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Atmospheric CO_2 and Destructivity of the Land Biota: Seasonal Variations.

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Summary. — The seasonal variations of the carbon content in the ocean are shown to be small as compared to those taking place in the atmosphere. Atmospheric meridional mixing is not intense enough to compensate for the variations of the atmospheric CO_2. If we assume meridional mixing to be zero, then the seasonal variations of carbon in the atmospheric column should be equal to those of carbon in the continental bionass but opposite to them in sign. This latter value is essentially the difference between productivity and destructivity of the land biomass. Productivity of humid areas at any latitude is proportional to the diurnal mean solar radiation flux at that latitude. In the present study the temporal variations of this flux are harmonically approximated. Further, an harmonic approximation is found for expressing the temporal course of biomass destructivity at various latitudes. Productivity/destructivity oscillations appear to be almost in couterphase but amplitudinally close to each other.

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1. – Introduction.

The aim of the present study is to obtain the data on the spatial-temporal distribution of the global destructivity of the land surface biota from the measurements of its productivity and of the atmospheric CO_2 concentration.

The land surface biota productivity is limited by the fluxes of solar energy and of precipitated water. Productivity may be theoretically estimated from the empirical data on the latter variables (1-3) (see sect. **3**). The limits of productivity variations are known. Quite a few studies dedicated to direct measurements of land surface biota productivity have been published (1,2,4). Moreover, this productivity has been mapped (2,4). Although there are some discrepancies in the referenced data on the global distribution of the land surface biota productivity, it may be considered known to the accuracy of (20÷÷30)% (1,3).

At the same time almost nothing is known about the spatial and temporal distribution of the land surface biota destructivity. There are no natural limits to its value (a bacteria layer about 1 mm thick, containing close to 10^8 cells in the vertical column may effect destructive power comparable to the solar constant (3)). Measurements of the natural biotic destructivity are either extremely complicated or totally impossible. References to measurements of destructivity are practically absent. Various estimates of the destructivity from the data on soil temperature and moisture (5) may differ by several orders of magnitude (3,6). The only feasible way to obtain reliable data on destructivity is to simultaneously measure the changes in biomass and its productivity.

The variations in the land surface biomass are related in a unique way to variations in the atmospheric CO_2 concentration ($[CO_2]_{atm}$). In particular, the analyses of the isotope content in the atmosphere show that variations of the $[CO_2]_{atm}$ reflect primarily the variations in the land surface biomass and not the seasonal meridional redistribution of CO_2 within the atmosphere. In the beginning of the 60's the atmospheric concentration of ^{14}C suddenly leaped and doubled. With biota still containing the same amount of ^{14}C and releasing CO_2, the ratio of $^{14}C/^{12}C$ in the atmosphere should have decreased. As a results the oscillations of this ratio ($\Delta\,^{14}C$) should have been in counterphase to those of $[^{12}C]_{atm}$, which was found to be exactly the case (7,8). The situation is similar for the isotope ^{13}C since its biotic content is lower than the atmospheric one (9). If the variations in the concentration of carbon in the atmosphere were primarily

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(1) F. H. WHITTAKER and G. E. LIKENS: in *Primary Production of the Biosphere*, edited by H. LIETH and R. WHITTAKER (New York, N. Y., 1975).

(2) H. LIETH: in *Primary Production of the Biosphere*, edited by R. WHITTAKER (New York, N. Y., 1975).

(3) V. G. GORSHKOV: *Energetics of the Biosphere* (Leningrad Polytechnical Institute, Leningrad, 1982), in Russian.

(4) L. E. RODIN, N. I. BAZILEVICH and N. N. ROZOV: in *Productivity of Worls Ecosystems*, edited by R. H. REICHLE, J. F. FRANKLIN and D. W. GOODALL (Washington, D.C., 1975).

(5) I. FUNG, K. PRENTICE, E. MATTHEWS, J. LERNEL and G. RUSSELL: *J. Geophys. Res. C*, **88**, 1281 (1983).

(6) G. G. WINBERG: *Proc. Mod. Biol.*, **21**, 401 (1946).

(7) R. NYDAL and K. LÖVSETH: *J. Geophys. Res.*, *C*, **88**, 3621 (1983).

(8) E. M. DRUFFEL and H. S. SUESS: *J. Geophys. Res. C*, **88**, 1271 (1983).

(9) G. I. PEARMAN and P. HYSON: *J. Geophys. Res. C*, **85**, 4468 (1980).

due to redistribution of the atmospheric CO_2, such a phenomenon would not have been observed.

The annual cycle of the atmospheric CO_2 is observed practically everywhere on Earth (10). Since the total amount of terrestrial carbon is constant, such variations of the atmospheric CO_2 reflect the seasonal redistribution of carbon among the atmospheric, biospheric and oceanic reservoirs. The observed oscillations display certain informative features (fig. 1):

1) The seasonal amplitude of the oscillations is at its maximum in the northern areas where it reaches 3% of the $[CO_2]_{atm}$, dropping linearly from 8.5 p.p.m.v. over Sweden and Alaska to 1 p.p.m.v. at the equator. In the Southern Hemisphere such amplitude nowhere exceeds 1 p.p.m.v. (10-12).

2) At a given latitude the amplitude of the oscillations apparently remains constant and unchanging both above the oceans and the continents (13,14).

3) In the northern areas (Alaska, Sweden) the oscillations have sharp minima and broad plateaulike maxima; against these maxima further oscillations may be observed. Such secondary fluctuations remain in the range of tenths of the value of the amplitude itself. The plateaux broaden with increasing latitude, while in the low latitudes the oscillations are practically symmetrical (10-15).

4) In the low latitudes of the Northern Hemisphere (~ 20 N) the oscillations minima take in the beginning of October and shift with increasing latitude to summer months, so that at (60÷70) N they occur in late August (16). At a given latitude the oscillations synchronously peak both over land and sea (10-14).

Latitudinal variations of the oscillations' amplitudes shown that the characteristic time constant of meridional mixing of the atmosphere, τ_M, should not be much shorter than the oscillation period $T = 1$ year. The presence of

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(10) L. Machta, K. Hansen and C. D. Keeling: in *The Fate of Fossil Fuel* CO_2 *in the Oceans*, edited by N. R. Andersen and A. Malahoff (London, 1977).

(11) D. C. Lows, P. R. Guenther and C. D. Keeling: *Tellus*, **31**, 58 (1979).

(12) C. D. Keeling, J. A. Adams, C. A. Elcdahl and P. R. Guenther jr.: *Tellus*, **28**, 533, 552 (1976).

(13) J. T. Peterson, W. D. Komhyr, T. B. Harris and L. S. Waterman: *Tellus*, **34**, 166 (1982).

(14) Ocean Station Charlie: *Atmospheric carbon dioxide flask sample 1968-1973*, in: *Global Monitoring of the Environment for Selected Atmospheric Constituents*, Part III: *Carbon Dioxide Environmental Data Service* (New York, N. Y., 1977).

(15) C. S. Wong, Y.-H. Chen, J. S. Page and R. D. Bellegay: *J. Geophys Res. D*, **89**, 9527 (1984).

(16) P. J. Fraser, G. I. Pearman and P. Nyson: *J. Geophys. Res. C*, **88**, 3591 (1983).

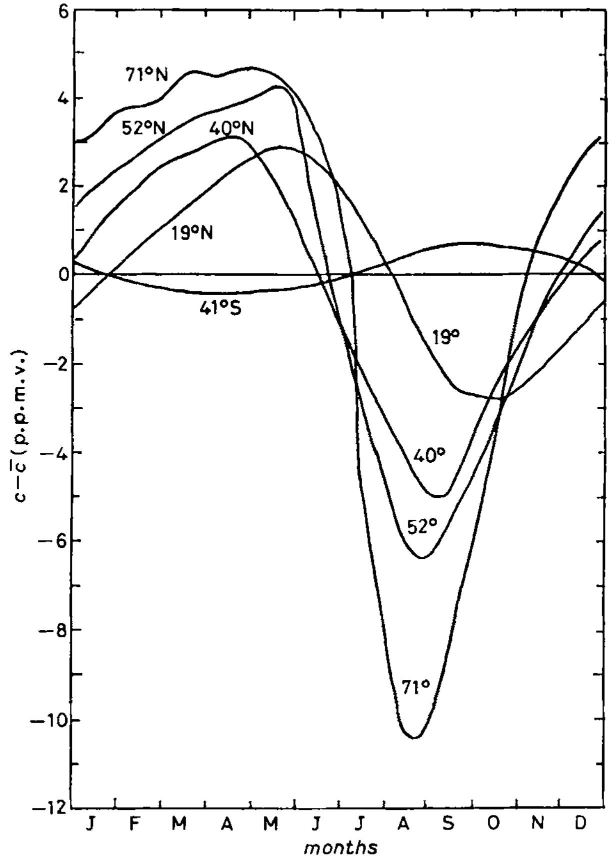

Fig. 1. – Atmospheric carbon dioxide oscillations at various latitudes. The linear increase in the annual averages is detracted from the montly means for each year. Obtained values are averaged for every separate year. Each solid line corresponds to a separate station: BA: Barrow, Alaska (71.19 N, 156.36 W, elevation: 11.3 m, 1971-1975) (^{10,13}); SC: Ocean Station Charlie (52.00 N, 35.00 W, 6.4 m, 1968-1973) (^{10,14}); NR: Niwot Ridge, Colorado (40.03 N, 105.38 W, 3749 m, 1970-1976) (^{10}); ML: Mauna Loa (19.32 N, 155.35 W, 3397 m, 1973-1976) (^{10,12}); BH: Baring Head (41.24 S, 179.54 E, 80 m, 1973-1976) (^{11}); SP: South Pole (0.0 S, 2800 m, 1973-1976) (^{10,11}).

wintertime plateaux in the oscillation curves for high latitudes of the Northern Hemisphere may be attributed to lack of vegetation in these areas. During this season variations of CO_2 concentration are equalized through meridional mixing. The low slope of the plateaus and the fact that their mean levels vary from site to site at different northern latitudes show that $\tau_M > T$. Therefore, to a first approximation, meridional mixing may be neglected. The presence of CO_2 oscillations over an oceanic area removed more than 1000 km from shore (Station Charlie, 52.00 N, 35.00 W) testifies to quite short times of latitudinal mixing, so that $\tau_L \ll T$. Thus the amplitudes of CO_2 oscillations may be considered to be approximately independent of longitude. Such an approximation agrees with the data on the mean structure of global circulation to a relative accuracy of about 20% (17).

2. – Oceanic CO_2 content: assessment of seasonal oscillations.

It may be suggested from the presence of such oscillations that the physicochemical absorptivity of the oceanic waters is weak. Their carbon-storing capacity exceeds that of the atmosphere by two orders of magnitude. The time constant for absorption of excessive carbon dioxide by the ocean cannot be significantly less than one year: were it not so, the atmospheric CO_2 oscillations would have been absent.

Variations in the concentration of oceanic CO_2 ($[CO_2]_{oc}$) are governed by variations in the $[CO_2]_{atm}$ and in the CO_2 solubility (β). The latter is temperature dependent:

$$\beta = 1.0 \quad \text{at} \quad t = 15\ ^\circ\text{C}, \qquad \Delta\beta = 0.3 \quad \text{for} \quad \Delta t \sim 10\ ^\circ\text{C}.$$

The atmosphere/ocean fluxes of CO_2 are governed by the rate of molecular diffusion through the surface film of a thickness $L_a = 30\ \mu\text{m}$ (16, 18):

$$F_a = \mu(D_a/L_a)\big(\Delta(\beta[CO_2]_{atm})\big) = \mu F_a^{imp} \frac{\Delta(\beta[CO_2]_{atm})}{([CO_2]_{atm})},$$

$$F_a^{imp} = (D_a/L_a)\beta[CO_2]_{atm} \doteq 20\ \text{mol C}/(\text{m}^2\ \text{y}),$$

where μ is the ratio of total water surface to its projection upon the aquatoria ($\mu = 1$ for calm water, increasing manifold for rough seas; we shall assume $\mu \sim 1$ for our estimates); $D_a = 10^{-5}\ \text{cm}^2/\text{s}$ is the molecular diffusion coefficient for CO_2 (18); F_a^{imp} is the CO_2 import into the ocean through the horizontal surface.

If there is no CO_2 gradient, the CO_2 import is in balance with its export. If the concentration of oceanic CO_2 is zero, the value F_a^{imp} presents the maximum diffusion flux possible. The amount of CO_2 that penetrates into the ocean from the atmosphere (or *vice versa*) through the unit area of the aquatoria during the basic period of the $[CO_2]_{atm}$ turnover, τ ($\tau = 4$ months, cf. fig. 1) is given by

$$\Delta C_0 = \mu F_a^{imp}\, \tau(\Delta[CO_2]_{atm}/[CO_2]_{atm} + \Delta\beta/\beta).$$

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(17) E. Palmen and C. W. Newton: *Atmospheric Circulation Systems* (Academic Press, New York, N. Y., 1969).

(18) W. S. Broecker and T. H. Peng: *Tellus*, **26**, 21 (1974).

The variation of the amount of CO_2 in the atmospheric column, ΔC_a, is further given by

$$\Delta C_a = H_a \Delta[CO_2]_{atm} = C_a(\Delta[CO_2]_{atm}/[CO_2]_{atm}),$$

$$C_a = H_a[CO_2]_{atm} = 110 \text{ mol C/m}^2, \qquad H_a = p_a/(\varrho_a g) = 8.6 \text{ km},$$

$$[CO_2]_{atm} = 1.4 \cdot 10^{-2} \text{ mol C/m}^3,$$

where C_a is the above-said amount, H_a is the atmospheric scale height, p_a and ϱ_a are the surface atmospheric pressure and air density, respectively.

Let us assume that the oceanic waters mix instantly. Then the ratio of the seasonal variations of CO_2 in two media (atmosphere and ocean) is given by

$$\Delta C_0/\Delta C_a = (\mu F_a^{imp} \tau/C_a)(1 + x) = 0.05(1 + x),$$

$$x = (\Delta\beta/\beta)/(\Delta[CO_2]_{atm}/[CO_2]_{atm}).$$

If the water temperature is constant then $x = 0$. In that case not more than 5 % of the excessive atmospheric CO_2 has enough time to penetrate the ocean surface. The change of water temperature by 10 °C brings about a 30 % change in CO_2 solubility. Simultaneously, $[CO_2]_{atm}$ varies by 3 % only (cf. fig. 1). If this is the case, then $x \sim 10$ and up to 50 % of the excessive atmospheric CO_2 may penetrate into the ocean. However, the surface water layer in which such a temperature drop occurs is apparently not thicker than $H_T = (5 \div 10)$ m ([19]). The variation of the total amount of CO_2 in this layer may be readily assessed ([20,21]):

$$\Delta C_{ot} = H_T \Delta[\Sigma CO_2] = H_T(\xi\zeta)^{-1}[CO_2]_{atm}\Delta\beta,$$

$$\Delta[\Sigma CO_2] = (\xi\zeta)^{-1}\Delta[CO_2], \qquad \xi \equiv [CO_2]/[\Sigma CO_2] = 0.5 \cdot 10^{-2},$$

$$\zeta \equiv \ln [CO_2]/d \ln [\Sigma CO_2] = 10, \qquad (\xi\zeta)^{-1} = 20,$$

$$\Delta[CO_2] = [CO_2]_{atm}\Delta\beta.$$

It follows that:

$$\Delta C_{ot}/\Delta C_a = H_T/H_a(\xi\zeta)^{-1}(\Delta\beta)[CO_2]_{atm}/\Delta[CO_2]_{atm} \doteq 0.1 \div 0.2.$$

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[19] A. IVANOV: *Introduction à la Oceanographie*, Vol. **1** (Paris, 1972), Vol. **2** (Paris, 1975).

[20] V. G. GORSHKOV: *Nuovo Cimento C*, **5**, 209 (1982).

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

Therefore, with an error of $(10 \div 20)\%$, we may state that the ocean plays no role in the seasonal variations of CO_2. Hence, within the assumptions of weak meridional mixing of the atmosphere, the seasonal variations of the atmospheric carbon ($\mathrm{d}C/\mathrm{d}t$) should be equal to but opposite in sign to variations in the biomass ($\mathrm{d}B/\mathrm{d}t \doteq -\,\mathrm{d}C/\mathrm{d}t$). Variations of the phitoplanktonic mass are negligible, since it is low itself (1). Therefore, the variable $\mathrm{d}B/\mathrm{d}t$ is totally controlled by the variations in the continental biomass.

Note that it is the ocean and not the atmosphere which serves as the principal source of CO_2 for the phytoplankton. The amount of CO_2 reaching the oceanic photic layer is $F_a^{\mathrm{imp}} = (D_a/L_a)[CO_2]_{\mathrm{atm}} = 20$ mol C/m² year. At the same time the amount of CO_2 coming into the photic layer from the ocean is

$$F_o^{\mathrm{imp}} = (D_{\mathrm{ph}}/L_{\mathrm{ph}})[\Sigma CO_2] > 2000 \text{ mol C/(m}^2\text{ year)}\,.$$

Here

$$D_{\mathrm{ph}} > 10 D_{\mathrm{d}} \doteq 4\cdot 10^4 \text{ m}^2/\text{year}\,, \qquad D_{\mathrm{d}} = 4\cdot 10^3 \text{ m}^2/\text{year}\,,$$

are the eddy diffusion coefficients for the photic and deep oceanic layers, respectively (19,21,22); $L_{\mathrm{ph}} \sim 25$ m is the thickness of the photic layer (19). The values F_a^{imp} and F_o^{imp} are equal to the total import of carbon atoms into the photic layer from the atmosphere (a) and ocean (o). In a stationary case the import and export of carbon are mutually balanced. The ratio of the respective quantities of CO_2 utilized by the phytoplankton is $F_a^{\mathrm{imp}}/F_o^{\mathrm{imp}} < 0.01$.

3. – Primary continental output.

The variation of the biomass density, B, over the unit area of the land surface (this value is sometimes called « the net ecosystem productivity » NEP) is given by the equation

$$\mathrm{d}B/\mathrm{d}t = P - J\,, \qquad \mathrm{d}C/\mathrm{d}t \doteq -\,\mathrm{d}B/\mathrm{d}t\,, \tag{1}$$

where P and J are the fluxes, respectively, due to synthesis by vegetation (« net primary productivity » NPP) and to its destruction by all the heterotrophs. The net productivity of the ocean is comparable to that of the land surface, while the oceanic live biomass is less than that on land by a factor of 1000 (21). Therefore, even to the third decimal position, the seasonal variations of the oceanic productivity, P, are compensated by the synchronous variations of destructivity, J. Recalling (1) and noting the observed variations of the land surface biomass we may deduce that variations of P and J occur nonsynchronously.

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(22) H. OESHGER, U. SCHOTTERER and A. GUGELMAN: *Tellus*, **27**, 168 (1978).

Throughout the present study the symbol $\mathrm{d}Z/\mathrm{d}t$ stands for seasonal temporal derivative minus the respective mean annual value of a given variable $(\overline{\mathrm{d}Z_{\text{tot}}/\mathrm{d}t})$: $\mathrm{d}Z/\mathrm{d}t = \mathrm{d}Z_{\text{tot}}/\mathrm{d}t - \overline{\mathrm{d}Z_{\text{tot}}/\mathrm{d}t}$, where $Z = B$ or C. The principal features of the CO_2 seasonal variations remain basically unchanged throughout the geological epochs. However, the mean annual values of respective derivatives may have significantly changed during the industrial era. Any minor disbalance of the production and destruction fluxes in the ocean may result in enormous changes of the amount of dead organic matter as compared to negligible variations of live biomass:

$$\overline{\mathrm{d}B_{\text{tot}}/\mathrm{d}t} = \bar{P} - \bar{J} \sim 0.1\bar{P} \sim (10^2 - 5\cdot 10^3)\,\mathrm{d}B/\mathrm{d}t \ (^{20})\,.$$

The principal input to the global primary production is provided by the humid zones (^{21}). The primary productivity of the humid zones may be considered proportional to the diurnal mean solar energy flux, I. Within the latitudinal belt $15° \leqslant \varphi \leqslant 75°$ the dependence of I on time and geographical latitude may, to a 10% accuracy ($I \geqslant 0.10 I_{\max}$), be presented by the principal harmonic as follows (cf. table I):

$$(2) \qquad \begin{cases} I = I_0 + A_{\text{I}}\omega \sin\omega t\,, \quad I_0 = I_e r(\chi, n)\,, \quad A_{\text{I}}\omega = I_e k(\chi, n)\,, \\ \omega = 2\pi/T\,, \quad T = 1 \text{ year}\,, \quad \chi \equiv |\varphi|/90°\,, \end{cases}$$

where $t = 0$ corresponds to the moment of Spring equinox (22 March), I_e is the diurnal mean solar energy flux at the equator, $r(\chi, n)$ and $k(\chi, n)$ are the functions of latitude and atmospheric transparency, n. Applying the least-square technique (LST) we may retrieve these functions as polynomials of the variable χ. Table I gives respective linear and quadratic approximations for

TABLE I. – *Harmonic approximations of the diurnal mean solar energy flux within the latitudinal belt* $15° \leqslant |\varphi| \leqslant 75°$.

Atmospheric transparency n	Latitudinal interpolation									
	Linear				Quadratic					
	k_0^1	k_1^1	r_0^1	r_1^1	k_0^2	k_1^2	k_2^2	r_0^2	r_1^2	r_2^2
1.0	0.12	0.53	1.0	− 0.86	− 0.036	1.26	− 0.167	0.83	− 0.072	− 0.180
0.9	0.14	0.40	0.86	− 0.83	− 0.041	1.24	− 0.190	0.71	− 0.127	− 0.159
0.8	0.15	0.29	0.73	− 0.75	− 0.032	1.12	− 0.190	0.61	− 0.193	− 0.126
0.7	0.14	0.19	0.60	− 0.66	− 0.016	0.94	− 0.175	0.51	− 0.24	− 0.090
0.6	0.13	0.12	0.48	− 0.65	− 0.002	0.77	− 0.150	0.42	− 0.26	− 0.058

Note: here n is the atmospheric transparency; $I = I_e(r + k \sin\omega t)$ is the diurnal mean solar energy flux; I_e is the maximum diurnal mean solar energy flux at the equator ($I_e = I_c/\pi$ for $n = 1$, I_c is the solar constant); t is time, $t = 0$ is the moment of Spring equinox; $\omega = 2\pi/T$, $T = 1$ year; $k = k_0 + k_1^i\chi + k_2^i\chi^2$; $r = r_0^i + r_1^i\chi + r_2^i\chi^2$; $i = 1, 2$; $k_2^1 = r_2^1 = 0$; $\chi = |\varphi|/90°$; φ is latitude, degrees.

various values of n. The values presented in table I were derived applying LST. For $I \geqslant 0.10\ I_e$ the maximum deviation from the true value of I reaches 10% in case of linear interpolation ($15° \leqslant \varphi \leqslant 70°$) and 5% in case of quadratic interpolation ($15° \leqslant \varphi \leqslant 75°$).

The input of the mean latitudinal land surface productivity, P, may be obtained multiplying either the average land surface productivity ([2,4]) by the ratio of land to total Earth circumference at a given latitude (l_c), or the maximum output of the humid areas by the relative effective length of these areas (l) (fig. 2). Assuming that the maximum productivity is proportional to the incoming solar energy we obtain

$$(3) \quad \begin{cases} P = P_0 + A_p\,\omega \sin \omega t\,, \quad P_0 = P_e \cdot r \cdot l\,, \quad A_p \omega = P \cdot k \cdot l & \text{for } t_1 \leqslant t \leqslant t_2\,, \\ P = 0 & \text{for } t_2 \leqslant t \leqslant t_1 + T,\ \omega = 2\pi/T\,, \end{cases}$$

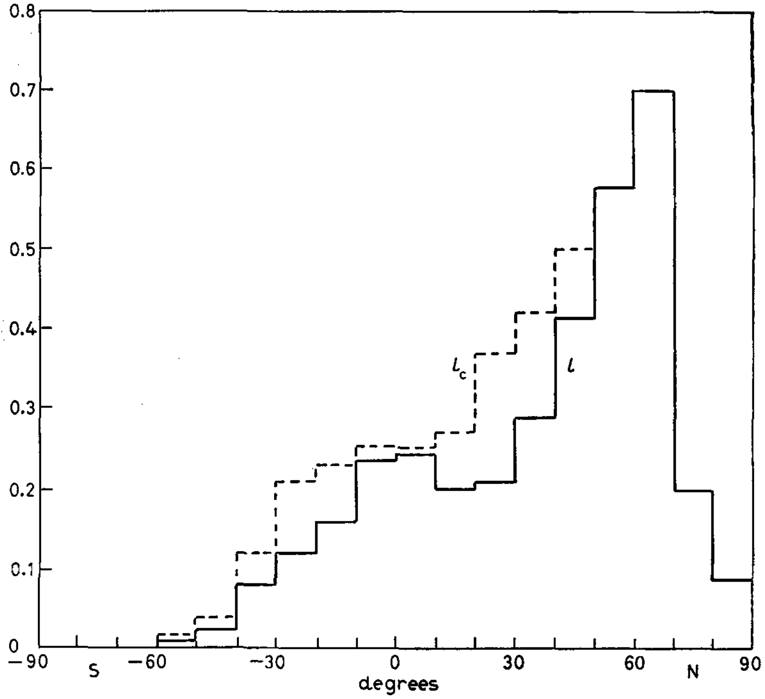

Fig. 2. – Observed and potential land surface productivity. The dashed line (l_c) is the ratio of the ice-free land to total Earth circumferences at a given latitude. The solid line corresponds to value $l = (\bar{P}/P_{\max})l_c$, where $\bar{P}$ and $P_{\max}$ are, respectively, the average and maximum productivity at a given latitude (the latter for humid areas). Both are estimated from the maps of productivity ([2,4]). The error bars present the estimated uncertainty in the measurement data on primary productivity of respective land areas. The area between the solid and dashed lines gives the ratio of the land surface with drawn from the productive cycle in the process of desertification to the total Earth surface.

where $P_e = 83 \text{ mol C}/(\text{m}^2\,\text{y})$ is the productivity of the equatorial humid areas (1), t_1 and t_2 are the starting and ceasing moments for the vegetation period.

4. – Oscillations: amplitudes and phases.

According to observational data the variations of $[\text{CO}_2]_{\text{atm}}$ have an indefinite phase lag with respect to the solar energy flux. This lag depends on the time needed for the bulk of carbon dioxide to mix throughout the vertical atmospheric column (23-26). With the vertical eddy diffusion coefficient having the value of $D_\perp = 2\cdot 10^5 \text{ cm}^2/\text{s}$ (23,26) such vertical mixing, even up to the level of the highest existing observational stations ($H_{\max} = 3.8$ km), takes about $\tau_\perp = H_{\max}/D_\perp = 8$ days.

The secularly averaged deviation of the atmospheric carbon content C from its annual mean $\bar{C}$ may be expressed as

$$(4)\qquad \begin{cases} C \equiv C_a - \bar{C} = C_0 + A_c \sin(\omega t + \pi/2 + \alpha)\,, & \\ \mathrm{d}C/\mathrm{d}t = -A_c\omega \sin(\omega t + \alpha) & \text{for } t_1 \leqslant t \leqslant t_2\,, \\ C = C_{\text{pl}}\,, \quad \mathrm{d}C/\mathrm{d}t = 0 & \text{for } t_2 < t < t_1 + T,\ \omega = 2\pi/T\,, \end{cases}$$

where C_a is the CO$_2$ content in the atmospheric column, C_{pl} is the winter plateau average, α is the phase shift, $T = 1$ year. Let us assume that C_{pl} is constant. Then the values t_1 and t_2 may be shown to relate as following: $t_1 + t_2 = T - \alpha T/\pi$. It follows from this condition that the average $\mathrm{d}C/\mathrm{d}t$ and, therefore, the difference $(P - J)$ (see (1)) are both equal to zero within the range $t_2 \leqslant t \leqslant t_1 + T$. Value t_1, C_0 and α may be used as free parameters to fit (4) to observational data applying LST. With t_1, α and C_0 values at hand the amplitude A_c in (4) may be uniquely expressed in terms of the observed value $C_{\min} = (\bar{C} - C_{a\max})$ (cf. fig. 1). $C_{\min}$ is the amplitude of the carbon content depletion against its annual mean. The amplitude thus retrieved appears to be somewhat larger than the half-distance between the maximum and minimum values of $[\text{CO}_2]_{\text{atm}}$ (fig. 1). For $\varphi < 40$ °N we may use the following approximation: $C_0 = 0$; $A_c = C_{\min}$, *i.e.* measure the amplitude as the difference between the minimum value of $[\text{CO}_2]_{\text{atm}}$ and its annual mean, thus avoiding the need to account for the finite duration of the vegation period. The phase α of the oscillating CO$_2$ concentration may also be determined from the temporal position

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(23) B. Bolin and W. Bischof: *Tellus*, **22**, 431 (1970).

(24) J. B. Carrat and G. I. Pearman: *Atmos. Environ.*, **7**, 1257 (1973).

(25) H. D. Freyer: in *The Global Carbon Cycle*, edited by B. Bolin, N. T. Degens, S. Kempe and P. Ketner (Wiley, New York, N. Y., 1979).

(26) P. Hyson, P. J. Fraser and G. I. Pearman: *J. Geophys. Res.*, *C*, **85**, 443 (1980).

TABLE II. – *Amplitudes and phases of* 1) *carbon content in atmosphere,* 2) *production and destruction of biota, and* 3) *duration of vegetation periods for the Northern Hemisphere.*

Observed site	A	BA	P	SC	S	NR	BH	KB	ML
latitude (degrees)	82.5	71.2	56	52	44	40	30	25.4	19.3
c_{pl} p.p.m.v.	2.7	3.8	3.0	3.0	4.4	2.3	—	—	—
c_{min} p.p.m.v.	7.5	10.3	8.0	5.6	9.4	4.0	2.7	3.0	2.9
α days	19	22	15	15	18	11	0	0	0
a_G p.p.m.v.	13.9	18.5	15.2	7.6	13.6	4.8	3.3	3.1	3.0
a_P p.p.m.v.	1.2	6.0	5.7	5.8	4.1	3.9	2	1.5	1.4
a_J p.p.m.v.	12.7	13.1	9.7	2.3	10.1	1.2	0.7	1.5	1.5
δ days	194	210	209	221	217	228	182	182	182
t_1 day	June 22	June 12	June 5	May 31	May 23	May 21	—	—	—
t_2 day	November 20	November 14	November 22	December 15	November 28	December 26	—	—	—
$t_{max\,j}$ day	December 1	November 15	November 29	November 4	November 8	October 28	December 22	December 22	December 22

Note: c_{pl}, c_{min} and α are the observed plato, minimum of CO_2 concentration and its phase shift. (Concentration count off from year mean.) The amplitude a_G, α and value t are calculated by least squares fitting (4) to the observed values (fig. 1). ($t = 0$ is the moment of Spring equinox, $t_2 = -t_1 + T(1 - \alpha/\pi)$). The value of a_P is calculated from productivity norms, using relationships (3); amplitude and phase of destructivity a_J and δ from relationships (5).

of its observed minimum. In case of such an approximation the differences in amplitudes and phases do not deviate from those retrieved using the LST (table II) by more than 24 %, *i.e.* they stay within the accuracies assumed for the purpose of the present study.

Using (1), (3) and (4) together we obtain

$$(5)\qquad \begin{cases} J = \mathrm{d}C/\mathrm{d}t + P = J_0 + A_J\omega \sin(\omega t + \delta) & \text{for } t_1 \leqslant t \leqslant t_2 , \\ J = 0 & \text{for } t_2 < t < t_1 + T , \\ J_0 = P_0 , \quad A_J = A_P\varepsilon , \quad \varepsilon = (1 - 2\gamma\cos\alpha + \gamma^2)^{\frac{1}{2}} , & \gamma = A_C/A_P , \\ \cos\delta = (1 - \gamma\cos\alpha)/\varepsilon , \quad \sin\delta = -(\gamma\sin\alpha)/\varepsilon , & \\ \delta = \begin{cases} \pi + [\gamma/(\gamma - 1)]\alpha + O(\alpha^2) & \text{for } \gamma > 1 , \\ -[\gamma/(1-\gamma)]\alpha + O(\alpha^2) & \text{for } \gamma < 1 . \end{cases} & \end{cases}$$

The value and sign of phase δ is uniquely determined by the values and signs of $\cos\delta$ and $\sin\delta$. For $\alpha = 0$ relationships (5) obviously yield the following: for $A_C > A_P$ the oscillations of J must be in counterphase with P and the components relate as following: $A_C = A_P + A_J$; P and J oscillate in phase and $A_C = A_P - A_J$ for $A_C < A_P$. Unlike the productivity, P, limited by the solar energy flux, the destruction flux, J, is practically unlimited and, during certain periods, may significantly outweigh the synthesis flux. In such a case there holds the relationship $A_C \doteq A_J \gg A_P$.

The atmospheric content of CO_2 is usually given in relative volume units: $C_a = [CO_2]_{atm}\,\varrho_a^{-1} M_a \cdot 10^{-6}$, parts per million (p.p.m.v.). Here $\varrho_a M_a^{-1}$ is the surface air molar density. The variations of the CO_2 content, productivity, destructivity and their amplitudes may be similarly expressed. To discriminate these values from those referring to the atmospheric column we shall use lower case to denote the latter: (c, p, j). The two sets of variables are related as follows:

$$(6)\qquad C/c = P/p = J/j = A/a = (p_a/g)\,M_a^{-1}\cdot 10^{-6} = 0.36\ \text{mol C/m}^2 ,$$

where p_a is the surface pressure, $M_a = 29$ g/mol is the molar mass of air. Thus 1 p.p.m.v. corresponds to 0.36 mol C/m², *e.g.* $P_e = 83$ mol C/(m² year) corresponds to $p_e = 230$ p.p.m.v./year.

The results of experimental data analyses are presented in fig. 3 and 4. The average observed values correspond to the case $A_C > A_P$, *i.e.* the destructivity oscillates almost in counterphase with productivity. The productivity is « turned on » at the beginning of the vegetation period, and the destructivity at its end, when both variables are close to their maxima (fig. 3). Since the measurement errors are large one cannot exclude the case of $A_C \doteq A_P$, *i.e.* of practically constant rate of consumption by the biota. The case in which

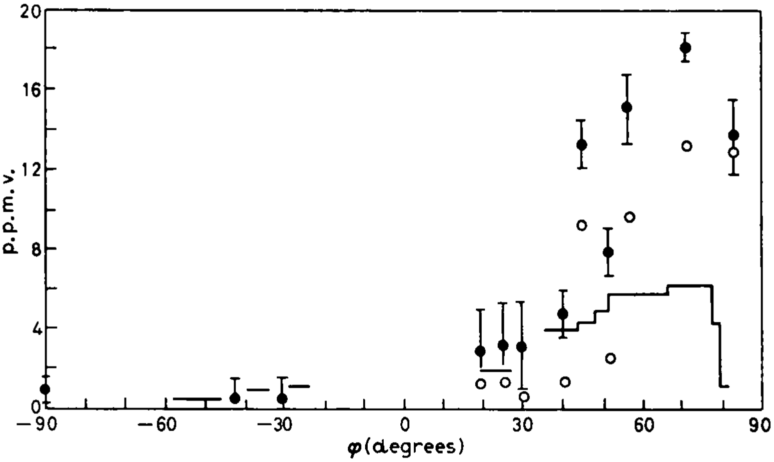

Fig. 3. – Biomass, land surface productivity and destructivity amplitudes. Measurement sites are as follows: A: Alert (82.5° N, 62.3° W, 140 m); P: Papa (50° N, 145° W, 6 m); S: Sable (44° N, 60° W, 5 m); B: Bermuda (32.23 N, 64.41 W, 30.5 m, 1975); KB: Kay Biscane (25.40 N, 80.10 W, 3 m, 1972-1974); A: Australia (28 S) (10,15); for other notations see fig. 1. The solid line gives the observed amplitude, a_p, of primary productivity oscillations $a_p = pl_c/\omega = p_{\max} l/\omega$ as computed from the productivity maps (2,4), cf. fig. 2. $\omega = 2\pi/T$; $T = 1$ y. Dashed line: the potential amplitude of oscillations of the primary productivity $a_p = p_{\max} l_c/\omega$, cf. fig. 2; ● observed amplitude, a_c, of the atmospheric oscillations of $[CO_2]_{atm}$, o calculated amplitude of destructivity of the primary output.

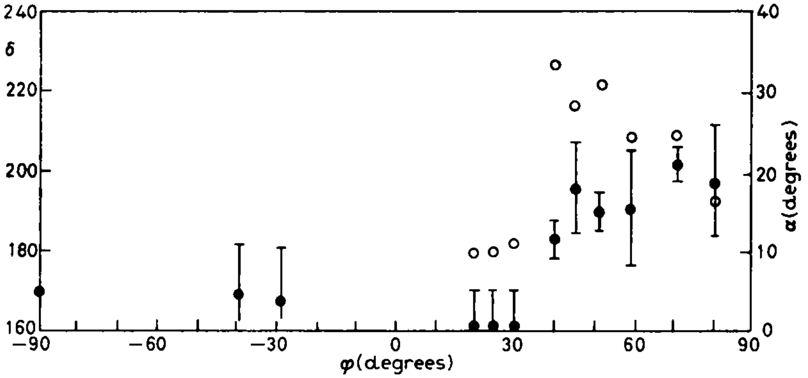

Fig. 4. – Oscillation phases of the land surface biomass destructivity. For notations see fig. 1, 3. ● observed phase lag, α, of the oscillations of $[CO_2]_{atm}$ with respect to the phase of the oscillations of primary output (*i.e.* the solar phase), degrees (right scale); o calculated phase lag, δ, of the oscillations of destructivity, degrees (left scale).

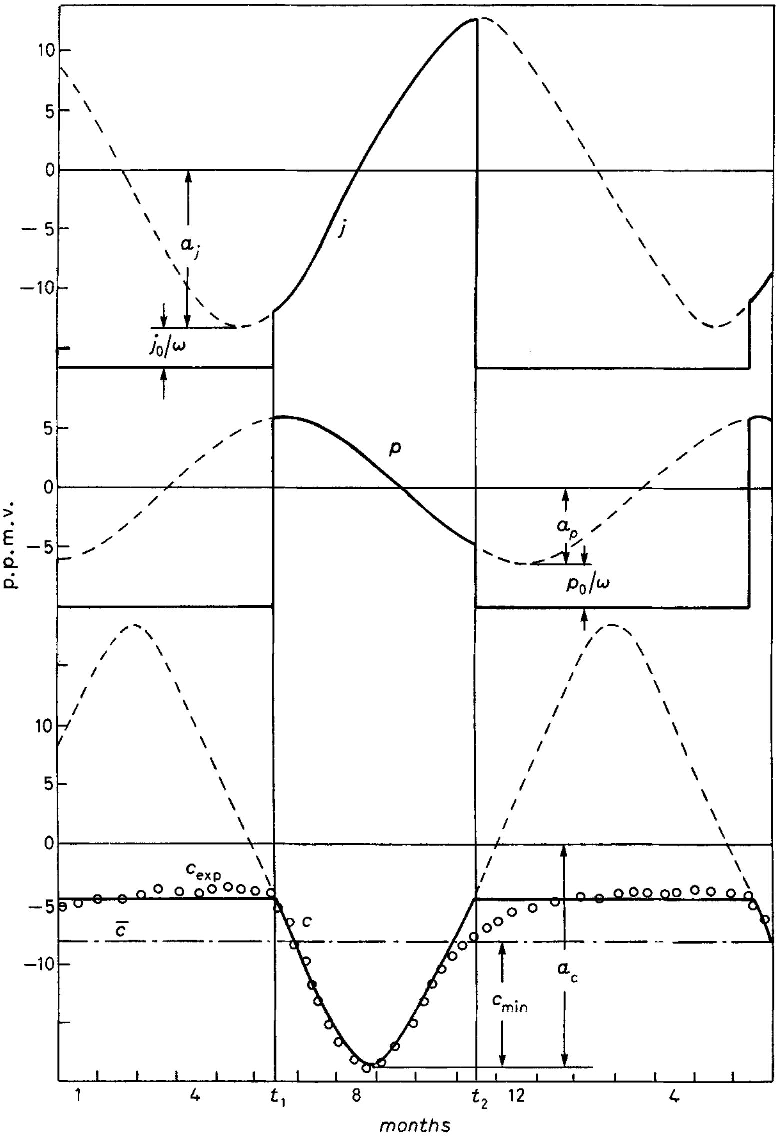

Fig. 5. – Productivity and destructivity at Barrow, Alaska. Heavy solid lines present: c is the harmonic approximation (4) of the variations of CO_2 content in the atmospheric column (c_{exp} is the same value, observed); p and j are the harmonic approximations of productivity and destructivity; t_1 and t_2 are time limits of the vegetation period; α and δ are phase lags of the values (curves) c and j, respectively, with respect to p; a_p, a_j and a_c are respective amplitudes. c_p is the average level of wintertime plateau; $\bar{c}$ is the annual mean.

both variables P and J have similar amplitudes $A_P \doteq A_J$ and oscillate in phase to each other is totally excluded. If no information on values and variations of the phase and amplitude of destructivity is available, the value and variations of productivity cannot be retrieved from the observed amplitude, A_C, alone (cf. ([10,27,28])).

5. – Discussion.

It was assumed for the purpose of the present study that

$$(7)\qquad \begin{cases} \tau_M > \tau \gg \tau_L & \text{or} \quad F_M < \mathrm{d}C/\mathrm{d}t \ll F_L\,, \\ \tau \equiv A_C/(\mathrm{d}C/\mathrm{d}t)\,, & \tau_M \equiv A_C/F_M\,, \quad \tau_L \equiv A_C/F_L\,, \end{cases}$$

where A_c is the amplitude of the oscillations of carbon content in the atmospheric column, as determined in sect. **4**, τ is the time span during which the value of $[CO_2]_{atm}$ goes through its basic annual overturn, τ_M and F_M (τ_L, F_L) are, respectively, time and atmospheric flux of CO_2 (due to advection plus diffusion), indexed for meridional (M) and latitudinal (L) components. The relationships (7) stem from analysing the features of $[CO_2]_{atm}$ oscillations over different parts of the globe (sect. **1**). If relationships (7) hold then the second approximation in (1) holds too. The atmospheric fluxes may be accounted for using the atmospheric general circulation models (GCMs). In a number of studies ([5,9]) such models were constructed using the data on diffusion of the industrial wastes ([26]). However, such an approach makes it possible to define only the orders of magnitude of the eddy diffusion coefficients and the average advection rates. The accuracy of such estimates may, for example, be evaluated through assessing the deviation of properties of the extended sources of industrial pollution from singularity.

Calculations of $\mathrm{d}C/\mathrm{d}t$ based on such models ([5]), performed assuming a given structure of P, J and $\mathrm{d}B/\mathrm{d}t$ do not provide a satisfactory agreement between the amplitudes and phases of CO_2 oscillations. Assumption of strong atmospheric latitudinal inhomogeneity leads to underestimates of such amplitudes over the ocean and to overestimates—over the central parts of the continents ([5]), as compared to observational data.

Thus the pattern of the atmospheric circulation may be easily incorporated into the picture of the atmospheric CO_2 oscillations. Such an incorporation should not alter the principal conclusion on the basic features of the destructivity

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([27]) C. A. S. Hall, C. A. Ekdahl and D. E. Wartenberg: *Nature (London)*, **255**, 136 (1975).

([28]) L. Machta: *Bull. Am. Meteorol. Soc.*, **53**, 402 (1972).

distribution as outlined in sect. 4. Adjustment of the results from the present study to atmospheric circulation pattern, based on the existing GCMs, may, on the whole, deteriorate reliability of such conclusions. Therefore, the authors do not consider such adjustments appropriate at the present state of the art.

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● RIASSUNTO (•)

Le variazioni stagionali del contenuto di carbonio nell'oceano sono piccole rispetto a quelle che si verificano nell'atmosfera. Il mescolamento atmosferico meridionale non è abbastanza intenso da compensare le variazioni del CO_2 atmosferico. Se si ammette che il mescolamento sia zero, le variazioni stagionali del carbonio nella colonna atmosferica dovrebbero essere uguali a quelle del carbonio nella biomassa continentale ma opposte a queste ultime come segno. Quest'ultimo valore è essenzialmente la differenza tra la produttività e la distruttività nella biomassa terrestre. La produttività delle aree umide ad ogni latitudine è proporzionale al flusso di radiazione solare diurno medio a quella latitudine. In questo studio si approssimano armonicamente le variazioni temporali di questo flusso. Inoltre si trova un'approssimazione armonica per esprimere l'andamento temporale della distruttività della biomassa a varie latitudini. Le oscillazioni di produttività/distruttività sembrano quasi in controfase ma prossime l'una all'altra per quanto riguarda l'ampiezza.

(•) *Traduzione a cura della Redazione.*

Сезонные колебания атмосферного CO_2 и деструктивности наземной биоты.

Резюме. - Показано, что сезонные изменения содержания углерода в океане малы по сравнению с изменениями в атмосфере. Меридиональное перемешивание атмосферы не успевает выравнивать атмосферные колебания CO_2. В приближении нулевого меридионального перемешиваиия сезонные колебания содержания углерода в атмосферном столбе равны по величине и противоположны по знаку изменению содержания углерода в континентальной биомассе, которое равно разности продуктивности и деструктивности. Продуктивность гумидных областей на разных широтах пропорциональна среднесуточному потоку солнечной радиации на этих широтах. В работе найдено гармоническое приближение для изменения во времени последних величин. С помощью этих данных определено гармоническое приближение для поведения во времени деструктивности на разных широтах. Колебание продуктивности и деструктивности оказались происходящими почти в противофазя с близкими по величине амплитудами.