradient is +2 ppm. Further improvement of the model under discussion, should primarily take into account the dynamically varying carbon and nitrogen reservoirs and prognostic parameterization of dynamics of the plant cover.

Mabuchi et al.[59b] described the regional climate–biosphere model reconstructing climate changes with interactive accounting for the carbon dioxide cycle. A Biosphere–Atmosphere Interaction Model (BAIM) developed for computation of the energy and carbon dioxide fluxes between terrestrial ecosystems and the atmosphere with the time step about several minutes and the horizontal resolution about 30 km provides parameterization of biophysical and physiological processes in the plant cover. A 23-layer climate model developed in the Japan Meteorological Agency is realized on the 129×129 grid with the resolution of 30 km (near 60°N). The period of 6.5 years was numerically simulated using the results obtained for the last six years (1986–1991).

Analysis of the results has shown that the model reproduces quite well the annual behavior of meteorological elements, as well as variability of the components of thermal and water balances for each set of years under consideration. The data on interannual variations of the CO_2 concentration represent the stepwise growth of the concentration in the lower troposphere. This is in agreement with measurements in Japan. Analysis of these data revealed such a characteristic phenomenon as the relation between the CO_2 concentration in the atmosphere and the interannual dynamics of the plant cover both in Japan and on neighboring islands.

As to the main factors of the plant cover dynamics responsible for interannual variations of CDF between the land surface and the atmosphere, the main role was played by the interannual variability of the net radiation on the land surface, whose contribution exceeded the effect of anthropogenic emissions of CO_2. In their turn, CDF variations caused variations in the CO_2 concentration in the atmosphere, which were caused, to a great degree, by anthropogenic emissions as well. Possible influence of El Niño/Southern Oscillation should be further analyzed as well.

Although predictions of the rise of the atmospheric carbon dioxide concentration, its climatic effect and social and economic consequences become more perfect, they still call for further development and justification. In this connection, Hulme et al.[43] performed combined numerical simulation of the global climate change (using the model of the atmosphere–ocean interactive system developed in the Hadley Center) and its consequences (changes in the river run-off and winter wheat harvest) in order to forecast the situation by 2050.

Joint consideration of the effects of natural and anthropogenic climatic changes has shown that anthropogenic scenarios reveal systematic growth of the river run-off in Northern Europe, but its decrease in the Southern Europe. These factors turn to be statistically significant as compared to natural variability. The changes predicted for Central and Western Europe are not statistically significant. Harvest in Europe is very sensitive to natural variations of air temperature and precipitation.

Under the effect of anthropogenic factors, the wheat harvest should increase significantly by 2050 only in three countries in Northern Europe. However, if to take into account the effect of fertilization due to the rise in the CO_2 concentration, then the growth in harvest can be predicted for all 10 European countries

under consideration (such predictions should be further analyzed for correctness).

The main inference from the numerical simulation is justification of the need in adequate consideration of the natural component in the climate change (climatic noise). The open problems of interdiurnal variability and extreme cases that require numerical simulation with high space and time resolution keep their urgency. Estimates of the corresponding risks are not of less importance too.

Reference 45 is a new example of interactive numerical simulation of the climate. However, it should be noted that this paper completely ignores the dynamics of social and economic development, without which the adequate long-term prediction of the climate is absolutely impossible. In this connection, development of integral models[4,11,53,66,74,80] is of great significance. The extreme complication of long-term climate forecasts prompts to conclude that a solution of this problem, if ever possible (keeping in mind, first of all, unpredictability of global social and economic development), is still a long way in the future.

In particular, the data on formation of the global carbon cycle and its dynamics are still far from adequacy. As the processes to be taken into account are very complex and numerous, approximate parameterization of the carbon cycle dynamics with allowance for changes in the density of population and following application of the diffuse-upwelling model are very important for estimation of the effect of CO_2 anthropogenic emissions on the climate.[2,3]

Conclusion

Summarizing the studies of the global carbon cycle, it should be noted that in recent years a number of international projects have been completed within the framework of the IGBP. The main goal of these projects was to answer the questions: (1) Can we recognize and evaluate reliably the anthropogenic effect on the biogeochemical cycle and climate? (2) How sensitive is the global climate to variations of the CO_2 concentration in the atmosphere? As was already mentioned above, for answering these questions it is particularly important to use paleoinformation, especially, for the period of recent geological history, for which sufficiently reliable data are in hand.

According to the paleoclimatic data, discussed by Falkowski et al.,[31] changes in the surface air temperature (SAT) and CO_2 concentration for the last 420 000 years are restricted to a phase space (in the coordinate system SAT–CO_2 concentration), characterized by the 100 000-year-long SAT cycle with 100 ppm change of the CO_2 concentration (from 180 to 280 ppm). On the millennium scale, a strong correlation is observed between the CO_2 concentration and SAT, although the cause-and-effect relation was not unique. Besides, there were periods, when SAT changed relatively fast without marked variations in the CO_2 concentration (reversed situations were not observed).

Analysis of the data on the current CO_2 concentration clearly indicates that the global climatic system left the phase space characteristic of the last 420 000 years, because now the CO_2 concentration is roughly 100 ppm higher than the maximum value for this period, and the rate of its change was at least an order of magnitude higher. Thus, the global climatic system turns out to be beyond the phase space characteristic of the preindustrial epoch. In this connection, of key importance is to understand whether the climatic system is now in a transient stage to a new stable state, what are main climate-forming factors under these conditions, and what will be the reaction of ecosystems to climate changes.

The data from Table 2 (Ref. 31) illustrate volumes of the main carbon reservoirs. The fact engaging our attention is that, on the millennium scale, the total ocean reservoir of inorganic carbon roughly 50 times exceeds the carbon content in the atmosphere. Consequently, on such time scales, the ocean determines the CO_2 concentration in the atmosphere rather than vice versa. The intense ocean–atmosphere gas exchange (about 90 GtC/year in each direction) provides fast leveling of the CO_2 concentration in the atmosphere and surface layer of the ocean. The concentration of the total dissolved inorganic carbon increases significantly at the depth more than 300 m and far exceeds (in all ocean basins) the equilibrium concentration on the ocean surface. Two processes determine the increased concentration of inorganic carbon in inner parts of the oceans, namely, the "solubility pump" and "biological pump."

Table 2. Main global carbon reservoirs (Gt)

Reservoir	Carbon amount
Atmosphere	720
World Ocean	38 400
Total inorganic carbon	37 400
Surface layer	670
Deep layers	36 730
Total organic carbon	1 000
Lithosphere	–
Carbonate sedimentary rock	> 60 000 000
Kerogens	15 000 000
Terrestrial biosphere	2 000
Living biomass	600–1 000
Dead biomass	1 200
Biosphere of in-land waters	1–2
Fuel burning	4 130
Coal	3 510
Oil	230
Natural gas	140
Others (peat and others)	250

The efficiency of functioning of the solubility pump depends on the character of thermohaline circulation, as

well as on space and time (depending on the latitude and season) variations of ocean ventilation. Solubility of CO_2 proves to be higher in cold and salt waters, and therefore accumulation of atmospheric CO_2 by inner ocean layers is controlled by the processes of formation of cold and dense water masses in high latitudes. As such masses descent in depth and spread, the upper layer of lighter waters prevents leveling the CO_2 concentration with respect to its level in the atmosphere. However, such leveling can occur only decades or centuries later, when the deep waters will come to the surface (this process may change significantly under conditions of climate warming[4]).

Functioning of the biological pump contributing to assimilation of CO_2 by the ocean is connected with the fact that the CO_2 partial pressure decreases in the process of phytoplankton photosynthesis in the upper ocean layer, and this favors assimilation of CO_2 from the atmosphere. As this takes place, about 25% of chemically bound CO_2 descend to deeper oceanic layers, where it experiences oxidation in the process of heterotrophic respiration. This favors the increase of the dissolved inorganic carbon (DIC) concentration. The amount of organic carbon coming from the surface into the ocean depth was estimated as 11–16 GtC/year. This process keeps up the CO_2 concentration at the level 150–200 ppm lower than the level corresponding to the absence of phytoplankton.

In addition to the described mechanism of the organic biological pump, some plankton and zooplankton species form $CaCO_3$ skeletal structures, which descend in the ocean depth, where they are partially dissolved. This process, sometimes called a carbonate pump, causes a decrease of the DIC concentration in the surface layer as compared to the deeper ocean layers. This process favors the increase of the CO_2 partial pressure. Therefore, on the century scale, the carbonate pump, favoring the decrease of the DIC concentration in the ocean surface layer, assists in CO_2 transporting from the ocean to the atmosphere.

The results of numerical simulation with application of interactive climate–biosphere models indicate that the biological pump can oppose the decrease of CO_2 assimilation by ocean caused by the solubility pump. The efficiency of the biological pump in assimilation of anthropogenic CO_2 will likely increase in the 21st century under the effect of some of the following processes: (1) intensification of nutrients use in the upper ocean layer; (2) addition of one or more nutrients limiting primary productivity; (3) change in the elemental composition of organic matter in the ocean; (4) growth of the concentration ratio of organic carbon and calcite in the downwelling flow.

Although the CO_2 assimilation by the World Ocean is not still estimated undoubtedly, the mechanism of the biological pump can likely be considered as being too weak to compensate assumed future emissions of anthropogenic CO_2 to the atmosphere. It is almost undoubted that changes in the structure of ocean ecosystems will be accompanied by changes in the oceanic circulation (and, consequently, income of nutrients), decrease of pH, and changes in the hydrological cycle. Current ideas on the factors determining the dynamics of populations of the main species of sea organisms are so imperfect that such changes can hardly be predicted reliably for the next decade. Nevertheless, it is quite probable that the capability of the World Ocean to assimilate anthropogenic CO_2 will weaken. This means that the load on terrestrial ecosystems as a factor of CO_2 assimilation will increase.[31]

Unlike oceans, terrestrial ecosystems have no physical or chemical pump. Carbon dioxide is removed from the atmosphere due to photosynthesis and accumulation of carbon in organic matter of the ocean. It returns to the atmosphere through different processes connected with respiration and having different time scales: (1) autotrophic respiration of plants themselves; (2) heterotrophic respiration, through which the organic matter of plants is oxidized as a result of activity of soil microbes; (3) disturbing action similar to forest fires, when a great amount of organic matter is oxidized for a short time.

On the global scale, carbon is largely accumulated in forests, and the total content of carbon in living biomass on land (including soil) roughly three times exceeds the CO_2 content in the atmosphere (see Table 2). However, it is important that the characteristic time of the carbon cycle on land is of the order of decades. This complicates the study of its dynamics.

Under conditions of the current level of the CO_2 concentration in the atmosphere, the net primary productivity (NPP) on land does not achieve the saturation level. Therefore, as the CO_2 concentration increases, the terrestrial biosphere is a potential sink of anthropogenic CO_2, but the efficiency of this mechanism decreases.

According to the available estimates, NPP can saturate with the increase by only 10–20% as compared to the current level (because of the limited content of nutrients), if the CO_2 concentration in the atmosphere will achieve 550–650 ppm, i.e., twice as high as that in the preindustrial epoch.[31] Besides, it is important that the increase of the temperature may lead to intensification of microbe heterotrophic respiration, which can compensate or even exceed the NPP increase mentioned above.

The presence of such opposite processes complicates seriously the prediction of the terrestrial biosphere contribution to formation of the carbon cycle under conditions of the rising CO_2 concentration, growing temperature, and changes in the soil humidity regime in interaction with the dynamics of ecosystems. However, we can assume that transformation of forests from a sink (as they are now) to a source of carbon in the near future is improbable, although it is undoubted that this sink will decrease.

Table 3. Examples of anthropogenic effects on global biochemical cycles of carbon, nitrogen, phosphorus, sulfur, water, and river sediments (the data are dated to the middle XX century)

Element	Process	Flow, mln. t/year.		Change due to anthropogenic impact, %
C	Respiration on land and assimilation of CO_2	61 000		
	Fossil fuel and land use		8 000	13
N	Natural biological fixation	130		
	Fixation at rise growing, fossil fuel burning, and producing fertilizers		140	108
P	Chemical erosion	3		
	Mining		12	400
S	Natural emissions to the atmosphere	80		
	Fuel and biomass burning (emissions)		90	113
O and H (as H_2O)	Precipitation on land	$111 \cdot 10^{12}$		
	Global water consumption		$18 \cdot 10^{12}$	16
River sediments	Preindustrial river suspensions	$1 \cdot 10^{10}$		
	Current river suspensions		$2 \cdot 10^{10}$	200

All biogenic sinks of CO_2 depend on the content of nutrients. In this context, two circumstances are important: (1) interactivity of biogeochemical cycles and (2) significant anthropogenic impact on all cycles (Table 3). This manifests itself, in particular, in simultaneous intensification of nitrogen fixation and phosphorous income to the biosphere (the latter has increased roughly four times mostly due to production of phosphorous fertilizers). At first sight, such processes must seemingly stimulate biological processes of carbon accumulation in terrestrial and marine ecosystems and thus prevent the dangerous growth of the CO_2 concentration in the atmosphere.

However, the sophisticated analysis has shown that this possibility is not realistic by a number of reasons.[31] Complication of the problem of the global carbon cycle consists in the need to take into account its interactivity with other cycles and climate under conditions of growing anthropogenic impact. In particular, it is important that, although the anthropogenic impact is short on a geological time scales, nevertheless its consequences will manifest themselves on the dynamics of biogeochemical cycles during centuries.

The results of numerical simulation, although being not sufficiently reliable now, indicate that inhibition of the anthropogenic growth of the CO_2 concentration in the atmosphere due to intensification of natural carbon sinks is improbable. Under these conditions, further improvement of the methods of "integral" numerical simulation becomes extremely important.[4,20,29,53,54,74,80]

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