Atmospheric Disturbance of the Carbon Cycle: Impact upon the Biosphere.

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Summary. — The rate of net oceanic absorption of carbon from the atmosphere is shown to linearly follow the increment in atmospheric carbon relative to its preindustrial stationary level. The amount of carbon absorbed depends on the intensity of the biogenic processes in the ocean, since the rate of biogenic absorption by the ocean appears to be approximately an order of magnitude higher than that of physico-chemical absorption. The accumulation of carbon in the atmosphere is governed by the emissions of carbon from the land biota and not from fossil fuel reservoir.

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1. – Introduction.

The natural cycles of substances lead to constant exchange of carbon between the atmosphere, the ocean and the biosphere. During the preindustrial era the carbon content variations in each of these natural reservoirs took hundreds of thousand of years. Therefore, within the comparatively short temporal intervals of tens and hundreds of years the processes of substance exchange may be considered to have been stationary. This means that the carbon content in each reservoir remained constant and the net fluxes of carbon (*i.e.* the differences between the export and import fluxes for each reservoir) remained at zero level ([1,2]).

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[1]   V. G. GORSHKOV: *Oceanology*, **24**, 453 (1984), in Russian.
[2]   V. G. GORSHKOV: *Nuovo Cimento*, **50**, 209 (1982).

Upon the advance of the industrial era a considerable amount of carbon was released into the atmosphere due to combustion of fossil fuel (coal, oil, natural gas). Moreover, because of the over broadening agricultural activities and of increasing processing of wood the active organic land reservoir—forests and soils—has suffered drastic changes ([3]). Much of the carbon released into the atmosphere has found its way into the ocean thus changing the content of carbon in that reservoir ([4-6]).

By now the rate of combustion of fossil fuel as well as the total amount of fuel so far burned has been assessed for various temporal intervals ([7,8]). Such assessment is performed by totalling the regional data. At present the latitudinal distribution of emissions is also known ([7,9,10]). Since year 1958 the CO_2 concentration in the atmosphere is being closely monitored over different parts of the globe ([11,12]).

According to the data from deep ice cores the preindustrial ratio of the partial presure of CO_2 to the total atmospheric pressure was $(270\pm10)\cdot10^{-6}$ ([13,14]). This value corresponds to the following preindustrial mass of carbon in the atmosphere (M_{ao}) and the carbon dioxide surface concentration ($[CO_2]_{ao}$):

$$(1) \qquad M_{ao} = (570\pm20)\,\text{Gt C}\,, \qquad [CO_2]_{ao} = (1.08\pm0.04)\cdot10^{-2}\,\text{mol C/m}^3\,.$$

By 1980 y the above ratio reached $(338\pm3)\cdot10^{-6}$ ([11,12]). It follows that the

([3]) R. H. HOUGHTON, J. E. HOBIE, J. M. MELILLE, B. MOORE, B. I. PETERSON, G. R. SHAVER and G. M. WOODWELL: *Ecol. Monogr.*, **53**, 235 (1983).

([4]) W. S. BROECKER, T. TAKAHASHI, H. J. SIMPSON and T.-H. PENG: *Science*, **206**, 409 (1979).

([5]) E. T. DEGENS, S. KEMPE and A. SPITZY: *Carbon dioxide: a biochemical portrait*, in *The Handbook of Environmental Chemistry*, Vol. 1, Part C, edited by C. HUTZINGER (Springer-Verlag, Berlin, 1984), p. 127-215.

([6]) H. OESCHGER, U. SIEGENTHALER, H. SCHOTTERER and A. GUGELMANN: *Tellus*, **27**, 160 (1975).

([7]) R. M. ROTTY: *J. Geophys. Res.*, **88**, 1301 (1983).

([8]) J. A. WATTS: *The carbon dioxide question: data sampler*, in *Carbon Dioxide Review*, edited by W. C. CLARK (Clarendon Press, New York, N. Y., 1982), p. 431-469.

([9]) P. J. FRASER, G. I. PEARMAN and F. HYSON: *J. Geophys. Res.*, **88**, 3591 (1983).

([10]) G. I. PEARMAN, P. HYSON and P. J. FRASER: *J. Geophys. Res.*, **88**, 3581 (1983).

([11]) R. B. BACASTOW and C. D. KEELING: *Atmospheric carbon dioxide concentration and observed airborne fraction*, in *Carbon Cycle Modelling*, SCOPE, edited by B. R. BOLIN (J. Wiley & Sons, Chichester and New York, N. Y., 1981), p. 103-112.

([12]) C. D. KEELING, R. B. BACASTOW and T. P. WHORF: *Measurements of the concentration of carbon dioxide at Mauna Loa Observatory, Hawaii*, in *Carbon Dioxide Review*, edited by W. C. CLARK (Clarendon Press, New York, N. Y., 1982), p. 377-385.

([13]) B. R. BOLIN: *How much CO_2 will remain in the atmosphere*, The WMO/ICSU/UNEP Intern. Assessment of the Impact of Increased Atmospheric Concentration of Carbon Dioxide on the Environment, 5 December 1984, p. 40.

([14]) A. NEFTEL, H. OESCHGER, J. SCHWANDER, B. STAUFFER and R. ZUMBRUM: *Nature* **295**, 220 (1982).

atmospheric carbon which increased in mass by m_a and the atmospheric carbon dioxide concentration which increased by $\delta[CO_2]_a$ have both relatively increased by

$$(2) \qquad \varepsilon_a = m_a/M_{ao} = \frac{\delta[CO_2]_a}{[CO_2]_{ao}} = 0.25 \pm 0.03, \quad m_a = (140 \pm 20)\,GtC\,.$$

By 1980 y the accumulation of carbon in the atmosphere, $\dot{m}_a$, and emissions from the fossil fuel, $\dot{m}_f$, occurred at the following rates:

$$(3) \qquad \dot{m}_a = (3.0 \pm 0.2)\,Gt\,C/y\,, \quad \dot{m}_f = (5.3 \pm 0.1)\,Gt\,C/y\,[5]\,.$$

The mass of carbon released into the atmosphere during the industrial era (up to 1980) constituted [7,8]:

$$(4) \qquad m_f = (162.2 \pm 1.0)\,Gt\,C\,.$$

The assessments of the rate of carbon emission into the atmosphere from continental forests and soils, published lately, vary by an order of magnitude, ranging from -1 to $+18\,Gt\,C/y$ [3,5,15]. Such considerable uncertainty in the rate of depletion of carbon in forests and soils is caused by the difficulties which one faces when performing global direct measurements of this process [3]. The indirect assessments are based on the data from measurements of the isotope ^{13}C in tree rings [16,17].

Since the emissions of CO_2 from fossil fuel principally take place in the northern hemisphere there develops a measurable inhomogeneity in the CO_2 distribution throughout the atmosphere: the annual mean concentration of CO_2 in the northern hemisphere appears to be higher than that in the southern one [10,11]. Calculations based on a low-accuracy model of the general atmospheric circulation demonstrate that the observed latitudinal distribution of the atmospheric CO_2 concentration is hard to simulate if only emissions from the tropical biospheric belt, comparable as it were, to the total fossil fuel emissions, are taken into account [10]. No decisive comparison of the relative input of emissions from the biospheric and fossil fuel sources can be made if both are assumed to have similar latitudinal distributions.

To satisfy the law of matter conservation the carbon in the global cycle must somehow be distributed among the mentioned global reservoirs, *i.e.* fossil

[15] W. C. CLARK, K. H. COOK, G. MARLAND, A. W. WEINBERG, R. M. ROTTY, P. R. BELL, L. J. A. ALLISON and C. L. COOPER: *The carbon dioxide question: perspectives for 1982*, in *Carbon Dioxide Review 1982*, edited by W. C. CLARK (Clarendon Press, New York, N. Y., 1982), p. 3-53.

[16] T.-H. PENG, W. S. BROECKER, H. D. FREYER and S. TRUMBORE: *J. Geophys. Res.*, **88**, 3609 (1983).

[17] M. STUIVER: *Science*, **199**, 253 (1978).

fuel, atmosphere, biosphere and ocean. Indeed, all the other existing reservoirs are either inactive or display negligibly small capacity for carbon. Therefore, obtaining accurate data on the rate of change of carbon content for even one of the reservoirs—the biosphere or the ocean—would yield a complete picture of what is happening to the carbon cycle on the whole. Similarly, obtaining accurate data on the reduction of carbon in land biota and in soils would provide information on the structure of oceanic processes as well. Conversely, the exact data on the oceanic absorptivity for carbon would outline the stars of deterioration of forests and destruction of soils.

Presently direct measurements of variations of the global oceanic carbon content are not feasible ([4,5,13]). The rate of net carbon income to the ocean through the air-sea interface is known only to a factor of 2-3 ([4,5,18,19]). Cal-
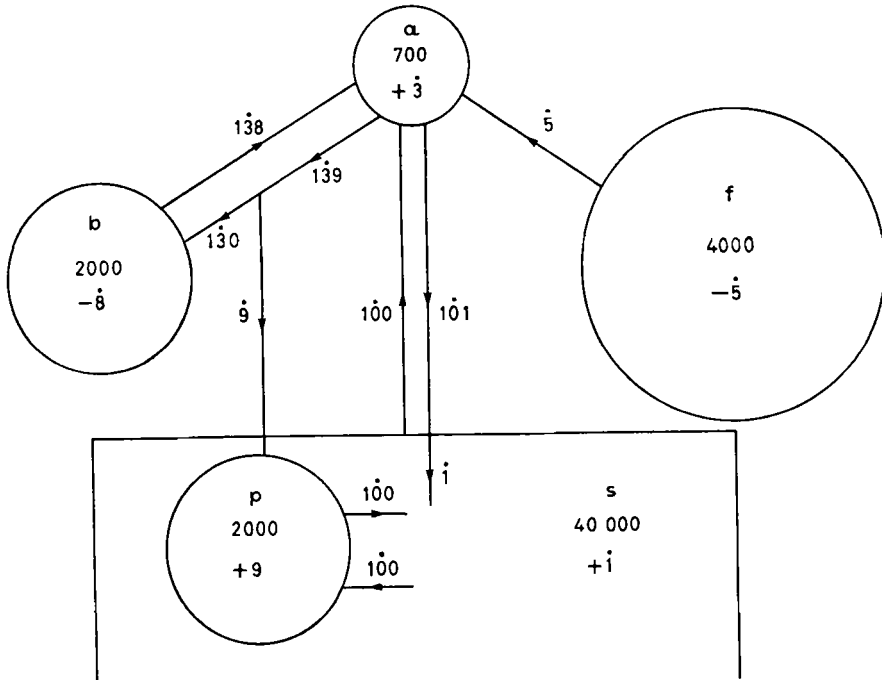

Fig. 1. – Carbon cycle, present state. Reservoirs are denoted as follows: atmospheric (a); land (b) and ocean (p) biotic; fossil fuel (f); oceanic(s). Numbers for every reservoir read: unmarked figures: carbon store, Gt C ([5]); dotted figures: rates of net carbon store variations, Gt C/y; dotted figures at arrows: overall reservoir to reservoir carbon import and export rates ([5]), $k_s = 0.07$ y^{-1}.

([18]) I. ENTING and G. I. PEARMAN: *Description of a one-dimensional global carbon cycle model*, CSIRO Aust. Div. Atmos. Res. Techn. Pap., No. 42 (1982), p. 1-95.

([19]) I. G. ENTING and G. I. PEARMAN: *Refinements to a one-dimensional carbon cycle model*, CSIRO Aust. Div. Atmos. Techn. Pap., No. 3 (1983), p. 1-35.

culations of the oceanic absorptivity are based on indirect data concerning the feature of the physico-chemical processes within the ocean, and the results of such calculations strongly depend on fine details of these processes ([2,6]). According to calculations which neglect biotic processes in the ocean, the rate of physico-chemical absorption of carbon by the ocean amounts to 2 Gt C/y ([5,6]). This value is rather close to the stationary mass of carbon in forests and soils. However, due to increase in its biotic intake of carbon, the ocean is capable of additional absorption of $(6 \div 10)$ Gt C/y ([1,2,20,21]). Similar features emerge from the direct measurements of the annual losses of carbon from forests and soils if those latter are based on extreme assumptions ([2,5,15]).

The present study treats various approaches to the problem of retrieval of the oceanic carbon absorptivity. Numerical values are obtained for the physico-chemical and biotic rates of absorption of carbon by the ocean. The principal features of the global carbon cycle following from these results are presented in fig. 1.

2. – The absorption of atmospheric CO_2 by the global ocean through the air-sea interface.

The rate of absorption of carbon by the ocean depends on the process of diffusion of CO_2 through the air-sea interface ([5]). This rate linearly follows the difference in partial pressures of carbon dioxide in the atmosphere and in the oceanic surface layer:

$$(5) \quad \dot{m}_s = \Delta[CO_2]S_s/R_a, \quad \Delta[CO_2] \equiv [CO_2]_a - [CO_2], \quad S_s = 3.6 \cdot 10^{14} \, \text{m}^2,$$

where $[CO_2]_a$ and $[CO_2]$ are the concentrations of CO_2 in the atmosphere and in the surface oceanic layer, respectively. S_s is the total surface area of the global ocean. In writing (6) the fact is taken into account that CO_2 solubility at the mean global temperature of 15 °C is equal to 1.0 ([4,22]) (*i.e.* at this temperature under equilibrium conditions $[CO_2] = [CO_2]_a$). Finally, R_a is the resistance to penetration of CO_2 through the air-sea interface ([5]). Relationship (6) may be rewritten in the form of a difference between the oceanic import and export fluxes of carbon:

$$(6) \quad \dot{m}_s = (F_s^- - F_s^+)S_s, \quad F_s^- = [CO_2]_a/R_a, \quad F_s^+ = [CO_2]/R_a,$$

([20]) K. YA. KONDRATYEV and N. I. MOSKALENKO: *Atmospheric greenhouse effect and climate*, in *Meteorology and Climate Series*, Vol. **12** (VINITI, Moscow, 1984), p. 262 (in Russian).

([21]) V. G. GORSHKOV: *On the role of the land and oceanic biota in the global carbon budget*, Leningrad Nucl. Phys. Inst. Preprint, L., No. 534 (1979), p. 23.

([22]) W. S. BROECKER and T.-H. PENG: *Tellus*, **26**, 21 (1974).

where $F_s^{\pm}$ are the overall mean global import $(+)$ and export $(-)$ fluxes of CO_2 [5]. The equality of resistances to import and export fluxes follows from the lack of difference $(\Delta[CO_2] = 0)$ between CO_2 concentrations in both media in a stationary case. With the increase in either $[CO_2]_a$ or $[CO_2]$ the export and import fluxes linearly increase.

It follows from (6) that it is totally sufficient to measure the values of R_a (or F_s^+) and $\Delta[CO_2]$ to further retrieve the air-to-sea transport of CO_2. This may be done irrespective of the structure and character of the physico-chemical and biotic processes within the ocean. Although the local values of $\Delta[CO_2]$ and F_s^+ are measured rather accurately, the global mean value $\dot{m}_s$ is known to a factor of 2-5 only [5,18,19], since the effective ocean surface strongly depends on wind speed. At high wind speeds the air-sea interface drastically increases because the sea becomes rough and the airborne droplets appear. Under such conditions the import flux F^+ per unit surface of the aquatoria may increase as much as tenfold [5]. Attempts of global averaging of the letter with the account of the global wind field result in considerable errors in the mean value, F_s^+. The respective referenced values vary from 15 mol C m^{-2} y^{-1} [23] to 25 mol C m^{-2} y^{-1} [5], while the extreme locally measured values of F_s^+ reach in excess of 200 mol C y^{-1} [5].

For further assessments we choose the following values (cf. [5]):

$$(7) \qquad F_s^+ = (20 \pm 5) \text{ mol C m}^{-2} \text{ y}^{-1}, \qquad R_a = (0.68 \pm 0.17) \text{ y km}^{-1}.$$

The measured air-sea differences in CO_2 concentrations $(\Delta[CO_2])$ vary even stronger. Such broad global variations take place because CO_2 is absorbed by the ocean from the atmosphere in the polar region while in the equatorial belt the process is reversed: here the gas is released from the ocean into the atmosphere. For the major part of the global aquatoria [5,11] the observed relative difference in concentration (1) remains within the boundaries:

$$(8) \qquad \Delta[CO_2]/[CO_2] \sim \pm(0.1 \div 0.3).$$

Since we have agreed on (7) such a ratio corresponds to the following range of the net fluxes: $F_s^+ - F_s^- = \pm(2 \div 6)$ mol C m^{-2} y^{-1} [5,10]. To obtain the annual mean globally averaged differences in concentration the observed local monthly means are averaged. As all such differential values these differences in concentration contain extremely large errors of the order of the sought values (*i.e.* relative differences in concentration) themselves.

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[23] N. Z. ARIEL, E. K. BUETTNER and L. A. STROKINA: *Calculations of the rate of gas exchange through the air-sea interface*, in *Physics of the Atmosphere and Ocean Series*, No. 10, Izvestia of the USSR Acad. Sci. (1981), p. 1056-1063, in Russian.

On the whole, the existing measurement data on the net CO_2 fluxes through the air-sea interface make it possible to state: the global rate of absorption of CO_2 by the ocean from the atmosphere $\dot{m}_s$ belongs to the range

$$0 < \dot{m}_s < (9 \div 40) \text{ Gt C y}^{-1}.$$

3. – Physico-chemical absorption of carbon by the ocean.

In order to more accurately determine the net flux of carbon from the atmosphere into the ocean one has to consider the features of the physico-chemical and biotic processes within the ocean itself ([1,2,4,6]).

The upper well-known oceanic layer is about 100 m thick. The amount of nonorganic carbon it contains is of the same order of magnitude as that in the atmosphere ([5]). Within the approximation of the chemical equilibrium (i.e. $\Delta[CO_2]/[CO_2]_a \ll 1$) one could assume, at first glance, that the carbon content of this upper layer linearly follows that of the atmosphere. Consequently this layer would absorb about half the CO_2 released into the atmosphere. This, however, is expressely not the case because of the particular feature of the oceanic chemistry.

The nonorganic carbon in the oceanic waters exists in the forms of dissolved gas (CO_2), the carbonate (CO_3^-) and bicarbonate (HCO_3^-) ions ([5,18,19]):

$$(9) \qquad [\Sigma CO_2] \equiv [HCO_3^-] + [CO_3^-] + [CO_2].$$

For the ocean the ratios of these components are approximately as follows:

$$(10) \qquad [HCO_3^-]/[CO_3^-]/[CO_2] = 200/20/1 \text{ ([5,19,18])}.$$

As the same time another ratio holds $[HCO_3^-]/[H^+] \sim 10^5$ ([5]). Therefore, the electrical neutrality of the ocean water depends on the presence of certain positive ions other than H^+. Their concentration, $[A^+]$ ([5]), must satisfy the following relationship:

$$(11) \qquad [A^+] = [HCO_3^-] + 2[CO_3^-].$$

The condition of chemical equilibrium, governing chemical transmutations of various components in (9) leads to a relationship between their respective concentrations ([5,18,19,21]):

$$(12) \qquad [HCO_3^-]^2 [CO_2]^{-1} [CO_3^-]^{-1} = \text{const}.$$

If the value $[CO_2]_a$ increases only $[CO_2]$—the least of the components in (9) follows it linearly. However, if the approximation $[CO_3^-]/[HCO_3^-] \ll 1$ holds

and $[A^+]$ remains constant, the largest of the components, *i.e.* $[HCO_3^-]$, does not vary. If one looks at the relationship (9) and recalls that $[CO_3^-]$ is different from zero, it becomes obvious that the first two terms in (9) increase when a given number of CO_3^- ions disappear and are substituted by twice their number in HCO_3^- ions. It is clear that since CO_3^- concentration is low the concentration of HCO_3^- will increase but quite slightly. The overall picture may be quantitatively described by means of a buffer factor:

$$\xi \equiv d \ln [CO_2]/d \ln [\Sigma CO_2].$$

Neglecting the minor component $[CO_2]$ and using (9) and (11) one can express the $[HCO_3^-]$ and $[CO_3^-]$ values through $[A^+]$ and $[\Sigma CO_2]$. Introducing the expressions thus obtained into (12) we may calculate the buffer factor. To do this we also apply relationship (10) and confine ourselves to the main approximation with regard to the minor value $[CO_3^-]/[HCO_3^-]$ as in ([18,21]):

$$(13) \qquad \frac{\partial[CO_2]}{[CO_2]} \bigg/ \frac{\partial[\Sigma CO_2]}{[\Sigma CO_2]} = \frac{[HCO_3^-]}{[CO_3^-]} = 10 .$$

It follows that a 20% increase in the atmospheric CO_2 concentration over the industrial era (2) has brought about only a 2% increase in the carbon content of the upper oceanic layer. Therefore, to a 10% accuracy the upper mixed oceanic layer may be considered to be nonabsorbing with respect to the atmospheric CO_2 ([6]). The bulk of absorption of the atmospheric CO_2 must take place in the deep oceanic layer.

If we assume that there is no gradient of ΣCO_2 concentration in the upper mixed oceanic layer, then the net flux of dissolved carbon into the deep layer must be determined by the presence of such a gradient in the deep layer itself ([6,14,24]). Denoting the rate of physico-chemical absorption of the dissolved nonorganic carbon in the deep layer as $\dot{m}_d$ we obtain from the law of diffusion

$$(14) \qquad \dot{m}_d = D \frac{\partial[\Sigma CO_2]}{\partial Z} \cdot S_s ,$$

where D is empirical value for the eddy diffusion coefficient in the deep layer ([6,16]). Let us further assume that the concentration gradient is constant through the whole layer of a depth L, in which the CO_2 variations exist. Then

([24]) G. T. CHEN, P. J. MILLERO and R. M. PYTKOWICZ: *J. Geophys. Res.*, **87**, 2083 (1982). For simplicity we assume that the stationary preindustrial gradient of $[\Sigma CO_2]$ is absent. The natural presence of this gradient does not change the final results (19), (26).

we may write instead of (14)

$$(15) \quad \partial[\Sigma CO_2]/\partial Z = \delta[\Sigma CO_2]/L \,, \quad \delta[\Sigma CO_2] = [\Sigma CO_2] - [\Sigma CO_2]_0 \,,$$

where $[\Sigma CO_2]$ and $[\Sigma CO_2]_0$ are, respectively, the ΣCO_2 concentrations in the surface layer and in the lower deep layer. The latter is considered not to be subject to anthropogenic disturbance yet. The value $[\Sigma CO_2]_0$ corresponds to the preindustrial equilibrium state when the oceanic concentration of CO_2 was $[CO_2]_0$. It is further convenient to rewrite (14) as follows:

$$(16) \quad \delta[\Sigma CO_2] = \frac{\partial[\Sigma CO_2]}{\partial[CO_2]} \delta[CO_2] \,,$$

$$(17) \quad \delta[CO_2] = [CO_2] - [CO_2]_0 \geqslant 0 \,,$$

where $\delta[CO_2]$ is the difference between the present $([CO_2])$ and the preindustrial $([CO_2]_0)$ concentrations of CO_2 in the surface oceanic layer.

The depth L of the diffusion layer within which the concentration gradient in (15) is different from zero may be measured directly. It is of the order of $(200 \div 500)$ m [24]. Considering the dimensional relationships one may write (in accordance with the well-known expressions for diffusion [6]):

$$(18) \quad L = \sqrt{D\tau} \,,$$

where τ is the characteristic temporal interval of the process. If one neglects the biotic processes then only one such interval is left, that is the interval during which the combustion of fossil fuel doubles or else increases by the factor of « e »: $\tau_f = 23$ y [6,7,13]. Introducing $\tau = \tau_f$ together with the empirical value for $D = 4 \cdot 10^6$ m^2 y^{-1} [6,16] into (18) we obtain $L = 300$ m. This value agrees with the data from direct measurements [24]. Finally, combining relationships (10), (13) and (15)-(18) one may express the net physico-chemical flux of nonorganic carbon from the atmosphere into the ocean in the following form [2]:

$$(19) \quad \dot{m}_d = \frac{\delta[CO_2]}{R_d} S_s \,, \quad R_d = \frac{\partial[CO_2]}{\partial[\Sigma CO_2]} \sqrt{\tau/D} \,,$$

where R_d is the resistance to penetrating of CO_2 into the deep oceanic layer. Expression (19) coincides with the result yielded by the exact solution of the equations of eddy diffusion (cf. expression (32) from [6]). From (10) and (13) we obtain $\partial[CO_2]/\partial[\Sigma CO_2] = 1/20$. Using the empirical values for D $(D = 4 \cdot 10^3$ m^2 y^{-1} [6]$)$ and for τ $(\tau = 23$ y [7,19]$)$ we further obtain

$$(20) \quad R_d = 4 \text{ y km}^{-1} \,, \qquad\qquad R_d \gg R_a \,.$$

4. – Biotic absorption of carbon by the ocean.

The empirical data [25-28] demonstrate that the consumption of CO_2 by the majority of plants linearly increases with the increase in CO_2 itself when CO_2 concentration is close to its present atmospheric level, *i.e.* the consumption processes are far from saturation [1,2,20,29]. The total flux of synthesyzed organic matter or the gross productivity of the ocean, P^+, may be expressed as follows:

$$(21) \qquad P_s^+ = [CO_2]/R_p .$$

In the nonsaturation range the gross productivity resistance, R_p, may be considered independent of CO_2 concentration. According to direct measurements [5,20] the mean annual gross productivity of the oceanic phytoplankton coincides with the value of carbon import through the air-sea interface (cf. [2]) and is approximately twice as large as net productivity. Thus we obtain

$$(22) \qquad P_s^+ = F_s = 20 \text{ mol C m}^{-2} \text{ y}^{-1}, \qquad R_p = R_a = 0.68 \text{ y km}^{-1} .$$

During the preindustrial era the gross productivity, P_{so}^+, $\left(P_{so}^+ = [CO_2]_0/R_p\right)$ must have been compensated by destructivity (*i.e.* community respiration flux), P_s^-, since the net biotic flux of CO_2 from the atmosphere into the ocean was equal to zero. Now with the increase in the value $[CO_2]_a$ the productivity (21) started to increase as well. However, since all the other nutrients in the ocean remained constant, the destructivity and, consequently, the upward CO_2 flux from the deep remained unchanged (the possibility of changes in the destructivity is treated in detail in [1]). Generally speaking, the productivity may increase due to absorption of additional CO_2 from the atmosphere and to synthesis of the respective amount of primary carbohydrate products. These products are inaccessible for further synthesis of the cellular substances because the concentration of other nutrients (nitrogen, phosphorous, etc.) remains constant. The additional primary products must, therefore, be removed from the biotic cycle increasing the amount of dissolved and suspended organic matter. So we may write the rate of additional biotic absorption of CO_2 from

[25] V. LARCHER: *The Plant Ecology* (MIR, Moscow, 1978), p. 384, in Russian.
[26] V. D. FEDOROV and T. G. GILMANOV: *Biology*, Moscow State University (Moscow, 1980), p. 463, in Russian.
[27] G. F. COOPER: *Food and fiber in a world of increasing dioxide*, in *Carbon Dioxide Review 1982*, edited by W. C. CLARK (Clarendon Press, New York, N. Y., 1982), p. 299.
[28] H. H. ROGERS, J. P. THOMAS and G. B. BINGHAM: *Science*, **220**, 428 (1983).
[29] V. G. GORSHKOV: *Energetics of Biosphere*, Leningrad Polytechnic Inst. (Leningrad, 1982), p. 80, in Russian.

the atmosphere, m_p, in the form

(23)
$$\dot{m}_p = \frac{\delta[CO_2]}{R_p} S_s,$$

where $\delta[CO_2]$ in the difference between the present and the preindustrial concentrations of CO_2 in the ocean, as in (17). The expressions (21) and (23) do not contradict the existing empirical data [1,2,20], although there are still no direct proofs of their exactness on a global scale. Since $R_p \ll R_d$ the rate of botic absorption of carbon by far exceeds that of the respective physico-chemical process: $\dot{m}_p \gg \dot{m}_d$.

The additional biotically absorbed carbon must accumulate in the ocean in the form of carbohydrate organic substances. These substances may be deposited on suspended organic particles and then be removed from the surface layer through gravitation sedimentation. The fluxes which thus originate exceed those generated by the eddy diffusion [5,30]. The existing empirical data on the distribution and age of the dissolved organic matter and on the flux of suspended organic matter into oceanic depths [5,30] do not contradict the estimates following from relationships (29).

5. – Distribution of CO_2 concentration gradient in and total net carbon absorption by the ocean.

During the preindustrial era there existed a physico-chemical equilibrium for CO_2, so, setting the CO_2 solubility at a unit value, we have

$$[CO_2]_o = [CO_2]_{ao} .$$

The increase in atmospheric concentration of CO_2 is by definition

(24)
$$\delta[CO_2]_a \equiv [CO_2]_a - [CO_2]_{ao} ,$$

where $[CO_2]_a$ and $[CO_2]_{ao}$ are, respectively, the present and preindustrial values of the atmospheric concentration of CO_2. Therefore we arrive at an obvious equation:

(25)
$$\delta[CO_2]_a = \Delta[CO_2] + \delta[CO_2] ,$$

which states that the difference in CO_2 concentrations between the atmosphere and the deep oceanic layer is essentially the sum of two such differences: one at the air-sea interface ($\Delta[CO_2]$, see (5)) and the other between the well-mixed surface and the deep oceanic layers ($\delta[CO_2]$, see (17) and (24)).

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[30] B. Suess: *Nature*, **288**, 260 (1980).

Equating the total rate of absorption of CO_2 by the ocean, $\dot{m}_s$, (cf. (9), (7)) with the sum of physico-chemical, $\dot{m}_d$ (cf. (19), (20)), and the biotic, $\dot{m}_p$ (cf. (22), (23)) fluxes we obtain the following relationship for the values of $\Delta[CO_2]$ and $\delta[CO_2]_a$ (see also eq. (25)):

$$(26) \qquad \Delta[CO_2] = \frac{R_a}{R_a + R_s}\,\delta[CO_2]_a\,, \qquad \delta[CO_2] = \frac{R_s}{R_a + R_s}\,\delta[CO_2]_a\,,$$

$$R_s = R_p R_d/(R_p + R_d) = 0.58 \text{ y km}^{-1}\,,$$

where R_s is the total resistance to the « parallel » biotic and physico-chemical fluxes of absorbed carbon. Taking into account the fact that $R_p = R_a \ll R_d$ (cf. (7), (20) and (22)) and using eq. (2) to express the relative increase in the atmospheric concentration of CO_2 we conclude that the air-sea drop in the CO_2 concentration must be evenly distributed between the surface interface film and the deep oceanic layer:

$$(27) \qquad R_s = R_p = R_a\,, \qquad \Delta[CO_2] = \delta[CO_2] = 0.5\delta[CO_2]_a\,.$$

Note that

$$(28) \qquad \Delta[CO_2]/[CO_2]_a \doteq 0.1\,.$$

The estimate presented in (28) does not contradict the observed values (see (8)). Applying (26) we obtain the following rates for biotic (see (22), (23)), physicochemical (see (19), (20)) and total rates of absorption of carbon by the ocean:

$$(29) \qquad \dot{m}_p = 9 \text{ Gt C/y}\,, \qquad \dot{m}_d = 1 \text{ Gt C/y}\,, \qquad \dot{m}_s = \dot{m}_p + \dot{m}_d = 10 \text{ Gt C/y}\,.$$

Note that in the absence of biotic absorption, i.e. in case the relationships $\dot{m}_p \ll \dot{m}_d$ and $R_p \gg R_d = R_s$ hold, the drop in carbon concentration shifts to the deep layer exclusively. Then the physico-chemical absorption appears to be higher by the factor of 2 and the total absorption—to be less by the factor of 5 than these in the discussed case [2]:

$$(30) \qquad \delta[CO_2] = \delta[CO_2]_a \gg \Delta[CO_2] = \frac{R_a}{R_d}\delta[CO_2]_a = 0.15\,\delta[CO_2]_a = 0.03\,[CO_2]_a,$$

$$(31) \qquad \dot{m}_s = \dot{m}_d = 2 \text{ Gt C/y}\,.$$

With the help of relationships (2), (6), and (26) the rate of total net absorption of carbon by the ocean may be written as follows:

$$(32) \qquad \dot{m}_s = k_s m_a\,, \qquad k_s = (0.07 \pm 0.02) \text{ y}^{-1}\,,$$

$$(33) \qquad k_s \equiv \gamma/H_a R\,, \qquad R \equiv R_a + R_s = (1.2 \pm 0.3) \text{ y/km}\,, \qquad \gamma \equiv S_s/S_a = 0.71\,,$$

$$(34) \qquad H_a \equiv p_a/\varrho_a g = 8.6 \text{ km}\,, \qquad S_a = 5.1 \cdot 10^{14} \text{ m}^2\,, \qquad m_a \equiv \delta[CO_2]_a H_a S_a\,.$$

Here H_a is the atmospheric scale height; S_a is the Earth surface area; p_a and ϱ_a are the atmospheric pressure and air density; γ is the ratio of the oceanic to total Earth surface areas; R is the total resistance to absorption of carbon, *i.e.* the resistance to successive fluxes through the interface film and through the oceanic depths.

6. – Mass and rate of emission of carbon from land biota.

The balance equation of the conservation of matter has the form

$$(35) \qquad \dot{m}_b = \dot{m}_a + \dot{m}_s - \dot{m}_f , \qquad \dot{m}_s = k_s m_a .$$

Combining the value of k_s from (32), the data on m_f from ([8]) and the data on m_a and $\dot{m}_a$ (the latter two start from 1958 y ([9])) we may retrieve the temporal course of $\dot{m}_b$. The so far incomprehensible major fluctuations of $\dot{m}_a$ are caused in reality by minor fluctuations of $\dot{m}_b$ coupled with the almost monotonous increase in $\dot{m}_f$ and $\dot{m}_s$. Summing (45) year by year from $t_3 = 1958$ y to a given year we further obtain the temporal trend of the mass of emissions from land biota since 1958 y, fig. 2.

The total means of emissions by land biota during the industrial era up to any given moment t is given by an obvious equation of balance:

$$(36) \qquad m_b(t) = m_a(t) + m_s(t) - m_f(t) ,$$

$$(37) \qquad m_s(t) = k_s \int_{t_0}^{t} m_a(t^*) \, dt^* ,$$

where the mass of carbon absorbed by the ocean, $m_s(t)$, depends on the unknown temporal trend of the value $m_a(t)$ prior to 1958 y. The moment t_0 corresponds to the beginning of the industrial era, defined as the moment when the value of increment, m_a, outgrows for the first time the natural fluctuations of CO_2 constant in the stationary atmosphere. To retrieve the temporal trend of m_a prior to 1958 y, let us assume that the relative growth rate for atmospheric carbon $k_a = \dot{m}_a/m_a$ prior to that year had been the same as later. According to ([11]) we have $k_a = (0.019 \pm 0.007)$ y^{-1} during the period from 1960 y to 1980 y (see fig. 2a)). Such a figure is quite close to the relative rate of population growth ([8]). For slowly varying k_a (*i.e.* $\dot{k}_a/k_a^2 \ll 1$) the integral (47) yields for $t = t_3$:

$$(38) \qquad m_s(t_3) = (k_s/k_a) m_a(t_3) = (350 \pm 100) \text{ Gt C} ,$$

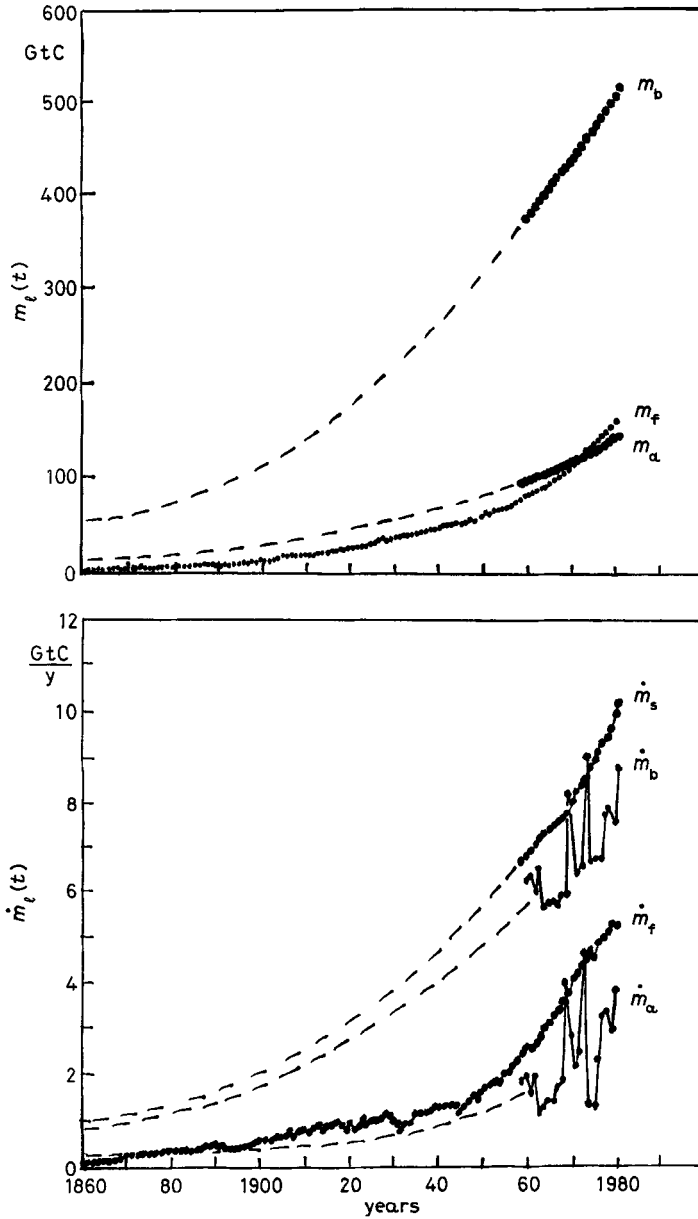$$(39) \qquad m_a(t_3) = 96 \text{ Gt C} , \qquad t_3 = 1958 \text{ y} .$$

Fig. 2. – Temporal variations of the masses of carbon exchanged between the reservoirs since 1860 y, m_l are the masses and $\dot{m}_l$ are the rates of carbon releases or absorption; $l = f, b, a, s$, see fig. 1 for legend. Points present the data of Mauna Loa ([11,12]) and eqs. (35), (36), which are connected by solid lines. Broken lines present the result of extrapolation in the case of constant $k_a = 0.019 \ y^{-1}$ during all industrial era.

If one lets m_a increase linearly from $m_a(t_0)$ to $m_a(t_3)$ the result will coincide with (38) at $k_a = 2/(t_3 - t_0)$. Substituting the values from (38) and (39) into eq. (36) we obtain $(m_t(t_3) = 76 \text{ Gt C } (^8))$:

$$(40) \qquad m_b(t_3) = (370 \pm 100) \text{ Gt C}.$$

Combining relationships (2), (3), (4), (35) and (36) we arrive at the following rate emission and the total name of carbon released from land biota by the year 1980:

$$(41) \qquad \dot{m}_b = (8 \pm 3) \text{ Gt C},$$

$$(42) \qquad m_b = (500 \pm 100) \text{ Gt C}.$$

The error margin in (51) depends on the error in estimating the value of k_a (32). The margin in (42) depends on the error in the retrieval of the value of $m_a(t_3)$ (cf. (38)). The temporal course of the rate of emission and of the total mass of carbon released from all the reservoirs and accumulated in the atmosphere is presented in fig. 2. The results in that figure embrace the whole industrial era.

7. – Conclusion.

The rate of absorption of carbon by the ocean may exceed the calculated physico-chemical rate of absorption of CO_2 in oceanic depths by the factor of 5 $(^{1,6})$. Absorption of carbon by the ocean at such a high rate can results from biotic activity of phytoplankton only $(^{1,2})$.

The equation of balance makes it possible to retrieve the rate of emission of carbon from forests and soils. This rate is considerably higher than that of emission of carbon from fossil fuel during the whole industrial era (see fig. 2). The exaustion of carbon stored in forests and soils must lead to curbing of the process of accumulation of carbon in the atmosphere, whether the emissions from fossil fuel continue or not. Therefore the increase in the atmospheric CO_2 is not going to induce a greenhouse effect of a magnitude sufficient to drive the Earth temperature outside its natural variability range $(^{13,15,20})$.

Thus, the principal change of the stationary state of the natural system caused by an anthropogenic disruption of the carbon cycle lies not in disturbance of climate stability but in reduction of the mass of carbon stored in land biota.

* * *

● R I A S S U N ȚO (*)

Si mostra che il tasso di assorbimento oceanico netto del carbonio dall'atmosfera segue linearmente l'incremento di carbonio atmosferico relativo al suo livello stazionario pre-industriale. La quantità di carbonio assorbito dipende dall'intensità dei processi bio-genici nell'oceano, poiché il tasso di assorbimento biogenico dell'oceano sembra appros-simativamente maggiore di un ordine di grandezza rispetto a quello dell'assorbimento fisico-chimico. L'accumulo di carbonio nell'atmosfera è regolato dalle emissioni di car-bonio dai biosistemi della Terra e non dalle riserve di combustibile fossile.

(*) *Traduzione a cura della Redazione.*

Антропогенное нарушение углеродного цикла и биосферы

Резюме. — Показано, что скорость чистого поглощения углреода океаном из атмосферы пропорциональна приросту массы углерода в атмосфере по сравнению с прединдустриальным стационарном уровнем. Константа пропорциональности найдена из данных об изменении содержания радиоуглерода в древесных кольцах и данных о выбросах CO_2 из ископаемого топлива. Величина поглощения опреде-ляется биологическими процессами в океане. Скорость биологического поглощения океаном примерно на порядок превосходит физико-химическое чистое поглощение океаном. Накопление углерода в атмосфере определяется в основном выбросами углерода из наземной части биосферы, а не из резервуара ископаемого топлива.