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Statistical analysis of the increase in atmospheric CO_2 concentrations and its relation to the possible existence of CO_2 fertilization on a global scale

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ABSTRACT

Correlation coefficients r between seasonal amplitudes and annual means of atmospheric CO_2 concentrations are calculated for 17 stations which have 10 or more data and whose latitudes range from the South Pole to Alaska. Although signs of r are random, %s of stations with positive r increase as the number of data n for each station increases, and for stations with $n > 25$, all 4 stations have positive r. The CO_2 fertilization coefficient λ defined by photosynthesis increase per CO_2 increase of 1 ppm is calculated for each station, and weighted averages of r and λ are calculated changing values of the minimum n. They are found to be always positive and both of them increase as n increases. These trends indicate that the random sign of r for small n is due to small numbers of data and that r would be positive if the number of data were sufficient, which suggests that CO_2 fertilization exists on the global scale. However there are still large uncertainties and further investigations are necessary to clarify the situation.

1. Introduction

It is well-known that in many experiments using greenhouses or open top chambers CO_2 increase gives rise to stimulation of photosynthesis, which is called CO_2 fertilization (Strain and Cure, 1985). However, its existence in actual field conditions, especially on the global scale, is not yet clear for several reasons.

In almost all experiments mentioned above comparisons are made between different CO_2 concentrations (usually between ambient levels and doubled CO_2 concetration both of which are steady) maintained for a short period (usually one year or less), but in actual field conditions changes in CO_2 concentrations are due mainly to use of fossil fuels, which are gradual and persist for a very long period (decades or even centuries). Moreover, in laboratory experiments pure CO_2 is usually used, but the atmospheric CO_2 increase is accompanied by emissions of other pollutants, such as dust, sulphur and nitrogen compounds and ozone, most of which suppress photosynthesis. Although nitrogen compounds are sometimes regarded as beneficial and may be so after they have fallen to ground, as long as they stay in the air they are harmful to plants, directly by themselves as a cause of acid rain, and as air pollution when coexistent with sulphur compounds; and indirectly through photochemical reactions to produce ozone when coexistent with hydrocarbons. These effects might cancel their possible benefits. There are many other factors which could affect photosynthesis in the actual environment, and so the existence of CO_2 fertilization cannot be inferred from laboratory experiments.

This problem is important both from academic and practical viewpoints. First, sources and sinks of global carbon cycle have been long-standing problems. Traditional interpretation was that

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ocean was a major sink absorbing about 40% of the total, but recent arguments rather support lower absorption (Tans et al., 1990). On the other hand the latest attempt using oxygen measurements again favours the traditional interpretation (Keeling and Shertz, 1992). If CO_2 fertilization exists on the global scale, its effect may be appreciable and could affect these arguments.

Practically the greenhouse effect is becoming a social and political issue, and suppression of atmospheric CO_2 increase is discussed seriously. There are many methods for such suppresion, and forestation is raised as one of them. If CO_2 fertilization exists for forests, it would increase their CO_2 absorbing capability considerably, which would be very desirable.

For these reasons, the existence of CO_2 fertilization on the global scale should be investigated more carefully. Although detailed analyses of one or a few CO_2 monitoring stations have been made previously (Kohlmaier et al., 1989; Bonan, 1992), analyses of many stations all over the world covering wide range of latitudes would be desirable to discuss this problem from the global viewpoint. In this paper, such analyses are made using statistical methods. It is a continuation of previous work by one of us (Okano, 1990), about which a very brief report was already presented elsewhere (Okamoto, 1992).

2. Methods of calculation

Since seasonal change in photosynthesis of terrestrial biota gives rise to variations of atmospheric CO_2 concentration, CO_2 fertilization would appear as an increase in the amplitude of seasonal variation with the increase of CO_2 concentration, although previous investigations have shown that many other factors also affect the seasonal variation (Kohlmaier et al., 1989). In any case the increase in the amplitude must be confirmed, because it can be regarded as a *necessary* condition for the existence of CO_2 fertilization.

For this purpose, data on atmospheric CO_2 concentration are taken from compilations by the Carbon Dioxide Information and Analyses Center (CIDIAC) and the World Meterological Organization (WMO) (Trends, 90 and 91; WMO, 92). Since some of stations do not have sufficient numbers of data for analysis, 23 of them are

Table 1. *Stations for which calculations have been made*

Stations and leading authors[a]	Latitudes	Longitudes
Alert	82°31′N	62°18′W
Point Barrow/Conway	71°19′N	156°36′W
Point Barrow/Keeling	71°19′N	156°36′W
Point Barrow/Thoning	71°19′N	156°36′W
Langenbrugge	52°48′N	10°46′E
Deuselback	49°46′N	7°03′E
Schauinsland	47°55′N	7°55′E
Garmisch-Partenkirchen	47°28′N	11°03′E
Mt. Cimone	44°11′N	10°42′E
Niwot Ridge	40°03′N	105°38′W
Key Biscayne	25°40′N	80°10′W
Maula Loa/Conway	19°32′N	155°35′W
Mauna Loa/Keeling	19°32′N	155°35′W
Cape Kumukahi	19°31′N	154°49′E
Maula Loa/Thoning	19°05′N	155°06′W
Cape Matatula/Conway	14°15′S	170°34′W
Cape Matatula/Thoning	14°15′S	170°34′W
Amsterdam Island	37°52′S	77°32′E
Cape Grim (Beardsmore)	40°41′S	144°41′E
Palmer Station (Anver Island)	64°55′S	64°00′W
South Pole	89°59′S	24°48′W

[a] Names of leading authors are added when there are more than one measurement.

used. In Table 1, their names, latitudes and longitudes are listed. When there are two or more measurements for one station, in the analyses they are combined to increase the number of data. Since different groups usually use different methods of measurement, simple addition of their data may not be appropriate, but at the present stage when data are not sufficient this is necessary to improve statistical accuracy.

Thus the number of stations with 10 or more data is reduced to 17, and their latitudes range from 90° S to 82° N. Regression analyses are made to find the correlation coefficients r between seasonal amplitudes and annual means.

The parameter λ called CO_2 fertilization coefficient used for the analysis of agriculture of the Great Plains in the United States (Okamoto et al., 1990) is used in our calculation. It corresponds to a relative increase of photosynthesis by a CO_2 increase of 1 ppm. Its relations to the ordinary β factor and to net primary production and respiration are explained in the *Appendix*.

Since correlation is calculated between an annual mean and a seasonal amplitude, the amplitude must be defined for the same year. CO_2 peaks and troughs appear in April or May and in September or October. In the northern hemisphere, the former is a peak and the latter is a trough and vice versa in the southern hemisphere. Therefore, in the northern hemisphere, the amplitude is a peak-to-trouph (PT) amplitude whereas in the southern hemisphere, it is a trough-to-peak (TP) amplitude. This definition is somewhat confusing, but cannot be avoided if correlation is calculated for the *same* year, because if either a PT or a TP amplitude were used for both the hemispheres, calculation must be made crossing over two years for one of them, in which case an annual mean cannot be defined unambiguously.

Actually since the PT and TP amplitudes are not just a measure of net primary production NPP but of respiration as well, they seem unsuitable for the present purpose. However the heterotropic respiration factor ρ (see *Appendix*) is assumed to be constant for specified regions (for instance $\rho = 0.65$ for tropical forests, 0.87 for grasslands, etc., (Kohlmaier et al., 1989)). Since ρ is a ratio of respiration to NPP, NPP and heterotrophic respiration are proportional to each other, and so are PT and TP amplitudes for a specific CO_2 observing station. Since the essential point of the present work is to find the effects of CO_2 from the correlation between amplitudes and annual means, both PT and TP amplitudes can be used for this purpose.

The value of λ depends on year and is calculated for the starting year of measurement of each station. For instance let x and y be the annual mean of CO_2 concentration and its seasonal amplitude. Then for Mauna Loa the regression analysis gives $y = 0.014x + 1.05$. Since λ is a relative increase of y for an increase of x by 1 ppm and the value of x for the year when measurements started is about 315 ppm, $y = 5.46$ ppm by this regression equation and λ is given by $0.014/5.46 = 0.00256$.

3. Results and discussion

Examples of such analyses are shown in Figs. 1, 2, in which r, λ, a regression line and the number of data n are shown. These are the two cases with large n. Results for the 17 stations are summarized in Table 2.

The most important point for determining the existence of CO_2 fertilization is that the sign of r is positive, but it is both positive and negative as shown in Table 2. However, when results are classified according to n, fairly consistent trends in favour of positive r appear as follows.

First, stations are classified according to their minimum n, and results are shown in Table 3. Although the percentage with positive r is less than 50% of all stations, it increases monotonically as n increases, and is positive for stations with more than 25 data points. This suggests that the random

Table 2. *Results of calculations*

	Station	Correlation coefficient	CO_2 fertilization coefficient	No. data
81°N	Alert	−0.109	−3.07E-03	14
71°N	Point Barrow	0.384	3.92E-03	52
52°N	Langenbrugge	−0.415	−1.44E-02	10
49°N	Deuselback	−0.621	−1.89E-02	10
47°N	Schauinsland	−0.365	−9.55E-03	10
47°N	Garmisch-Partenkirchen	−0.034	−1.09E-03	10
44°N	Mt. Cimone	−0.185	−3.65E-03	22
40°N	Niwot Ridge	−0.305	−6.13E-03	18
28°N	Amami Oshima	−0.520	−1.25E-03	11
25°N	Key Biscayne	0.286	9.48E-03	13
19°N	Mouna Loa	0.289	2.57E-03	62
19°N	Cape Kumukahi	−0.147	−2.67E-03	11
14°S	Cape Matatula	0.164	1.09E-02	29
37°S	Amsterdam Island	0.290	1.99E-02	12
40°S	Cape Grim	0.086	4.21E-03	10
64°S	Palmer Station	0.259	1.82E-02	10
89°S	South Pole	0.018	3.56E-04	53

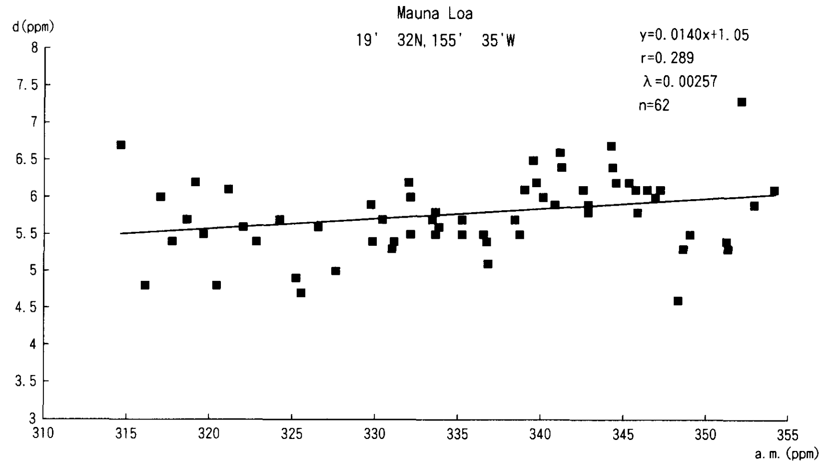

Fig. 1. Results of analysis of data on CO_2 concentration at Mauna Loa. Ordinate: seasonal difference d. Abscissa: annual mean $a.\ m.$ In the figure, $y = ax + b$ is the regression line; r is the correlation coefficient between d and $a.\ m.$; λ is the CO_2 fertilization coefficient (increase of photosynthesis by CO_2 increase of 1 ppm); n is the number of data.

signs of r in Table 1 are due to small n and if n were sufficiently large, the correlation would be positive.

Next, for each group of stations classified in Table 3, values of r and λ are multiplied by n to get their weighted averages. The results are shown in Fig. 3. As can be seen, the weighted averages increase monotonically with n except for one point of λ, which indicates that the larger the number of data is, the stronger is the positive correlation.

The trends in Table 3 and Fig. 3 are consistent with each other and show that the correlation would be positive if a sufficiently large number of data were available. Namely the amplitude of seasonal variation of atmospheric CO_2 becomes

Table 3. *Ratios of positive correlation with respect of number of data*

No. data	r positive/all	
all	8/17	0.47
more than 10	6/11	0.55
more than 15	4/6	0.67
more than 20	4/5	0.80
more than 25	4/4	1.00

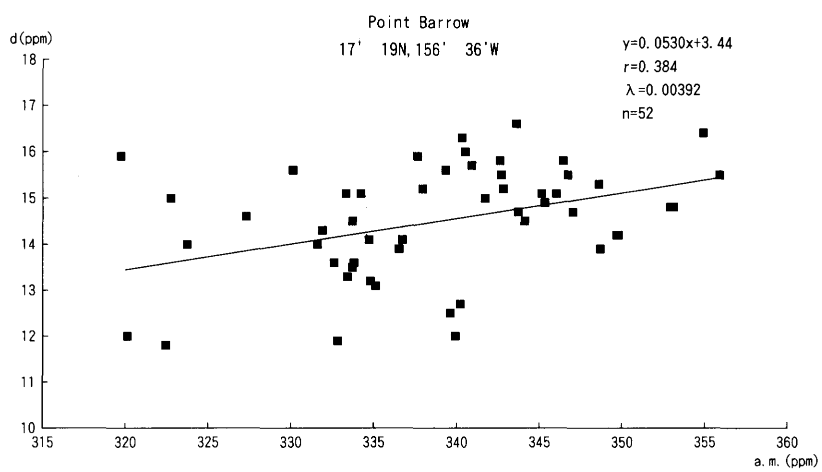

Fig. 2. Same as Fig. 1 but for Point Barrow.

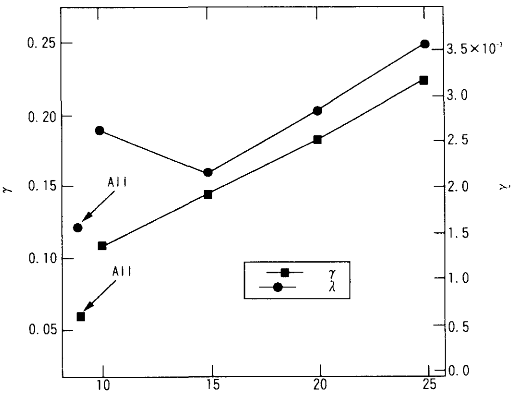

Fig. 3. Changes in weighted averages of r and λ with respect to changes in the minimum of n. Left ordinate: r. Right ordinate: λ. Abscissa: minimum $n-1$. Two points denoted as "all" are those using all data and correspond to the first line of Table 3. Other points correspond to the 2nd, 3rd, 4th, 5th lines of Table 3, respectively.

larger as the annual mean increases. This trend is common for many stations all over the world, which satisfies the *necessary* condition for the existence of CO_2 fertilization on the global scale.

Statistical significance of the analyses has been checked. For most of the stations, the results are insignificant. But for Point Barrow ($p<0.003$), Mauna Loa ($p<0.012$) and Deuselback ($p<0.028$) the results are significant at better than 95% level; and for the best two stations the correlation is positive as shown in Table 2. Thus although statistical test *as a whole* is unfavourable, combined with the facts shown above the over-all results seem to favour positive correlation.

Many factors other than CO_2 fertilization contribute to seasonal variation including seasonal change of interhemispheric transport of CO_2, that of fossil fuel combustion, seasonal difference in CO_2 absorption by the ocean. According to detailed analysis of data of Mauna Loa by Kohlmaier et al. (1989) the sum of their contributions are larger than that of CO_2 fertilization. Therefore further investigations would be necessary to confirm the existence of CO_2 fertilization on the global scale.

4. Appendix

Relation between λ, β and the net primary production

The ordinary β factor is defined as

$$\beta = (\Delta \text{NPP}/\text{NPP})/(\Delta D/D), \qquad \text{(A1)}$$

where D is original CO_2 concentration, ΔD is its increase, NPP is original net primary production, ΔNPP is its increase due to ΔD. When ΔD is 1 ppm, $\beta = D(\Delta \text{NPP}_1/\text{NPP})$, where ΔNPP_1 is ΔNPP for $\Delta D = 1$ ppm.

By definition λ is expressed as

$$\lambda = \Delta \text{NPP}_1/\text{NPP}. \qquad \text{(A2)}$$

Therefore the relation between β and λ is very simply given by

$$\beta = D\lambda. \qquad \text{(A3)}$$

In this paper, λ is calculated from observed changes in seasonal amplitudes, namely, let the amplitude be A and its change be ΔA. Then

$$\lambda_{\text{cal}} = \Delta A/A. \qquad \text{(A4)}$$

On the other hand, according to Kohlmaier et al. (1989), $\Delta A/A$ is given by

$$\Delta A/A = (\Delta \text{NPP}/\text{NPP})\{\rho + (1-\rho)\sigma\}, \qquad \text{(A5)}$$

where ρ is the heterotrophic respiration factor ($0 \leqslant \rho \leqslant 1$), which is a ratio of heterotrophic respiration to net primary production, and σ is the reference state partition function (for details see Kohlmaier et al. (1989)).

Thus the relation between λ_{cal} and NPP is not so simple as eq. (A2). In this work, ρ is assumed to be 1 for simplicity, in which case the relation between λ_{cal} and NPP is reduced to eq. (A2).

This assumption of $\rho = 1$ is of course open to question. The purpose of this work is *not* to make a *quantitative* estimate of CO_2 fertilization, but to confirm (or deny) its existence *qualitatively*. Hence, the main purpose of calculation is to find the sign of r, and λ is merely a supplementary variable introduced to provide rough estimates of the effects of CO_2 fertilization. Thus it need not be discussed so rigorously at this stage.

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