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Long-term changes in amplitudes of atmospheric CO_2 concentrations at Ocean Station P and Alert, Canada

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ABSTRACT

Atmospheric CO_2 concentrations sampled at Ocean Weather Station P and Alert, Canada, were analyzed for possible increase in the seasonal amplitudes. The sampled data sets were reduced by smoothing spline method to obtain mean monthly values. Each set of the monthly means was detrended with a 21-point moving-average filter, and then was fitted with a mixed additive-multiplicative model. The changing amplitudes of the seasonal components were adjusted with the local amplitude scaling factors which were estimated from seven-month moving regressions. Linear regression was used to estimate the rates of change of the amplitudes. Trends of the seasonal components were also approximated by regressing the scaling factors of the same calendar months on time increments. Our results suggest that the growth rate of CO_2 amplitudes was $\sim 1.4\%\ yr^{-1}$ from 1971 to 1979 for Station P. However, the growth rate for Alert between 1977 and 1985 was about $-0.02\%\ yr^{-1}$, which is not statistically significant above zero. The different trends obtained are attributed mainly to the geographical differences in CO_2 sources and sinks, one of which may be the biosphere. Factors such as the winter-season photosynthesis, which probably is increasing and may be altering the CO_2 amplitudes, are discussed.

1. Introduction

In a previous report (Wong et al., 1984), we summarized the monthly mean concentrations of atmospheric CO_2 sampled at Canadian monitoring stations from 1973 to 1981 for Ocean Weather Station P (145° W, 50° N), and from 1975 to 1981 for Alert. As in other CO_2 data sets (Komhyr et al., 1985; Peterson et al., 1986; Conway et al., 1988), each of these Canadian time series also shows a strong seasonal component superimposed on a steadily rising long-term trend. The average amplitude between the spring maxima and the summer minima is about 13–14 parts per million by volume (ppmv).

The seasonal amplitudes of atmospheric CO_2 are almost certainly associated with oscillations of net ecosystem metabolism of the biosphere (Hall et al., 1975; Pearman and Hyson, 1980). If the rising level of atmospheric CO_2 does enhance net ecosystem production or phytomass storage, then the positive effect may be detected from the seasonal amplitudes of atmospheric CO_2 measurements especially those sampled at high northern stations.

Several statistical analyses on the seasonal amplitudes of atmospheric CO_2 data have been published previously. Most of these studies make use of the time series from Mauna Loa and the South Pole. Hall et al. (1975) and Machta et al. (1977) found no significant change in the amplitudes of the Mauna Loa CO_2 data. Later analyses of the updated data from this station (Pearman and Hyson, 1981; Cleveland et al., 1983; Bacastow et al., 1985) support a slow increase in the amplitudes of 0.45–1.5%/year. Analyses of the Station P data (Pearman and Hyson, 1981; Keeling et al., 1985) also imply an increase of about 0.72–0.79%/year. The analysis of Cleveland et al. (1983) on the South Pole data shows that the CO_2 amplitudes increased from about 1 ppmv in 1965 to 1.3 ppmv in 1978. In the same report, they provide two graphs for the Barrow data, but give no numerical result. Recently Peterson et al. (1986) reanalyzed the 1973–1982 Barrow data, and found a statistically insignificant increase in the CO_2 amplitudes over time.

We report here our attempt in deriving a method to analyze the long-term changes in CO_2 amplitudes using the Canadian data. The method could use the monthly mean concentrations of CO_2 commonly adopted to report CO_2 levels in various publications. From the Station P and Alert data, the detrended monthly mean concentrations of atmospheric CO_2 were fitted with a mixed additive-multiplicative model as described fully by Durbin and Murphy (1975). Local amplitude scaling factors representing the average departures of the detrended values from these models were estimated. The seasonal components were then adjusted with these scaling factors. Changes in the seasonal amplitudes were investigated by analyzing the trends of the differences between maxima and minima of the adjusted seasonal components. Trends of the scaling factors from the same calendar months were also obtained to assess whether the summer or the winter seasons might be responsible for the secular changes in the CO_2 amplitudes at these stations.

2. Data

The data sets used in this study include most of the available CO_2 measurements before mid-1987. The majority of the samples were analyzed at the Centre for Ocean Climatic Chemistry (COCC), Institute of Ocean Sciences. Details of the COCC schemes for adjustment and selection of sample data are described in Wong et al. (1984). Only those modifications made for this work are presented here.

For the Station P data set, samples collected between May 1969 and October 1973 were analyzed by the Scripps Institution of Oceanography (SIO). These data were appended to the beginning of the COCC data set. In addition, SIO data were also used to fill several gaps (i.e., 20 February 1974 to 14 April 1974, 4 August 1974 to 12 January 1975, 1 June 1975 to 21 June 1975, and 22 February 1976 to 8 April 1976) of the time series. Each of these sample values in SIO I-index scale was adjusted downward by 0.23 ppmv (Wong et al., 1984) before converting to the WMO 1985 mole fraction scale. This was to correct a slight bias observed in the SIO samples (Keeling et al., 1985). High summer CO_2 values were recorded in some years (cf. Wong et al., 1984; Keeling et al., 1985); these data were not included in the edited data set.

All the Alert samples analyzed before 12 August 1986, were recorded in the SIO I-index scale. After this date, all CO_2 measurements were recorded directly in the WMO 1985 scale. For each of the CO_2 values in I-index scale, a correction factor to account for the different NDIR analyzers installed at SIO and COCC was applied before converting to the WMO 1985 scale (Wong et al., 1984). A visual inspection of the whole data plot revealed no obvious discontinuities which would be attributed to the change in scales.

As an additional validation of the method, we also estimated the change in amplitudes of the 1973–1982 mean monthly CO_2 concentrations from Barrow, Alaska (Peterson et al., 1986). To make full use of this data set, we extended the series with the provisional mean value of the first four months of 1983 (Gammon et al., 1986).

3. Analysis

3.1. Data reduction

In our studies, data reduction was accomplished first by fitting the edited CO_2 values from each station with a smoothing cubic spline (Reinsch, 1967). We followed basically the spline algorithm developed by de Boor (1978) except with a chosen smoothing parameter (λ) as suggested by Enting (1986, 1987b). In brief, λ was calculated from the transfer function $H(\omega)$ of the spline function, i.e.,

$$H(\omega) = 1/(1 + \lambda \Delta t \omega^4).$$

$\Delta t = T/n$ is the mean sampling interval of the time series where T is the length of the series and n is the total number of the data. For convenience, Enting (1987b) suggested setting an angular frequency ω or its corresponding period

$2\pi/\omega$ at which a signal is 50% attenuated by the spline fitting process. Thus, for $H(\omega_0) = 0.5$,

$$\lambda_0 = 1/(\Delta t \omega_0^4).$$

For our data sets, by taking a half-attenuation period of 60 days, the algorithm could produce smooth curves without underfitting the data. This gave $\lambda = 863$ and $\lambda = 1078$ for the Alert and the Station P data sets respectively (Figs. 1 and 2). From these spline functions, CO_2 values on the 15th of each calendar month were calculated. These values were taken to be the monthly means in our analyses.

3.2. Time-series model

For each of the three data sets, a 21-point moving-average filter with weights as given in Durbin and Murphy (1975) was applied to the monthly means (z_t) to estimate the long-term trends (x_t). As shown by Durbin and Murphy

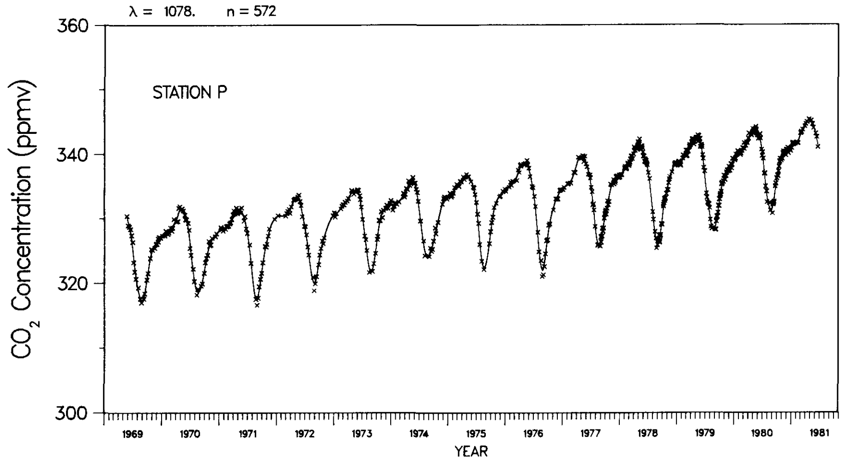

Fig. 1. Atmospheric CO_2 concentrations (WMO 1985 scale) from selected dried samples collected at Station P. The curve is the smoothing cubic spline showing seasonal variations. The total number of sample (n) and the smoothing parameter (λ) used for fitting the spline are given on the top of the frame.

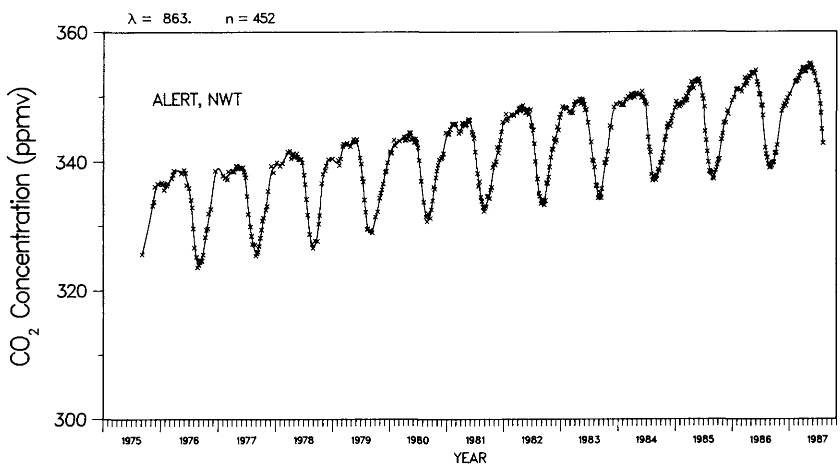

Fig. 2. Atmospheric CO_2 concentrations (WMO 1985 scale) from selected dried samples collected at Alert. The curve is the smoothing cubic spline showing seasonal variations. The total number of sample (n) and the smoothing parameter (λ) used for fitting the spline are given on the top of the frame.

(1975), this filter has good trend-estimating properties for seasonal time series. The detrended monthly mean concentrations $(z_t - x_t)$ were used in the subsequent analyses. Thus, there were altogether 10 full years of monthly mean data available for both Station P and Alert, and nine full years for the Barrow series.

In the next step, each set of the detrended monthly means was fitted with a simple model to identify the seasonal components of the time series. The general model adopted here included a mixture of additive and multiplicative coefficients. A full description of the model is given by Durbin and Murphy (1975). In terms of the estimated CO_2 monthly means, all at time $t = 12(i-1)+j$, and for year $i = 1, 2, \ldots,$ and month $j = 1, 2, \ldots, 12$, the model is of the form,

$$y_{ij} = z_{ij} - x_{ij} = a_j + b_j x_{ij} + r_{ij}, \tag{1}$$

with constraints,

$$\sum_{j=1}^{12} a_j = \sum_{j=1}^{12} b_j = 0, \tag{2}$$

where z_{ij} is the observed CO_2 concentrations, x_{ij} is the estimated trend value, a_j is an additive seasonal factor, b_j is a multiplicative seasonal factor, and r_{ij} is the residual. The constraints (eq. (2)) ensure that the factors do indeed measure departure from the general level of the series. Since the seasonal component of CO_2 is basically a periodic function with a period of 12 months, it may be represented by a sum of sine and cosine waves of the fundamental frequency and its first five harmonics (i.e., $k = 1, 2, \ldots, 5$). This representation of the seasonal components amounts to a Fourier transformation of the data (Durbin and Murphy, 1975; also cf. Thompson et al., 1986).

The model (eq. (1)) can be written in vector notation as

$$\boldsymbol{F}\boldsymbol{y}_i = \boldsymbol{F}\boldsymbol{a} + \boldsymbol{F}\boldsymbol{x}_i\boldsymbol{b} + \boldsymbol{F}\boldsymbol{r}_i, \tag{3}$$

where

$\boldsymbol{y}_i$ is the vector $[y_{i1}, y_{i2}, \ldots, y_{i,12}]'$,

$\boldsymbol{r}_i$ is the vector $[r_{i1}, r_{i2}, \ldots, r_{i,12}]'$,

$\boldsymbol{a}$ is the vector $[a_1, a_2, \ldots, a_{12}]'$,

$\boldsymbol{b}$ is the vector $[b_1, b_2, \ldots, b_{12}]'$,

$\boldsymbol{x}_i$ is the matrix $\begin{bmatrix} \boldsymbol{x}_{i1} & & & 0 \\ & \boldsymbol{x}_{i2} & & \\ & & \ddots & \\ 0 & & & \boldsymbol{x}_{i,12} \end{bmatrix}$,

and $\boldsymbol{F}$ is the 12×12 Fourier matrix. For $p = 1, 2, \ldots, 12$, and $k = 1, 2, \ldots, 5$, the elements of the transformation matrix $\boldsymbol{F}$ are given by:

$$f_{1p} = 1/\sqrt{12},$$
$$f_{2k,p} = (1/\sqrt{6})\cos(kp\pi/6),$$
$$f_{2k+1,p} = (1/\sqrt{6})\sin(kp\pi/6),$$
$$f_{12} = (1/\sqrt{12})\cos(p\pi).$$

Let $\boldsymbol{y}_i^* = \boldsymbol{F}\boldsymbol{y}_i, \boldsymbol{a}^* = \boldsymbol{F}\boldsymbol{a}, \boldsymbol{b}^* = \boldsymbol{F}\boldsymbol{b}$, and $\boldsymbol{r}_i^* = \boldsymbol{F}\boldsymbol{r}_i$, the model (eq. (3)) becomes

$$\boldsymbol{y}_i^* = \boldsymbol{a}^* + (\boldsymbol{F}\boldsymbol{x}_i\boldsymbol{F}')\boldsymbol{b}^* + \boldsymbol{r}_i^*,$$

or

$$\boldsymbol{y}_i^* = (\boldsymbol{I}, \boldsymbol{F}\boldsymbol{x}_i\boldsymbol{F}')\boldsymbol{c} + \boldsymbol{r}_i^*, \tag{4}$$

where $\boldsymbol{I}$ is the 12×12 identity matrix, and $\boldsymbol{c} = (\boldsymbol{a}^*, \boldsymbol{b}^*)'$ is the vector of Fourier coefficients to be estimated. Since the seasonal patterns of atmospheric CO_2 data are relatively stable with no major spurious variations, application of ordinary least-squares (OLS) method to model (4) could give unbiased and efficient estimates identical to those obtained by applying the same to model (1) (Durbin and Murphy, 1975; Fuller, 1976). Taking into account the constraints (eq. (2)), the two coefficients, a_1^* and b_1^*, are both equal to zero as they correspond respectively to the sums of the additive and the multiplicative factors. Thus model (4) contains essentially 22 independent coefficients. When all $b_j^* = 0$, then we have a purely additive model, and likewise, a purely multiplicative model results if all $a_j^* = 0$.

Initially the seasonal components were analyzed to discover whether they are essentially additive, multiplicative, or a mixture of the two. The relative importance of both types of coefficients was investigated using simple F-tests of variance ratios in which the 11 additive coefficients were first fitted to the additive model and then the significance of adding all the multiplicative coefficients to the model was tested. This process was then repeated the other way round

(Durbin and Murphy, 1975). In our analyses, all critical values of the F-test were fixed at the 10% significance level. Results of all the tests suggested non-significant increase in the F-values on introduction of the multiplicative terms to the purely additive models, and also non-significant increase on introduction of the additive terms to the purely multiplicative models. Hence models with mixture of both additive and multiplicative coefficients were used in our analyses.

3.3. *Subset selection*

There are 22 independent coefficients in the full model (4) but only several of these coefficients are normally needed to represent the data. The best subset of these coefficients is taken to be the one that is parsimonious and also gives the smallest residual sum of squares. In this study, the significant coefficients (or variables) were selected by the leaps-and-bounds algorithm (Furnival and Wilson, 1974) which has been implemented by IMSL as subroutine RLEAP (IMSL, 1982). This efficient algorithm was designed to search incrementally from the full model to obtain a number of good subset models for each possible subset size. From these models, the one with the lowest Mallow's C_p criterion (Hocking, 1976) was then selected as the best subset model (IMSL, 1982).

3.4. *Local amplitude scaling factor*

The probable change in the amplitude of seasonality over a relatively short time period may be studied by analyzing the local amplitude scaling factor as defined by Durbin and Murphy (1975). Distinct changes in the local amplitude scaling factors could be considered as depicting the average departure of monthly mean CO_2 data from the assumed general model.

The scaling factor is calculated from a moving regression of the detrended CO_2 values on the estimated seasonal components s_{ij}, where

$$s_{ij} = a_j + b_j x_{ij}.$$

In other words, for a chosen period of monthly data as the regression base, the local amplitude scaling factor is defined as the regression coefficient d_{ij} in the regression

$$z_{ij} - x_{ij} = d_{ij} s_{ij} + r_{ij}, \qquad (5)$$

of $z_{ij} - x_{ij}$ on s_{ij} centred on the time point under study. In our studies, the regression was fitted over a chosen period of seven months moving along the whole data set. Hence no scaling factors were available for the first and last three months of the series. The chosen regression base of seven months was based on the assumption that the seasonal effects of biotic or geophysical factors on CO_2 amplitudes at mid-latitudes would usually extend for about half a year. Bacastow et al. (1985) also incorporated a different scale factor in the spline function to estimate the changes in the amplitudes of the Mauna Loa CO_2 data. Their method assumed that the seasonal amplitude maintains its shape and timing throughout the record but increases linearly with time (Bacastow et al., 1985). Our method allows for the variations in the shape of the seasonal amplitudes.

3.5. *Changes in amplitudes*

The adjusted seasonal components ($d_{ij} s_{ij}$) were used to estimate the rate of change in the seasonal amplitudes. In practice, the amplitude was defined as the difference between the maximum and the minimum of the seasonal component in the same year. Enting (1987a) found that, for the Mauna Loa data, only the spring maxima and the summer minima from the same year are highly correlated. Similar correlation was assumed for the data sets analyzed here. We used the May values as the spring maxima for all three stations (cf. upper panels of Figs. 3 to 5). For Station P and Barrow, the summer minima were the August values; the minima used for Alert were the September values. Trends of the seasonal amplitudes were estimated by OLS linear regression assuming no autocorrelated errors. One-sided t-tests were performed to judge whether any of the estimated trends is greater than zero at the 10% significance level.

3.6. *Trend of scaling factors*

The long-term changes in the CO_2 amplitudes probably reflect the slow changes in the rate of either the summer draw-downs or the winter releases, or in both processes. Is the increasing draw-down followed by an increasing release of similar magnitude? Are the three data sets displaying the same pattern in time of CO_2 uptakes and releases? We explore these questions indirectly by checking the trends over time of the

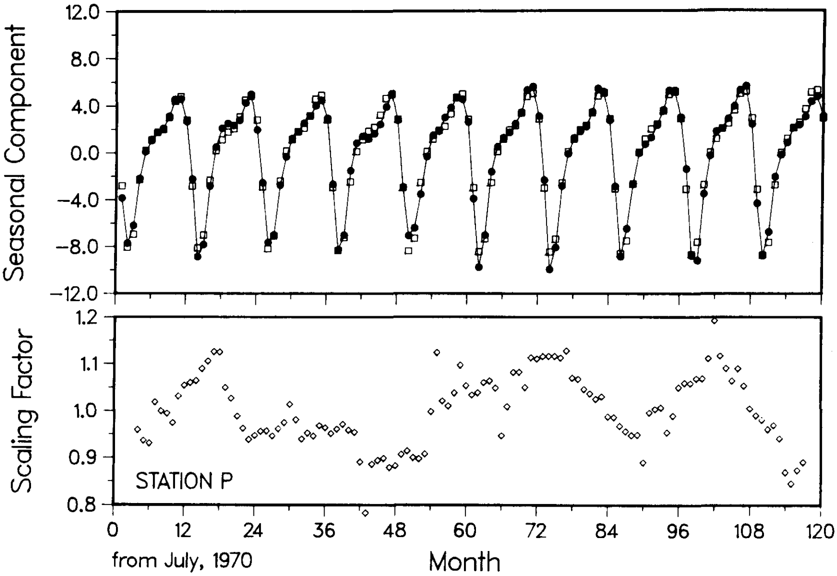

Fig. 3. (Top) Detrended monthly means (monthly mean – trend; solid dots) and modelled seasonal components (open squares) from the Station P data. (Bottom) Local amplitude scaling factors of the seasonal components.

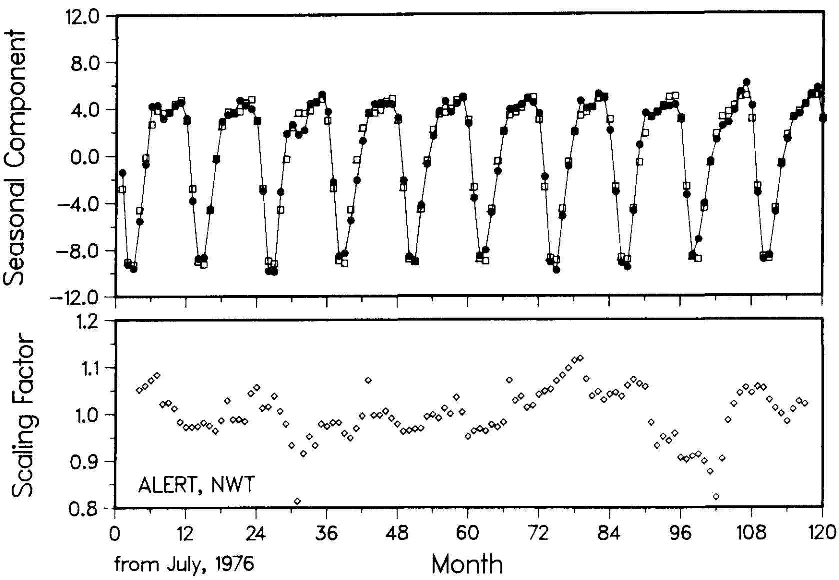

Fig. 4. (Top) Detrended monthly means (monthly mean – trend; solid dots) and modelled seasonal components (open squares) from the Alert data. (Bottom) Local amplitude scaling factors of the seasonal components.

scaling factors. A negative slope for the summer months could suggest increasing draw-down over time, whereas a positive growth over the winter and spring months could suggest increasing CO_2 release. In our study, these trends were estimated simply by linear regression of the scaling factors from the same calendar months on time increments.

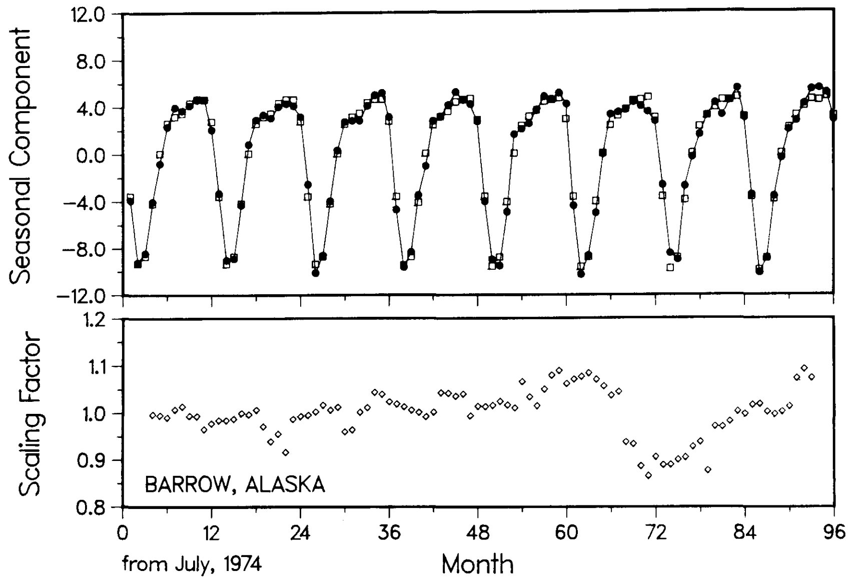

Fig. 5. (Top) Detrended monthly means (monthly mean − trend; solid dots) and modelled seasonal components (open squares) from the Barrow data. (Bottom) Local amplitude scaling factors of the seasonal components.

4. Results

As mentioned earlier, a mixed additive-multiplicative model is used to approximate the detrended monthly mean concentrations of atmospheric CO_2 (Figs. 3 to 5). Of the 22 coefficients describing the model, only subsets of 7–9 terms are chosen by the selection algorithm (Table 1). These coefficients represent mainly the first four harmonics of the Fourier series.

The bottom panels of Figs. 3 to 5 show the trend of the scaling factors which are calculated from eq. (5) of the respective data sets. Most of these scaling factors have values of between 0.9 and 1.1. For the Station P data set, the scaling factors have low values for the years 1974, 1977 and 1980, but relatively high values in 1971, 1975/1976 and 1979. Similar qualitative results are obtained by Keeling et al. (1985) in their analyses of the relative amplitudes of the Station P data. For the Alert data set, the scaling factors display a slight decrease from 1977 to 1979 followed by a slight increase to 1982 and then a sharp drop to the low values in 1984. The scaling factors from the Barrow data set display a gradual increase in the first five years but again drop in 1980.

The CO_2 amplitudes derived from the Station P data show an increase between 1971 and 1979 (Fig. 6). The average growth rate, as represented by the regression coefficient, is estimated to be about 0.2 ± 0.1 ppmv/year or 1.4%/year relative

Table 1. *Coefficients selected for the seasonal component models*

	Additive coefficient							Multiplicative coefficient						
Station	c_j, $j=$ 2	3	4	6	7	8	9	14	15	16	17	18	19	21
Alert	x	x	x		x		x	x		x	x	x		
Station P		x							x	x	x	x	x	x
Barrow	x		x	x		x	x		x		x	x	x	

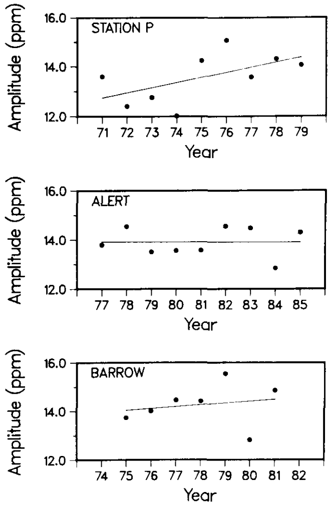

Fig. 6. Trends of the CO_2 seasonal amplitudes at Station P (top), Alert (middle) and Barrow (bottom). The amplitude is defined as the difference between the maximum and the minimum values of the detrended monthly mean concentrations in the same year.

to the 1971 seasonal amplitude. The one-sided t-test suggests that the slope estimate has a 92% chance of greater than zero. However a negative coefficient is obtained for the amplitude data from Alert (Fig. 6). The slope estimate is about -0.003 ± 0.08 ppmv/year or -0.02%/year relative to the 1977 seasonal components. For the Barrow data, the CO_2 amplitudes show a slight increase between 1975 and 1981 (Fig. 6) at a rate of about 0.08 ± 0.17 ppmv/year or 0.03%/year relative to the 1975 amplitude. In each of the latter two cases, the one-sided t-test rejects the hypothesis that the trend is greater than zero.

Trends of the scaling factors from the same calendar months display different patterns among the three stations (Table 2). However, most of the estimates are not statistically significant as their respective standard error is relatively large compared with the estimated coefficients. For Station P, the data show that the spring and the summer scaling factors are increasing over the period. However, in December and January, the rates are decreasing. In the case of Alert, the scaling factors might be decreasing slightly from October to January followed by positive values for the other months. A different pattern is obtained using the data from

Table 2. *Linear regression coefficients (%/year) of the scaling factors by calendar months; values within the parentheses are the standard error of individual estimate*

	Alert	Station P	Barrow
January	−0.29 (1.06)	−0.17 (1.27)	0.26 (1.04)
February	0.21 (0.54)	0.10 (0.88)	0.58 (1.04)
March	0.20 (0.36)	0.22 (0.75)	0.48 (0.78)
April	0.39 (0.55)	1.24 (0.70)	−0.21 (1.45)
May	0.27 (0.43)	0.99 (0.97)	−0.30 (1.42)
June	0.06 (0.71)	0.63 (0.92)	−0.28 (0.98)
July	0.37 (0.69)	0.51 (0.89)	−0.24 (1.14)
August	0.34 (0.65)	0.30 (0.90)	−0.22 (1.16)
September	0.20 (0.73)	0.06 (1.05)	−0.41 (1.12)
October	−0.10 (0.67)	0.23 (0.88)	−0.32 (0.74)
November	−0.23 (0.73)	0.28 (1.01)	−0.17 (0.58)
December	−0.61 (0.91)	−0.13 (1.27)	0.13 (0.67)

Barrow. Its scaling factors show negative trends from April to November but slight increases in February and March.

5. Discussion

The intra-annual variations of atmospheric CO_2 concentrations are the composites of all the seasonal oscillations associated with the many CO_2 sources and sinks (Junge and Czeplak, 1968). Of these oscillations, the dominant contribution comes from the biological activities of terrestrial ecosystems (Bolin, 1977; Olson et al., 1978; Armentano and Ralston, 1980; Gifford, 1982, 1988; Lemon, 1983). The role of land vegetation can be demonstrated indirectly by correlating the atmospheric CO_2 levels with a vegetation index of remotely sensed imageries (D'Arrigo et al., 1987; Fung et al., 1987). Models of carbon cycle are also used recently to deduce the magnitude of the atmosphere-biosphere exchange of CO_2 (Gillette and Box, 1986; Pearman and Hyson, 1986).

Two of the minor contributions are the seasonalities of fossil-fuel emissions and air-sea exchanges of marine CO_2. The contribution from the former may be small but there is a phase agreement of seasonalities between the fossil-fuel emissions and the atmospheric CO_2 concentrations (Rotty, 1987). For the marine CO_2, its contribution to the atmospheric CO_2 variation in 1980 was only in the order of 0.2 ppmv (Keeling, 1983). Furthermore, the seasonalities of atmospheric and marine CO_2 might not be in phase with each other. In fact, at Station P between 1976 and 1978, the partial pressures of CO_2 in surface seawater showed a small summer supersaturation and a winter undersaturation of similar magnitude (Wong et al., 1985).

5.1. Regional differences

In our analyses, the CO_2 amplitudes derived from all three data sets do not show a common trend. The inconsistency indicates that the regional variabilities of CO_2 sources and sinks are still dominating the seasonal patterns. For the Station P data, our estimate suggests a definite increase in the CO_2 amplitudes. The rate is higher than those obtained previously by others (Pearman and Hyson, 1981; Keeling et al., 1985). These differences may not be significant since slightly different data sets and incompatible statistical methods are used in the three studies. However, our estimated value is close to the growth rate derived from the Mauna Loa data for the same period (Bacastow et al., 1985).

In their study of CO_2 amplitudes, Cleveland et al. (1983) have noticed the different behaviour obtained from the Barrow data as compared with those using the Mauna Loa or the South Pole data. However Peterson et al. (1986), after analyzing the updated Barrow data with a different method, suggest a possible increase in the seasonal amplitudes. Our analysis, by just using the monthly mean values instead of the full data set, support the general results of Peterson et al. (1986). In addition, our results suggest that the trends for the scaling factors for April and May are not significantly different from zero (Table 2).

The hypothesis of an increasing CO_2 amplitude at Alert in recent years could not be accepted conclusively in our analysis. However, the trends of the amplitudes and the scaling factors (Table 2) suggest the releases of CO_2 in the autumn and early winter might be decreasing slightly over the years. In this case, the net result could be a slight accrual of CO_2 in the terrestrial ecosystems. Oechel et al. (1984) reported that, in the Arctic tundra, a higher ambient CO_2 level and a warmer climate might increase rather than decrease the sequestering of carbon to the plant/soil system.

Recently, D'Arrigo et al. (1987) incorporated the normalized-difference vegetative index (NDVI) obtained from remotely sensed data to an atmospheric tracer transport model (Fung et al., 1983) to estimate the contribution of boreal forests to the total CO_2 amplitude. They found that the seasonal growth of boreal forests accounts for about 50% of the mean CO_2 amplitude recorded at Barrow and 30% of the CO_2 amplitude at Mauna Loa. These results suggest that the findings of Houghton (1987) may have to be reconsidered. The analyses of Houghton (1987) are based on exploring the various scenarios of metabolic changes in a temperate deciduous oak-pine forest that might yield the increased amplitude of CO_2 concentration at Mauna Loa in recent years. The results of D'Arrigo et al. (1987) imply that the production and respiration data used by Houghton (1987) represent only about half of the total CO_2 amplitude at Mauna Loa. In addition, their results also indicate indirectly that the regional differences in the biospheric sources and sinks of CO_2 should be considered when assessing the possible changes in the amplitudes of atmospheric CO_2.

5.2. Possible causes of decreasing amplitudes

There are several causes that could influence the slope estimate of the seasonal amplitudes. In OLS regression, the occurrence of a few outliers in the data set could affect the magnitude of the coefficient estimate. Examples of these values are the particularly low values in 1983/1984 from Alert or similarly the 1980 values from Barrow (Fig. 6). The low Barrow values presumably reflect the decreases in land plant production caused by the summer droughts in this year (Karl and Quayle, 1981).

Another possible cause for a decrease in scaling factors might be the damping effect of a strong increasing signal (i.e., the anthropogenic CO_2) on the almost regular CO_2 oscillations (Brown et al., 1982), The actual rate of CO_2 draw-down in the summer would be much higher had it not been overwhelmed simultaneously by the continuous emission of anthropogenic CO_2. Since the emission rate is much higher than the expansion rate of the CO_2 seasonal components, a gradual decrease in the apparent amplitude of CO_2 concentrations would be expected.

A possible increasing CO_2 amplitude at high northern stations could also be the result of a slightly longer growing season. The possible decrease of the scaling factors during the late autumn and early winter at Alert (Table 2) might suggest an increasing draw-down (or decreasing release) of CO_2 during this period. At high northern stations, the seasonal patterns of atmospheric CO_2 are basically influenced by the biotic activities of the large stretch of boreal forests (D'Arrigo et al., 1987) and the Arctic tundra (Billings et al., 1983; Oechel et al., 1984).

Many evergreen trees growing in the southern and coastal fringes of the boreal forests are known to have net carbon gain from photosynthesis in the winter (Parker, 1961; Fry and Phillips, 1977). Several deciduous tree species growing in this region, such as the widespread trembling aspen (*Populus tremuloides*), possess chlorophylls in the cortex and the inner bark cells and can have some photosynthetic activities in the defoliated state (Pearson and Lawrence, 1958; Perry, 1971; Schaedle and Foote, 1971). Keller (1973) suggests that the winter-season photosynthesis of these species may account for the recycling of one third to one half of the CO_2 releases by stem respiration. The rising level of ambient CO_2 may also enhance the rate of winter-season photosynthesis when light is often limiting (Heath and Meidner, 1967). The enhancement is accomplished by two changes. One of these is the lowering of light compensation point thus extending the duration of net carbon gain. The other is caused by the increased intercellular pressure of internal CO_2 concentrations which improves the efficiency of CO_2 uptake per unit of absorbed light (Berry and Downton, 1982).

It is difficult to estimate the total amount of CO_2 draw-down by plant production within the boreal forests between late autumn and early spring. If the stimulation of organic matter decomposition by the warmer climate did not exceed the enhancement of CO_2 uptake by the increasing CO_2 level as was observed by Oechel et al. (1984) for an Arctic ecosystem, then the net result of extending the growing season would be a slow down in the expansion of the CO_2 amplitudes.

6. Concluding remarks

Our analyses of the seasonal amplitudes of atmospheric CO_2 concentrations show an increasing trend for the Station P data set and a very small, but not statistically significant, decreasing one for the Alert data set. An increasing though also statistically non-significant trend is also suggested for the 1973–1982 Barrow data.

The amplitude changes obtained for the high northern stations implies that the various regional factors might be important in influencing the amplitudes of atmospheric CO_2 concentrations. In Station P, the slow increase in the seasonal amplitudes of atmospheric CO_2 is not corroborated by data from Barrow or Alert. We hypothesize that the increasing level of atmospheric CO_2 may also have promoted winter-season photosynthesis of some plant species in the boreal forest. This has the effect of reducing the winter release of respiratory CO_2 or increasing the uptake of ambient CO_2. The net effect would be a gradual decrease in the seasonal amplitudes as suggested by the Alert result. It is very important to ascertain the total effect of the interannual variations when generalizing results of a few stations with short time series. These results have to be interpreted with caution since the idea that these could be artifacts caused by inadequate sample sizes, incomplete model representation or from data manipulation could not be ruled out totally. Obviously, several more years of air sampling at high northern stations are needed to filter the trend from the variable signals under similar climatic factors.

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