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CARBON DIOXIDE DYNAMICS OF THE BIOSPHERE[1]

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Abstract.--The seasonal oscillation in atmospheric CO_2 records measured at four worldwide stations were converted to monthly and annual rates of uptake (U) and release (R) of CO_2 to see if new information about the dynamics of the biosphere could be obtained. Our preliminary results show that annual rates of R and UR ratio (from the observed Mauna Loa data) appear to be responding to fossil fuel produced CO_2 inputs; annual U is not, suggesting carbon is accumulating in the biosphere. The amount of fossil fuel produced CO_2 remaining in the atmosphere is about 51-55% at Mauna Loa and the Southern Hemisphere stations, but about 25% at Point Barrow. However, the degree of uncertainty about these estimates is large. The consistency in the timing and magnitude of the monthly U and R rates in the Northern Hemisphere stations suggest no major human impact on the biota. Until more is known about the pattern of CO_2 exchange with the oceans, other sinks or sources of CO_2, and what the airsheds for the various monitoring stations are, we cannot use atmospheric CO_2 data to determine with certainty whether the biota is a source or sink for CO_2.

INTRODUCTION

The concentration of atmospheric CO_2 measured at several worldwide stations (Keeling et al. 1976a and 1976b, Lowe et al. 1979) has attracted the attention of many disciplines, each trying to relate the observations and their particular paradigms to the carbon balance of the world (Broecker et al. 1979, Hall et al. 1973, Junge and Czeplak 1968, Machta et al. 1977, Pearman and Hyson 1980, and Stuiver 1978). The long-term atmospheric CO_2 concentration data (fig. 1a-d) has two trends: a secular rise and a seasonal oscillation. The secular rise corresponds to about one-half of the CO_2 released from the burning of fossil fuels (major source) and the manufacture of cement remaining in the atmosphere, assuming that any releases from the world's biota are insignificant. The seasonal oscillation is attributed to the metabolism of the biosphere (Bolin and Bischof 1970, Hall et al. 1975, Junge and Czeplak 1968, Keeling et al. 1976a and 1976b, Lowe et al. 1979, Machta et al. 1977, Woodwell et al. 1973), and its amplitude varies with latitude from about 15 ppm at Point Barrow (71°N latitude) to about 1 ppm at the South Pole (c.f. Machta et al. 1977 for summary of long-term and short-term measurements). The decrease in amplitude of the seasonal oscillation generally parallels the decreasing ratio of land area to total area in a given latitudinal belt from north to south.

Our interest in the atmospheric CO_2 data was to analyze the seasonal oscillations at the four different stations (fig. 1) by converting CO_2 concentrations into monthly rates of net uptake (U) or net release (R) using established procedures in limnology and terrestrial ecology for analyzing diurnal O_2 or CO_2 measurements. We then applied modeling tools to these rates, with particular emphasis on the extensive Mauna Loa data base, to take out the fossil fuel effects (secular rise) and to see if new information can be obtained about the CO_2 dynamics of the biosphere. Specifically, we raised the following questions:

1. Are the uptake and release rates of CO_2 changing in response to fossil fuel produced CO_2 inputs?

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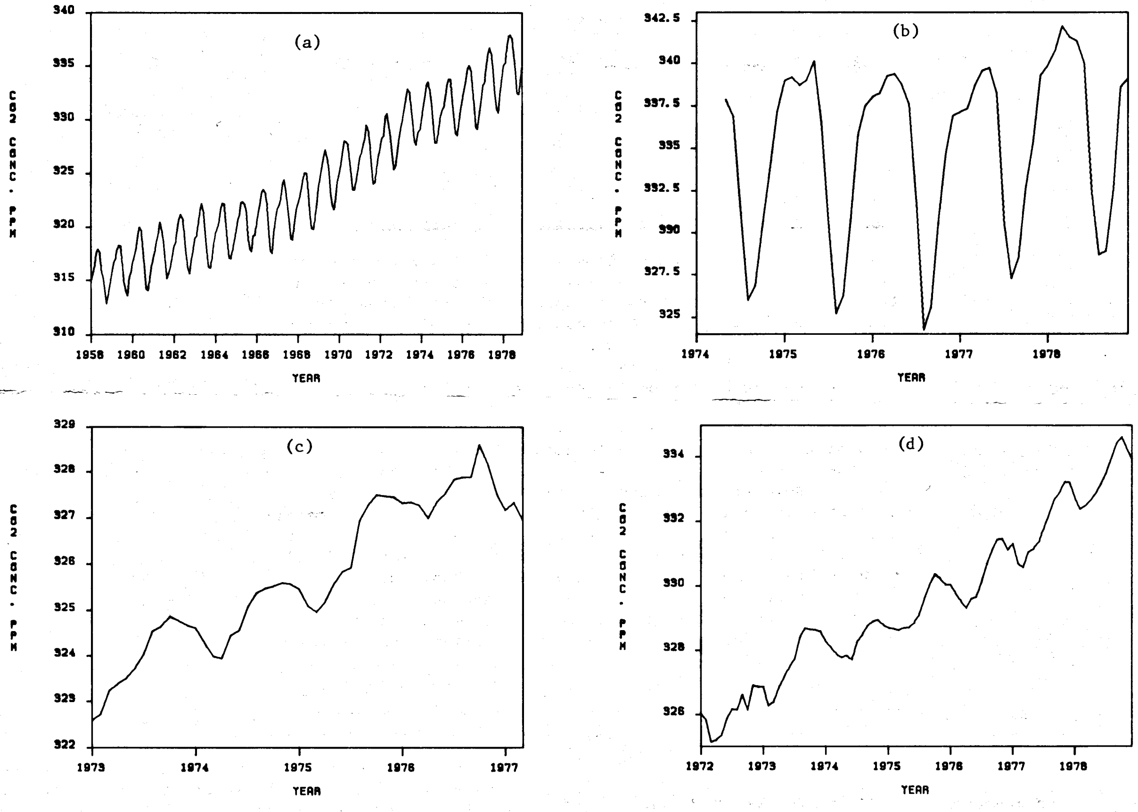

Figure 1.--Atmospheric CO_2 concentration at (a) Mauna Loa[4] (20°N latitude), (b) Point Barrow[5] (71°N latitude), (c) New Zealand (42°S latitude, Lowe _et al._ 1979), and (d) South Pole (90°S latitude, Keeling _et al._ 1976a).

2. Is the amount of fossil fuel-produced CO_2 remaining in the atmosphere the same at all monitoring stations?
3. Do the timing and magnitude of the rates of uptake and release of CO_2 relate to what we know about the functioning of terrestrial ecosystems?
4. Can the atmospheric CO_2 measurements help us determine whether the terrestrial biosphere is a sink for part of the fossil fuel produced CO_2 or is it itself a source?

Estimates of whole ecosystem metabolism have been made from atmospheric inversions (Woodwell and Dykeman 1966); however, only total respiration (release rate) could be estimated by this method. Others have used the Mauna Loa data to establish "net hemispheric metabolism" (Hall _et al._ 1975). They, however, looked only at annual rates of uptake and release calculated as the difference between peak to trough ("semiannual net photosynthesis") and trough to peak ("semiannual net respiration") after correcting for a presumed 42% uptake by the oceans. Other statements about biospheric activity have been made using atmospheric concentration data (Lowe _et al._ 1979, Woodwell _et al._ 1973), but the authors have confused concentration with rates. For example, Woodwell _et al._ (1973) showed that the lowest CO_2 concentration occurred in September and the highest in December-January. The authors commented that the largest decrease in CO_2 concentration occurred "in the fall as photosynthesis in the northern hemisphere stores carbon". By calculating the rate of change from their figure 4, however, we find that the peak _rate_ of CO_2 uptake occurred earlier in June-July.

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[4] Bacastow, R. 1979. Personal correspondence. Scripps Institute of Oceanography, La Jolla, California, U.S.A.

[5] Komhyr, W. D. 1979. Personal correspondence. NOAA-US Dept. Commerce, Boulder, Colorado, U.S.A.

Rust and Kirk (1978) also confused rates with concentrations in their analysis of the Mauna Loa data. They found that the waveform resulting from the detrended and normalized atmospheric CO_2 concentration measurements was strikingly similar to a waveform resulting from the normalization of the monthly rates of heat storage in the atmosphere of the Northern Hemisphere. Because they confused rates with concentrations, one must question their statement that "most of the seasonal variation of atmospheric CO_2 at Mauna Loa might be caused by the transport of CO_2 molecules across that (ocean-atmosphere) interface."

EFFECTS OF FOSSIL FUEL INPUTS ON ANNUAL RATES OF CO_2 UPTAKE AND RELEASE

The analysis in this section will deal only with the Mauna Loa data because it has the longest period of continuous record (1958-1978) and it is roughly representative of the Northern Hemisphere. Updated atmospheric CO_2 concentration data for Mauna Loa[4] was used for the analysis. These data are tentative because the measurement system is still being calibrated. However, we assumed that the errors are systematic and would not affect our analysis because we deal with differences in concentrations (rates). Data for the CO_2 production from burning of fossil fuel and manufacture of cement were obtained from Rotty (1979), and we assumed that most of this CO_2 production occurred in the industrial Northern Hemisphere.

The first step in our analysis was to calculate the monthly rate of change of CO_2 concentration. We did this by subtracting the mean monthly concentration at month m from the mean of month m+1 and, assuming that the mean concentration occurred in the middle of the month, we assigned the monthly rate value to the middle of month m+1. Positive rates of change represent net release of CO_2 (R) and negative rates of change represent net uptake of CO_2 (U). We next integrated the monthly rates of change to calculate the annual uptake and release of CO_2 for the period of record.

Annual R is always greater than annual U, and their shapes are very similar (fig. 2). Annual R varied between 5.1 and 8.0 ppm/yr and annual U between 4.6 and 6.1 ppm/yr. We applied ordinary least squares regression (OLSR) to estimate simple linear models of annual U vs. annual CO_2 input from fossil fuel burning (FFI), annual R vs. FFI, and annual UR ratio vs. FFI. We found: 1) no significant relationship between U ~~and~~ R and FFI at the 0.05 level, however, if we accept a significance level of 0.15, we found that R was increasing with increasing FFI, and 2) a significant (P = 0.05) negative relationship between UR ratio and FFI (fig. 3). Because the secular rise of atmospheric CO_2 represents a net source to the atmosphere, we should expect the annual U rates to be masked somewhat, resulting in an observed decrease in U, an observed increase in R, and an observed decrease in the UR ratio. This can be best explained by the following analogy: if CO_2 uptake of two identical plants is measured under identical conditions, except that the soil is isolated in one and not in the other, it would appear that the plant with the exposed soil was fixing CO_2 at a lower rate than the one with the isolated soil. In reality, both plants fixed the same amount of CO_2. At the global scale, production of CO_2 from fossil fuel is analogous to the production of CO_2 by the soil and biospheric CO_2 uptake (U) is analogous to plant CO_2 uptake. We did find that the observed annual UR ratio and annual R followed the expected trend, but not annual U. The fact that annual U is not changing with FFI suggests that 1) the storage of carbon in the Northern Hemisphere is increasing by either the rate of storage increasing (CO_2 enrichment) or the area of vegetated land increasing (more forest land) or 2) the oceans are taking up more in the summer than in the winter or 3) the rate of CO_2 accumulation is increasing in other unknown, but significant, processes.

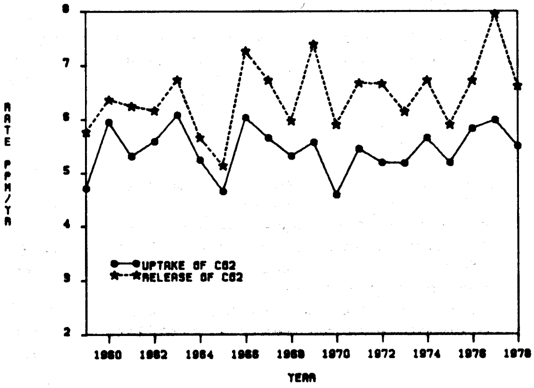

Figure 2.--The course of observed annual uptake and release of CO_2 (fossil fuel effects not removed) at Mauna Loa for the period of record.

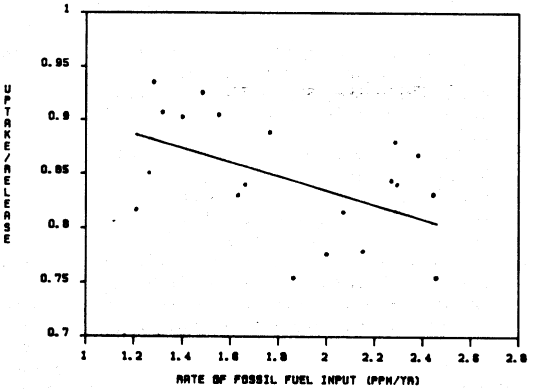

Figure 3.--Simple linear model of annual uptake to release ratio (U/R) vs. annual rate of fossil fuel produced CO_2. The equation is Y = 0.97-0.66 X (significant at P = 0.05).

AMOUNT OF FOSSIL FUEL CO_2 REMAINING IN THE ATMOSPHERE

Estimates of the amount of fossil fuel produced CO_2 remaining in the atmosphere at Mauna Loa range from 49 ± 12% (Bacastow and Keeling 1973) to 52 ± 4% (Broecker et al. 1979) and 54% (Keeling et al. 1976a); at the South Pole the airborne fraction is estimated to be 52% (Keeling et al. 1976a). These values were obtained either from the results of models or by determining the secular rise over a period of years by fitting cubic trend to the data (by OLSR) using time as the independent variable and expressing the rise as a fraction of the total input during the same period. These results assume that the fraction remaining airborne is constant over time. An analysis by Machta et al. (1977), however, indicated that the fraction remaining airborne at Mauna Loa was not constant from year to year but varied between 20-100% during the period 1961-74.

Our approach to determine the fraction remaining in the atmosphere was to fit a linear model to the CO_2 concentration data as a function of cumulative FFI using OLSR for the four monitoring stations shown in figure 1. The results of this analysis (table 1) show that the fraction remaining airborne at Mauna Loa and South Pole is within the range of values found by other investigators (see above). Our analysis also shows that the amount remaining airborne at New Zealand is similar to that at Mauna Loa and South Pole. Point Barrow, however, appears to be responding differently. We did not get a significant relationship at this station, suggesting that considerably less remains airborne at Point Barrow, or the amplitude of the seasonal oscillation is large (about 15 ppm) compared to the magnitude of the FFI, and/or the period of record was too short, which prevent us from obtaining a significant slope parameter (b_1). The standard errors of b_1 (table 1) should be viewed with caution. To use OLSR requires the assumption to be made that the observations of CO_2 concentration be independent; this requirement is violated when cumulative data are used. When the assumption of independence is violated, the estimate of the slope parameter is unbiased, while the standard error estimate of the slope parameter is biased downward, i. e., the standard error estimate is smaller than it should be (Mandel 1957). Therefore, the estimates of the fraction remaining airborne (table 1) are unbiased, but the estimated degree of precision of the parameter estimates are greater than they should be.

Converting cumulative data into rates helps partially overcome some of the problems of using OLSR, and as stated earlier, we are interested in rates rather than concentrations. We used, therefore, OLSR to fit a linear model to the monthly rates of change of CO_2 concentrations (ΔCO_2) and the monthly FFI rates (ΔFFI), assuming that the ΔFFI was constant throughout the year. The results of this analysis produced no meaningful estimates for the slope parameter for Point Barrow, New Zealand, or South Pole stations. This was probably caused by a combination of the small number of points (short record) and the large variation in the ΔCO_2 relative to the ΔFFI (which ranged from about 0.1-0.2 ppm/mo). The more extensive data base at Mauna Loa produced more meaningful results with a linear model (table 2), with an estimate of the slope comparable to that in table 1, but the standard error indicated that this estimate was not significant. Because of the large amplitude in oscillation of the ΔCO_2 relative to the magnitude of ΔFFI, we tried fitting more complex non-linear models to remove the oscillation effects (table 2). These models gave lower estimates of the fraction remaining airborne than did the linear model, and both had large standard errors showing that these estimates were insignificant, although the 12 and 6 mo model gave a smaller standard error than the 12 mo model.

Table 1.--Ordinary least squares regression parameter estimates of the linear model $[CO_2] = b_0 + b_1 FFI$.

Data base	b_0	b_1[1] ± 1SE	r^2
Mauna Loa (1958-1978)	315.21	0.55 ± 0.011	0.90
Point Barrow (1974-1978)	327.10	0.25 ± 0.210	0.03
New Zealand (1973-1977)	310.64	0.53 ± 0.027	0.89
South Pole (1972-1978)	314.45	0.51 ± 0.013	0.95

[1] Fraction remaining airborne.

Table 2.--Ordinary least squares regression parameter estimates of ΔCO_2 as a function of ΔFFI only and ΔFFI and time combined.

Model	b_0	b_1	$\pm$	1SE
Linear[1]	0.02	0.62	$\pm$	1.94
Non-linear				
12 mo sine[2]	0.02	0.42	$\pm$	1.03
12 mo and 6 mo sine[3]	0.01	0.48	$\pm$	0.58

[1] $\Delta CO_2 = b_0 + b_1 \Delta FFI$

[2] $\Delta CO_2 = b_0 + b_1 \Delta FFI + b_3 \sin(\frac{2\pi}{12}(t + b_4))$

[3] $\Delta CO_2 = b_0 + b_1 \Delta FFI + b_3 \sin(\frac{2\pi}{12}(t + b_4)) + b_5 \sin(\frac{2\pi}{6}(t + b_6))$

In conclusion, our analysis suggests that the fraction of FFI remaining airborne at Mauna Loa ranges from 42-62%, with a large degree of uncertainty. Our analysis produced values for Mauna Loa, New Zealand, and South Pole that were comparable to those published elsewhere. The fraction remaining airborne at Point Barrow appears to be considerably less than at the other three monitoring stations.

MAGNITUDES AND PHASING OF CO_2 UPTAKE AND RELEASE RATES

Monthly Uptake and Release Rates

The first step in this analysis was to remove the effects of fossil fuel produced CO_2 from the rate data. Our approach was first to fit a linear model using OLSR to the monthly ΔCO_2 and ΔFFI for all four stations shown in figure 1. We then plotted the residuals of this model against time as shown in figure 4a-d, with U rates plotted above the zero line and R rates plotted below the zero line. These results show the following:

- the pattern of monthly U rates in the two Northern Hemisphere stations is smoother than for the two Southern Hemisphere stations. This smoother pattern in the Northern Hemisphere possibly reflects the influence of the larger land masses.
- the magnitudes of the monthly U and R rates decrease latitudinally from Point Barrow to South Pole.
- maximum U rates are generally higher than maximum R rates at Point Barrow and Mauna Loa (monthly U=6-8 ppm/mo and 2 ppm/mo, respectively; monthly R=4-5 ppm/mo and 1.5 ppm/mo, respectively), whereas at New Zealand and South Pole maximum U rates are similar to maximum R rates (approximately 0.5 ppm/mo for both stations).
- all four stations show a minimum monthly R rate in their winter months that coincides with the period of peak monthly U in the opposite hemisphere, suggesting that not only do the air masses of the two hemispheres mix, but that they do so relatively quickly (on the order of a month). At the two Southern Hemisphere stations there is also a decrease in the monthly U rate in most years coinciding with peak R in the Northern Hemisphere; we cannot detect a similar trend in the Northern Hemisphere stations. We suspect, however, that Northern Hemisphere rates are similarly affected and this is one line of analysis we are presently pursuing. If they are affected by activity in the Southern Hemisphere, the timing of maximum monthly U may occur at some other time of the year than is indicated in figure 4a and 4b.
- the length of the growing season (the length of time $U \geq 0$, i.e., above the zero line) varies from 131 ± 15 (SE) days at Point Barrow to 142 ± 2 (SE) days at Mauna Loa and 195 ± 5 (SE) days at New Zealand (we did not calculate the length for South Pole because the pattern was too erratic). The small standard errors for the length of the growing season, particularly for Mauna Loa measurements, may be surprising when one considers that the world is composed of a variety of ecosystems, all adapted to different sets of environmental factors.
- peak monthly U occurred at approximately mid-August at Mauna Loa, late June at Point Barrow, and mid-January at New Zealand (table 3). This timing, of course, depends upon the validity of our assumption that the monthly rate of change between any two adjacent months occurs at the middle of month m + 1 (see first section). Regardless of the assumption, our analysis does show that peak U at Point Barrow occurs approximately 1.5 mo earlier than at Mauna Loa.

Table 3.--Timing of maximum monthly rate of uptake of CO_2.[1]

	b_4	± 1SE	Month of year[2]
Mauna Loa	7.16	± 0.08	7.84
Point Barrow	8.75	± 0.27	6.26
New Zealand	1.89	± 0.37	1.11

[1] Determine from fitting the model by OLSR: $\Delta CO_2 = b_1 + b_2\ \Delta FFI + b_3 \sin(\frac{2\pi}{12}\ (t + b_4))$.

[2] Monthly rate was assigned to the middle of the months (see first section), e.g., month 7 = mid-July.

In summary, monthly U and R rates in the Northern Hemisphere are more consistent and of greater magnitude than those in the Southern Hemisphere. The length of the growing season is shorter, the magnitude of U is higher, and the timing of peak U is earlier at Point Barrow than at Mauna Loa. The consistency in timing of peak U, the consistency of the annual pattern of monthly U and R, and the consistency in the magnitude of U and R for the periods of record at Point Barrow and Mauna Loa suggest that CO_2 exchange in the Northern Hemisphere does not reflect any impact by humans on the biota during the last two decades. The absence of a uniform pattern of monthly U and R at South Pole and New Zealand possibly reflects a lesser influence from large land masses (approximately 5% of the total surface area south of latitude 30°S and not including Antarctica is land; Pearman and Hyson 1980), interference from northern air masses; and a greater oceanic influence.

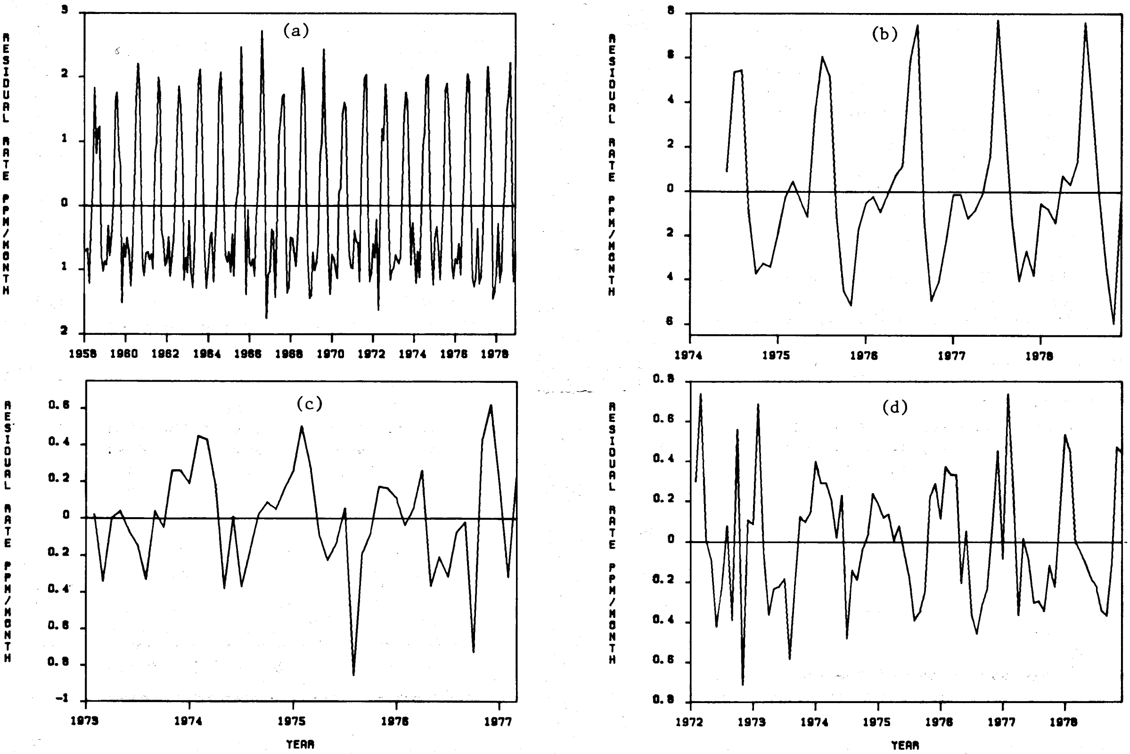

Figure 4.--Residual rates of change of atmospheric CO_2 vs. time obtained by fitting a simple linear model, using ordinary least squares regression, of monthly rate of change of CO_2 (ΔCO_2) vs. monthly fossil fuel produced CO_2 input rate (ΔFFI) for the following stations: a) Mauna Loa, b) Point Barrow, c) New Zealand, and d) South Pole. Monthly uptake rates are plotted above the zero line and release rates below the zero line.

Annual Uptake and Release Rates

In addition to monthly rates we were also interested in the annual rates of U and R. We tried fitting a Fourier series to the monthly rates because fitting a sine wave assumes a symmetry of U and R which would prevent us from seeing if there were differences between them in any given year. The model produced by fitting the Fourier series did not produce satisfactory results, so instead we used the empirical data. The annual U and R rates were calculated using the same method as described in the first section; we did not use South Pole data because of the erratic nature of the monthly rates (fig. 4d).

Annual U and R are, respectively, approximately 14 ppm and 14.5 ppm at Point Barrow, 5.5 ppm and 6 ppm at Mauna Loa, and 1.5 ppm for both U and R at New Zealand (fig. 5). Using the value of 2.12×10^{15} g C/ppm CO_2 (Verniani 1966) these rates translate to annual U and R of 29 and 31 x 10^{15} g C/yr for Point Barrow, 11.5 and 13 x 10^{15} g C/yr at Mauna Loa, and 3 x 10^{15} g C/yr for both U and R at New Zealand. If we assume that Mauna Loa represents the Northern Hemisphere, net ecosystem production there (NEP = net annual U) is approximately 11.5 x 10^{15} g C/yr. This is double the value obtained by Pearman and Hyson (1980) from their model of CO_2 exchange in the atmosphere.

During three out of the four years of data, annual R was greater than annual U at both Point Barrow and New Zealand; R was greater than U for about half the period of record at Mauna Loa (fig. 5). When R is greater than U, is the net release from the biosphere really greater than net uptake, or does it mean that more fossil fuel produced CO_2 is remaining in the atmosphere (i.e., more than the average amount estimated by the model, e.g., ≈ 62% at Mauna Loa, c.f. table 2) as was suggested by Machta <u>et al</u>. (1977)? Similarly, when U is greater than R, is the net uptake by the biosphere greater than net release, or is less remaining in the atmosphere and maybe more being removed by the oceans and other sinks? Until more is known about the pattern of CO_2 uptake by ocean processes and what the airsheds for the various stations are, we cannot answer this question at this time.

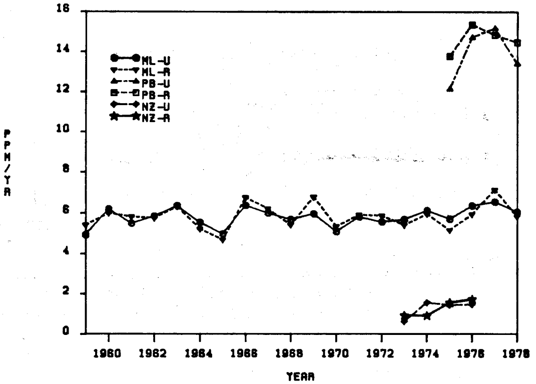

Figure 5.--The course of annual rates of CO_2 uptake (U) and release (R) with fossil fuel effects removed. ML = Mauna Loa, PB = Point Barrow, and NZ = New Zealand.

Conformity of Atmospheric CO_2 Rates With Ecosystem Function

Are the observed trends in the rates of U and R consistent with what we know about the functioning of terrestrial ecosystems? This question implies that all the uptake and release of CO_2 are due to the activity of the terrestrial biota. This may be a valid assumption for the Northern Hemisphere because total U during the growing season varies between 5-6 ppm at Mauna Loa to 13-15 ppm at Point Barrow (fig. 5) and results of ocean models suggest that only 1 ppm (40% of FFI) is being sequestered by the oceans during the whole year (Broecker et al. 1979). In addition, the ratio of land area to total area is approximately 40% (Pearman and Hyson 1980). In the Southern Hemisphere the situation is somewhat different because of the reasons given earlier. Therefore, the question posed at the beginning of this section will be answered in reference to the Northern Hemisphere stations only.

There are few studies that have measured CO_2 exchange from whole ecosystems for comparison with atmospheric exchange rates. Two studies in northern latitutde ecosystems (Coyne and Kelley 1975, Woodwell et al. 1973) did show peak net CO_2 uptake in June-July and net uptake approaching zero by the end of August, two trends exhibited by the Point Barrow data. There are no similar types of studies for lower latitude ecosystems with which to use as a reference for Mauna Loa, but peak net CO_2 uptake in early August is consistent with our expectations. We would also expect the length of the growing season to be longer for the Northern Hemisphere as a whole than for higher latitudes alone; this is supported by our analysis (fig. 4a and 4b). However, our analysis shows that net CO_2 uptake starts earlier at Point Barrow (generally April-May, when temperatures are close to zero) than at Mauna Loa (generally May-June). Our experience tells us that for the Northern Hemisphere, in general, plants break dormancy earlier than May-June. Because no net CO_2 uptake is observed until later suggests that processes in ecosystems that release CO_2 are more active than those that fix it. In high latitude ecosystems the reverse trend appears to be true. There is evidence that tundra plants can uptake CO_2 at temperatures as low as 0°C (Coyne and Kelley 1975). However, all the processes of CO_2 uptake and release at high latitudes may not be biological (see below).

The high annual U rate at Point Barrow appears to suggest that net ecosystem production is greater in high latitude ecosystems than in those typical for the Northern Hemisphere (represented by Mauna Loa). It has been suggested that these higher annual rates result from the large land areas in higher latitudes (Keeling et al. 1976b). However, if Mauna Loa is assumed to represent the whole Northern Hemisphere, then the total land area of its airshed is greater than for Point Barrow. We suggest that the difference in land area alone cannot account for the more than two-fold higher annual U and R at Point Barrow than at Mauna Loa. Factors other than the metabolism of high latitude ecosystems must be responsible for the high annual U and R rates. For example, Broecker et al. (1979) showed the North Atlantic Ocean (at 70° N latitude) to be a strong sink for CO_2 based on differences in the partial pressure of CO_2 (pCO_2) exerted by the ocean and atmosphere along the GEOSECS track, and they stated that large seasonal changes in ocean pCO_2 are to be expected at high latitude locations. However, the seasonal pattern of pCO_2 in high latitude oceanic waters is unknown (Broecker et al. 1979). This factor and possibly others may explain why annual U and R are high and why there is a lower fraction of the fossil fuel produced CO_2 remaining in the atmosphere at Point Barrow.

Assuming Mauna Loa does represent the Northern Hemisphere, we divided the average annual U rate (11.5×10^{15} g C/yr) by the area of land surface[6] and produced an estimate of net ecosystem production (NEP) during the growing season (annual U rate) of 115 g C/m^2. This is about half the average value of net primary production (NPP) estimated by Pearman and Hyson (1980, who used data from Whittaker and Likens [1973]) for four latitudinal belts which represent major ecosystems types found in the Northern Hemisphere. Because our estimate from atmospheric CO_2 data is in the right order of magnitude (NEP should be lower than NPP, and it should be greater than zero during the growing season so that

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[6] Surface area of Northern Hemisphere = $2.56 \times 10^{14} m^2$, ratio of land area to total surface area = 0.39 (estimated from data in Pearman and Hyson 1980), land area = $9.88 \times 10^{13} m^2$.

some organic production is available for the remainder of the year) we suggest that the annual rates of CO_2 U and R measured at Mauna Loa do represent production and respiration of the biosphere in the Northern Hemisphere.

ANNUAL RATES OF UPTAKE AND RELEASE WITH VARYING AMOUNTS OF FOSSIL FUEL PRODUCED CO_2 REMOVED

We tested the sensitivity of annual U, R, and UR ratio of the Mauna Loa data to varying amounts of FFI removed because the degree of uncertainty in the amount of fossil fuel produced CO_2 remaining in the atmosphere is large.

As the percent removed decreases (or percent remaining increases) corrected annual U increases, corrected annual R decreases and UR ratio changes from less than to greater than one (table 4). However, the annual rates of U and R and UR ratio appear not to be very sensitive to changes in the percent removed because none of them change by more than 2% around the average value and the annual course of U and R with, e.g., 40% removed (fig. 6) is the same as that shown in figure 5.

We can use the results in table 4 as another means of estimating the average amount of FFI remaining in the atmosphere. Because the secular rise (percent remaining) is the difference between all known and unknown sources and sinks of CO_2, removal of the exact amount of percent remaining must result in an average UR ratio of one; this occurs when 50-55% of FFI remains (or 45-50% is removed). This estimate is similar to the others discussed earlier.

Table 4.--Sensitivity of annual uptake (U), release (R), and uptake to release ratio (U/R) to varying amounts of fossil fuel produced CO_2 removed from the atmosphere.[1]

% Removed[2]	Rate of CO_2 U (ppm/yr ± 1SE)	Rate of CO_2 R (ppm/yr ± 1SE)	U/R (±1SE)
60	5.70 ± 0.10	5.93 ± 0.15	0.97 ± 0.02
55	5.74 ± 0.10	5.88 ± 0.15	0.98 ± 0.02
50	5.77 ± 0.10	5.83 ± 0.15	0.99 ± 0.02
45	5.81 ± 0.10	5.78 ± 0.15	1.01 ± 0.02
40	5.85 ± 0.10	5.73 ± 0.15	1.03 ± 0.02
35	5.88 ± 0.11	5.67 ± 0.15	1.04 ± 0.02

[1] Using the simple linear model:
(Residual ΔCO_2) = $\Delta CO_2 - b_1 \Delta FFI$, where

ΔCO_2 = rate of change of CO_2

ΔFFI = monthly rate of fossil fuel produced CO_2

b_1 = fraction remaining.

[2] Percent removed = 100 $(1 - b_1)$.

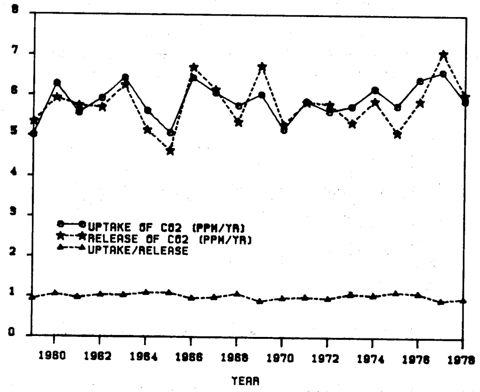

Figure 6.--The course of annual CO_2 uptake, release, and uptake to release ratio with 40% of the fossil fuel produced CO_2 removed (approximately the amount removed by oceans, Broecker et al. 1979) for the period of record at Mauna Loa.

To determine whether the biosphere is a sink or source of CO_2, we need to know the magnitude of the other global sinks. If we assume that the oceans remove between 35-40% of the FFI as suggested by Broecker _et al_. (1979), the biosphere is a small sink of CO_2 of the order 0.12 - 0.21 ppm/yr or 0.3 - 0.4 x 10^{15} g C/yr (table 4). This is contrary to other estimates based on models of the world's terrestrial ecosystems, which suggest that the biosphere is a source of 4 - 8 x 10^{15} g C/yr (Woodwell _et al_. 1978) or a source or sink of magnitude ± 2 x 10^{15} g C/yr (Seiler and Crutzen 1980).

The course of annual U, R, and UR ratio for 40% of FFI removed is shown in figure 6. There was no significant change ($P = 0.05$) in U, R, or UR ratio over time. Annual R was considerably larger than annual U during the three years 1966, 1969, and 1977; it was slightly larger than U in 1961. For the remainder of the period of record annual U was greater than R or approximately equal to it. Bacastow (1976) suggested that during those years when the Southern Oscillation Index (SOI = difference in the average monthly barometric pressure between Easter Island, near the center of a high pressure cell, and Darwin, representative of the equatorial low pressure zone) was high there was an increased loss of CO_2 from the atmosphere attributed to an increased uptake by either the oceans or biota, but most likely the oceans. When the SOI was low the converse was true. The SOI exhibited low values during 1961, 1966, 1969, and 1973 (Bacastow 1976). We found annual R greater than annual U during three of these years (fig. 6); no data were available for 1977 when R was also greater than U. The apparent relationship between those years when R is greater than U and the presence of a low SOI appears to indicate that less fossil fuel produced CO_2 was removed by the oceans rather than net R from the biosphere being greater than net U.

SUMMARY AND CONCLUSIONS

By converting atmospheric CO_2 concentration records into rates of uptake and release we have been able to determine the following about the CO_2 dynamics of the biosphere:

- observed annual R rate and UR ratio determined from the Mauna Loa data are changing significantly with increasing inputs of fossil fuel produced CO_2. The observed annual U rate has remained constant suggesting that carbon is accumulating in the biosphere.
- 42-62% of fossil fuel produced CO_2 appears to be remaining in the atmosphere, but the degree of uncertainty is large. Point Barrow appears to be much less affected by fossil fuel inputs than the other monitoring stations.
- the constancy in timing and magnitude of the monthly rates of U and R for the two Northern Hemisphere stations suggest little human impact on the biosphere during the last two decades.
- the timing of peak monthly U and the length of the growing season at Point Barrow and Mauna Loa are generally consistent with what we know about ecosystem processes.
- the magnitudes of monthly and annual U and R rates at Point Barrow suggest processes other than biological are responsible for the high rates obtained there.
- annual U and R rates for Mauna Loa are comparable to those reported in the literature for terrestrial ecosystems of the Northern Hemisphere.
- annual U, R, and UR ratio are fairly insensitive to varying fractions of fossil fuel produced CO_2 remaining in the atmosphere.
- if the fraction of fossil fuel produced CO_2 removed by the oceans is approximately 40%, the biosphere is a sink of about 0.3-0.4 x 10^{15} g C/yr.

Our analysis confirms the earlier ones that the seasonal oscillation in atmospheric CO_2 measurements is due mainly to biological processes in the biosphere. We also suggest that oceanic and other large scale atmospheric processes affect the annual rates of CO_2 exchange. Until more is known about the annual variation and seasonality in oceanic rate of uptake and release of CO_2 and the factors that affect these rates, we cannot exploit fully the atmospheric CO_2 measurements to address the question of whether the biosphere is a sink or source of carbon dioxide.

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