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ATMOSPHERIC CARBON DIOXIDE MEASUREMENTS AT SYOWA STATION, ANTARCTICA, 1984–1988

Shuhji AOKI[1], Takakiyo NAKAZAWA[2], Shohei MURAYAMA[2], Masashi FUKABORI[3], Takashi YAMANOUCHI[1], Haruta MURAYAMA[4], Masataka SHIOBARA[3], Sadao KAWAGUCHI[1] and Masayuki TANAKA[2]

[1]*National Institute of Polar Research, 9–10, Kaga 1-chome, Itabashi-ku, Tokyo 173*
[2]*Center for Atmospheric and Oceanic Studies, Tohoku University, Aramaki Aoba, Aoba-ku, Sendai 980*
[3]*Meteorological Research Institute, 1–1, Nagamine, Tsukuba 305*
[4]*Faculty of Education, Yokohama National University, 156, Tokiwadai, Hodogaya-ku, Yokohama 240*

Abstract: Precise and continuous measurements of atmospheric CO_2 concentration have been continued at Syowa Station (69°00′S, 39°35′E), Antarctica since February 1984. Diurnal CO_2 variation was hardly observable throughout the year. The secular CO_2 trend was variable with time, showing slow increase in 1984, 1986 and 1988 and rapid increase in 1985 and 1987. The annual CO_2 increase was remarkable, especially in 1987, which may be related to the 1987 ENSO event. The average rate of annual CO_2 increase over the last 5 years was about 1.6 ppmv yr^{-1}.

The average seasonal CO_2 cycle showed minimum and maximum concentrations in mid-April and in early October, respectively. Its peak-to-peak amplitude was about 1.1 ppmv for the period 1984–1988. The seasonal cycle was variable from year to year, but there was no indication of long-term amplitude increase.

It was found that irregular CO_2 variations with amplitudes of about 0.2 ppmv and with periods of a few tens of days have high correlation with air mass exchange by synoptic scale weather disturbances.

1. Introduction

Measurements of atmospheric carbon dioxide (CO_2) are being made by several institution in Antarctica, either by continuous sampling with an *in situ* analyzer or by discrete flask sampling with subsequent laboratory analysis (*e. g.*, KEELING *et al.*, 1976; KOMHYR *et al.*, 1985; BEARDSMORE and PEARMAN, 1987a; TANAKA *et al.*, 1987a). The *in situ* measurements initiated at Syowa Station (69°00′S, 39°35′E) in February 1984 have been continued up to the present. In our preceding paper (TANAKA *et al.*, 1987a), we concluded that Syowa Station is a site suitable for background monitoring of atmospheric CO_2 concentration, because no diurnal CO_2 variation is observable and day-to-day CO_2 variations are also extremely small, except for outliers due to station activities. This paper presents results of measurements for the period 1984–1988.

2. Sampling Site and Experimental Procedures

Detailed descriptions of the sampling site and our continuous measurement system have been given elsewhere (TANAKA *et al.*, 1987a). Only a brief description and supplemental explanations will be presented here.

Syowa Station is located at 69°00′S and 39°35′E on East Ongul Island in Lützow-Holm Bay, being separated from the Antarctic continent by about 4 km. The rock surface is covered with snow except in summer. The climate is comparatively moderate: the annual mean air temperature and wind speed are −11°C and 6 ms^{-1}, respectively. Prevailing winds are north-northeasterly, northeasterly or easterly for more than 70% of the time. The calm, *i. e.* wind speed is less than 0.3 ms^{-1}, occurs about 4% of the year.

Our continuous measurement system was installed in an atmospheric science laboratory of the station. The air intake is mounted atop an 8 m-high mast at the coast of the island, about 30 m away from the laboratory toward the prevailing wind. Air samples are introduced into the measurement system by pumping through an annealed copper tube from the intake. Water vapor is removed from air samples by a glass trap cooled at −60°C by an electric refrigerator, and aerosol particles larger than 1 μm are also removed by glass and membrane filters. The tubing of our measurement system, except for the air sample intake tube and the water vapor trap, is made of stainless steel.

VIA-500R nondispersive infrared (NDIR) CO_2 analyzers manufactured by Horiba Co. of Japan were used at Syowa Station. The analyzer is a differential type, with reference gas of CO_2 concentration 15–20 ppmv below ambient-air CO_2 levels flowing continuously through the reference cell at about 15 m*l* min^{-1}. We improved the analyzer as described by TANAKA *et al.* (1983) to attain an precision of ±0.01 ppmv.

We prepared three kinds of working standard gases: high gas, low gas and check gas. High and low gases are used for calibrating the analyzer automatically every 30 min. The check gas is used for confirming the non-linear relationship between the analyzer response and the CO_2 concentration once per 10 days. The CO_2 concentration of the check gas is selected nearly equal to that of the air sample to be measured. In order to minimize the non-linear correction and to be able to interpolate CO_2 concentrations of air samples precisely, the concentration difference between high gases and low gases should be as small as possible: we determined the difference to be 10–12 ppmv.

The CO_2 concentrations of the working standard gases are determined before and after their use to a precision of ±0.01 ppmv by comparing with our secondary standard gas system. About 17 working standard gases were used at Syowa Station every year from 1984 to 1988. All working standard gases were replaced by new ones every year at the station; it took about one year and a half to determine the CO_2 concentration drift of these gases: it takes about 4 months to transport the working standard gases between Syowa Station and Japan. The mean value of concentration drift was 0.037±0.057 ppmv. A slight positive drift very likely occurs with decrease of pressure of the cylinders. The drift of CO_2 concentration was within ±0.1 ppmv

for 87% of all working standard gases, and the maximum drift was +0.19 ppmv at most. The concentration drifts were extremely small, so we used mean value of both calibrations for each working standard gas to calculate the CO_2 concentration of air samples.

3. Results and Discussion

CO_2 concentration at Syowa Station has usually been very stable, but occasionally it shows large variability with high concentrations in weak wind conditions due to local contamination. Such contaminated data are eliminated by a simple statistical data selection scheme. We usually obtain 8 data for each hour, so hourly mean CO_2 concentrations and standard deviations are first calculated from all available data. Then hourly means of the data with standard deviations larger than 0.5 ppmv are excluded (*cf.* TANAKA *et al.*, 1987a). Only 8% of all available data were eliminated by this scheme. Figure 1 shows daily mean CO_2 concentrations calculated from the selected data. It is clear from this figure that variations of the CO_2 concentration can be divided into three components: secular trend, seasonal cycle and irregular variations. To separate these components, we used a digital-filtering technique including Fourier harmonics, Reinsch-type spline and Butterworth filter. The technique has been described elsewhere (NAKAZAWA *et al.*, 1991).

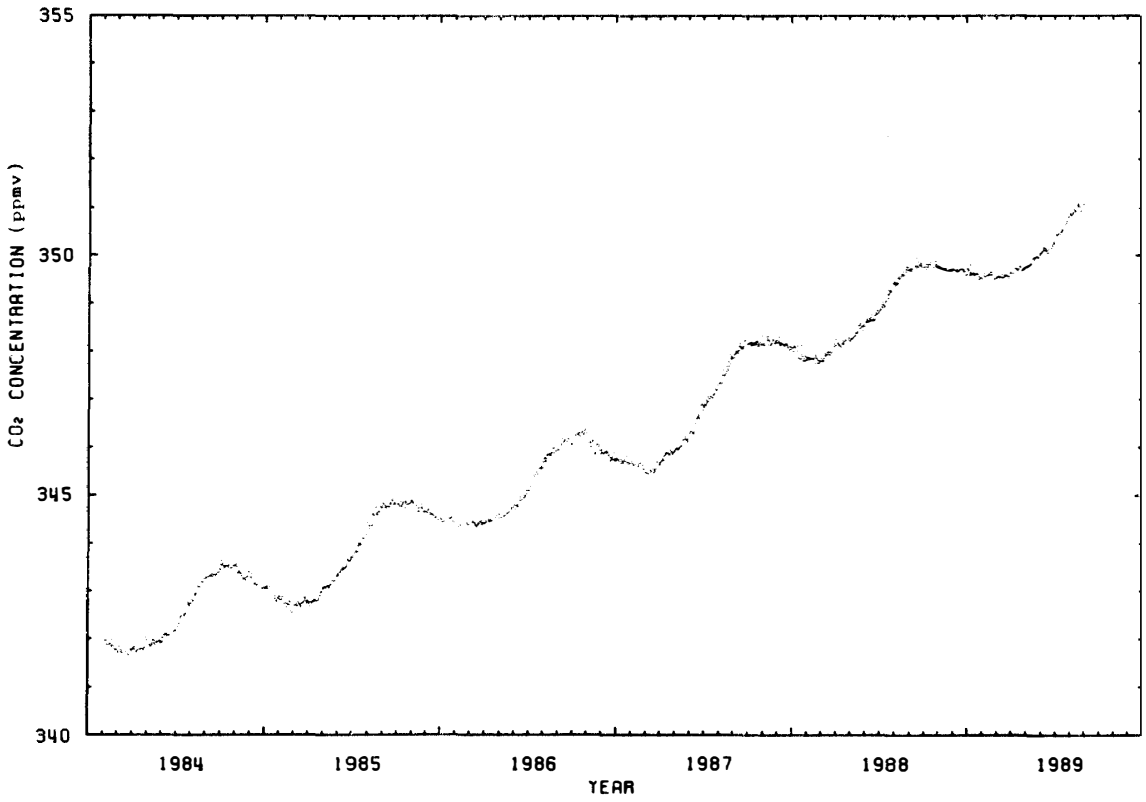

Fig. 1. Daily mean CO_2 concentration at Syowa Station obtained from selected data (see text). Concentrations for the period February 1989 to August 1989 are preliminary values without the final calibration of working standard gases.

The upper panel of Fig. 2 shows the secular trend and the annual rate of increase of the CO_2 concentration. The average annual rate of increase for the period February 1984 through January 1989 was 1.6 ppmv yr^{-1}. The secular trend was variable with time, showing slow increase in 1984, 1986 and 1988 and rapid increase in 1985 and 1987. The annual CO_2 increase was remarkable, especially in 1987. These interannual variations in the growth rate of CO_2 were found to correlate negatively with the Southern Oscillation Index (SOI) (BACASTOW, 1976; BACASTOW *et al.*, 1980; BACASTOW and KEELING, 1981; TANAKA *et al.*, 1987b; CONWAY *et al.*, 1988). The minimum value of five month running mean of the SOI (TAHITI-DARWIN) in recent years appeared in May 1987, as shown in the lower panel of Fig. 2. The maximum value of the rate of annual CO_2 increase at Syowa Station appeared early in September 1987. The time lag was estimated to be 3–4 months. BACASTOW and

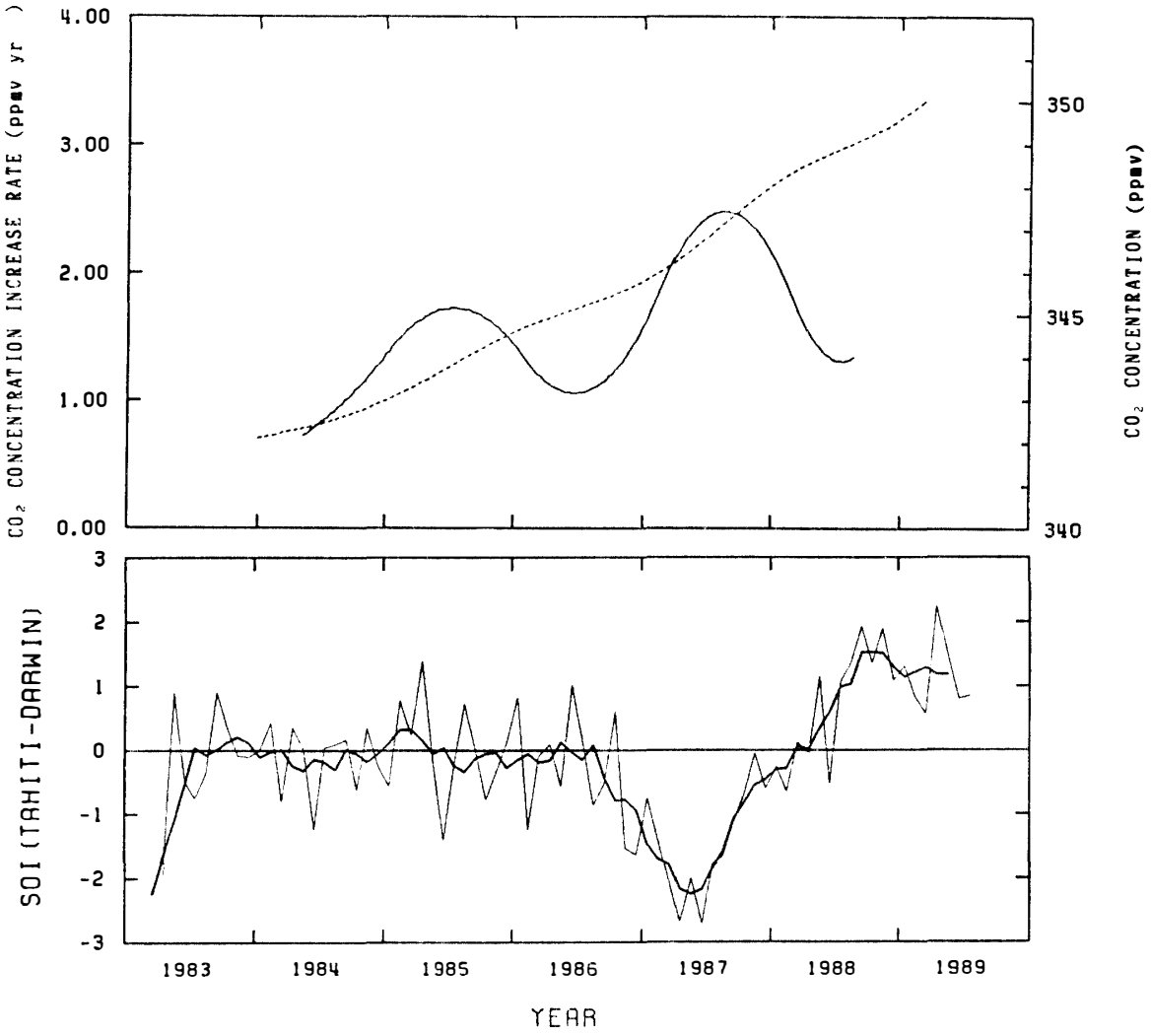

Fig. 2. The upper panel: secular trend (dashed curve) and rate of annual increase (solid curve) of the atmospheric CO_2 concentration observed at Syowa Station.
The lower panel: the Southern Oscillation Index, 1983–89 (JAPAN METEOROLOGICAL AGENCY, 1983–89). Thin line and thick line denote monthly and 5-month running mean values, respectively.

KEELING (1981) have found that the average time lag to attain maximum correlation between the rate of annual CO_2 increase and SOI is 6 months for the South Pole. Compared with their result, the present lag is shorter by 2–3 months. It is difficult to explain the difference of these lags at South Pole and Syowa Station. But the difference of these lags suggests that the change of the annual rate of CO_2 increase may be driven by the equatorial region. The enhanced rate of increase was also found in 1985 when no ENSO event occurred. Therefore, changes in the growth rate of the CO_2 concentration are associated not only with ENSO events but also with other factors.

The seasonal cycle of the CO_2 concentration, plotted as the deviation from the secular trend, is given in Fig. 3. The average seasonal cycle of CO_2 concentration showed a minimum and maximum in mid-April and early October, respectively, and its peak to peak amplitude was about 1.1 ppmv. The phase and amplitude of the measured seasonal CO_2 cycle were variable from year to year. The amplitude increased in 1985 and 1987 and decreased in 1984, 1986 and 1988, showing a biennial oscillation. There was no evidence for a long-term increase or decrease of the amplitude.

Regular diurnal CO_2 variation due to natural and anthropogenic activities is not observable, but irregular CO_2 variations with amplitude of about 0.2 ppmv and periods of a few tens of days were clearly seen at Syowa Station. Figure 4 shows the relation between such irregular variations and atmospheric temperature observed at the station. Negative correlation can be seen between these two fluctuations: CO_2 concentration tends to decrease when atmospheric temperature increases and *vice versa*. Synoptic scale weather disturbances are the main cause of these tem-

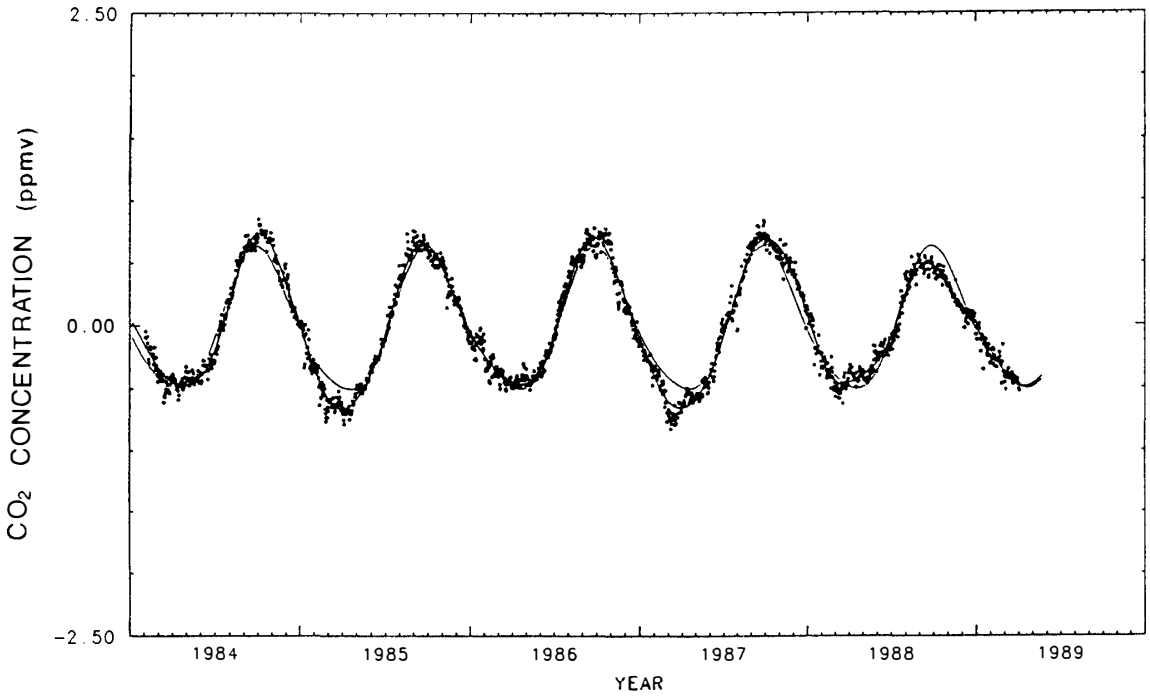

Fig. 3. Seasonal cycle of atmospheric CO_2 concentration observed at Syowa Station. Thin line is average seasonal cycle and thick line includes irregular parts of seasonal cycle.

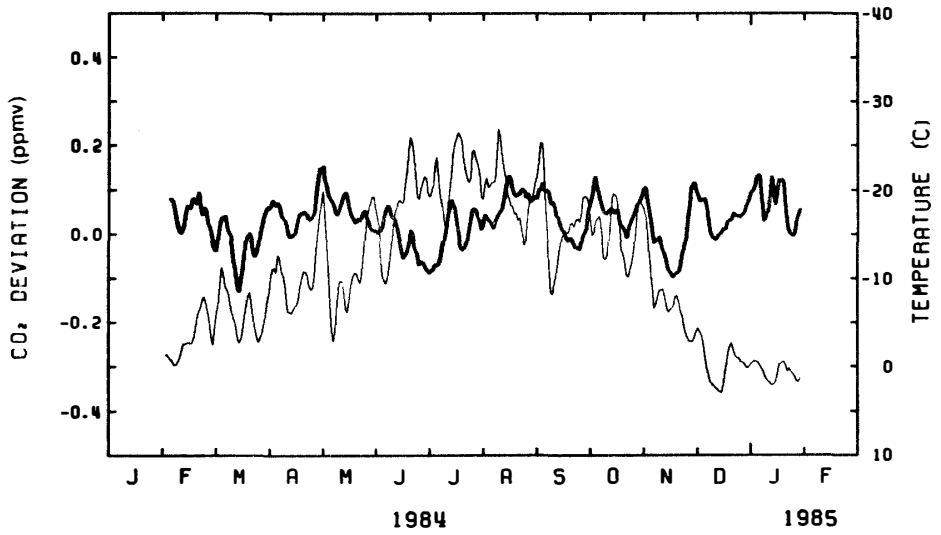

Fig. 4. Irregular variations of CO_2 concentration (thick line) and atmospheric temperature (thin line) at Syowa Station. Daily mean values of CO_2 concentration and temperature were smoothed by 5-day running mean. The ordinate for temperature (right-hand side) was reversed.

perature variations. Therefore, irregular CO_2 variations are primarily attributed to exchange of different air masses in association with such disturbances. This suggests that the CO_2 concentration of the Antarctic air mass is higher than that of the southern hemisphere mid-latitudinal air mass throughout the year.

To compare the results of continuous CO_2 measurements at high latitude in the southern hemisphere, monthly mean values of CO_2 concentration at Cape Grim (40°41'S, 144°41'E) (BEARDSMORE and PEARMAN, 1986, 1987b, 1988, 1989), Syowa Station (69°00'S, 39°35'E) and South Pole (90°S) (NICKERSON, 1985; SCHNELL, 1986, 1987; BODHAINE, 1988) are shown in Fig. 5. Annual mean values of the CO_2 concentration are also listed in Table 1. These values are calculated from measured monthly means and their smoothed curves, using the above-mentioned digital-filtering technique. The WMO X81 scale (World Meteorological Organization 1981 mole fraction scale) and the WMO X85 scale were used to calculate the CO_2 concentration in 1984 and after 1985, respectively, for Cape Grim and South Pole. The concentration scale at Syowa Station was originally prepared by ourselves. Annual mean CO_2 concentrations at South Pole and Syowa Station from 1984 to 1987, nevertheless, agree well with each other, the values at Syowa Station being higher by only 0.1 ppmv, on average, than those at South Pole. On the other hand, the yearly mean CO_2 concentration at Cape Grim was lower by about 0.7 ppmv, on average, than those at Syowa Station. This result is qualitatively consistent with that from our shipboard measurements (TANAKA *et al.*, 1987c). It is also seen that the difference between annual mean CO_2 concentrations at Cape Grim and in the Antarctic region was larger in 1986 and 1987 than in 1984 and 1985.

The seasonal CO_2 cycle in the Antarctic region is produced not only by biospheric activity and CO_2 exchange between the atmosphere and the oceans in the southern hemisphere, but also by dynamical atmospheric transport processes. Figure 6 shows

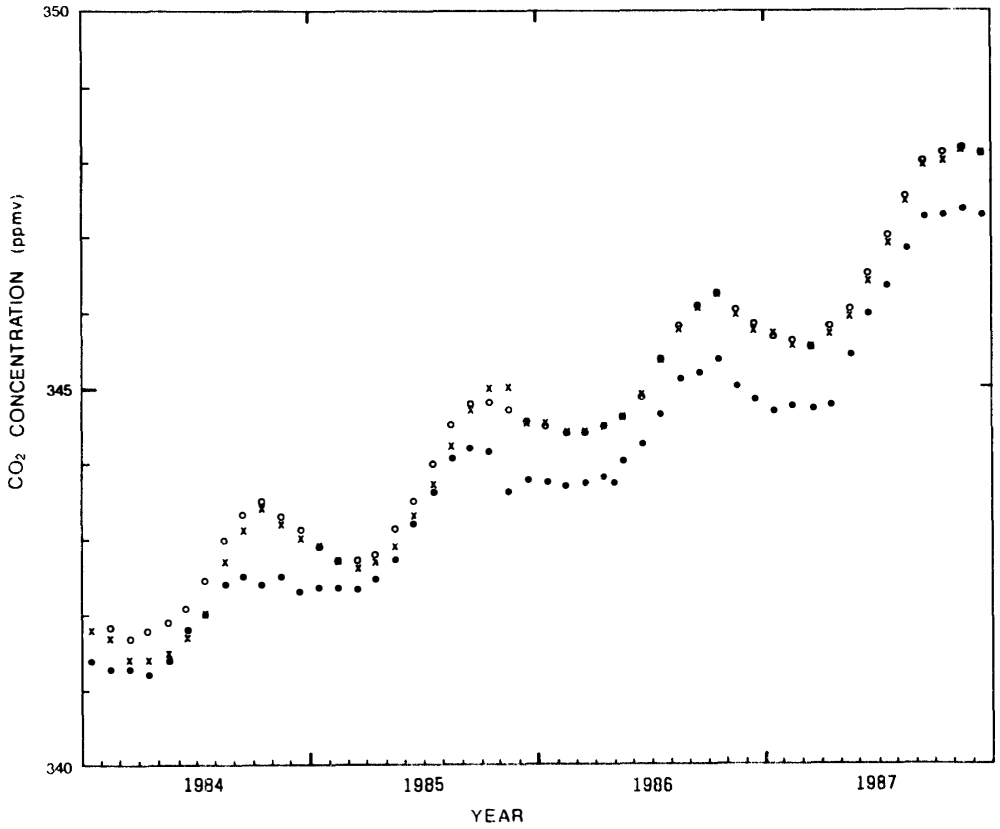

Fig. 5. Monthly mean values of CO_2 concentration at Cape Grim (solid circles), Syowa Station (open circles), and South Pole (crosses).

Table 1. Annual mean CO_2 concentration at Syowa Station, South Pole and Cape Grim. Column labeled data and fit contain annual means calculated from monthly means and fitting function, respectively. Annual means for the fitting function are computed from daily values.

	Syowa Station		South Pole		Cape Grim	
	Data	Fit	Data	Fit	Data	Fit
1984	342.55	342.51	342.24	342.25	341.88	341.88
1985	343.76	343.77	343.68	343.70	343.23	343.23
1986	345.22	345.23	345.20	345.21	344.46	344.46
1987	346.86	346.87	346.79	346.80	346.06	346.07

seasonal variations of CO_2 concentration at three stations. Minimum concentrations of the mean seasonal CO_2 cycle at Cape Grim, Syowa Station and South Pole appeared in 93, 97 and 112 days relative to January 1, and maximum concentrations in 253, 273 and 280 days, respectively. The seasonal CO_2 cycle is delayed gradually from middle latitudes of the southern hemisphere to the Antarctic region, suggesting poleward transport of the lower tropospheric air. Peak-to-peak amplitudes of the mean seasonal cycle at the respective stations were 1.11, 1.27 and 1.31 ppmv for the period 1984–1987. The average amplitude increases gradually from middle latitudes of the southern hemisphere to the Antarctic region where there are no strong CO_2 sources

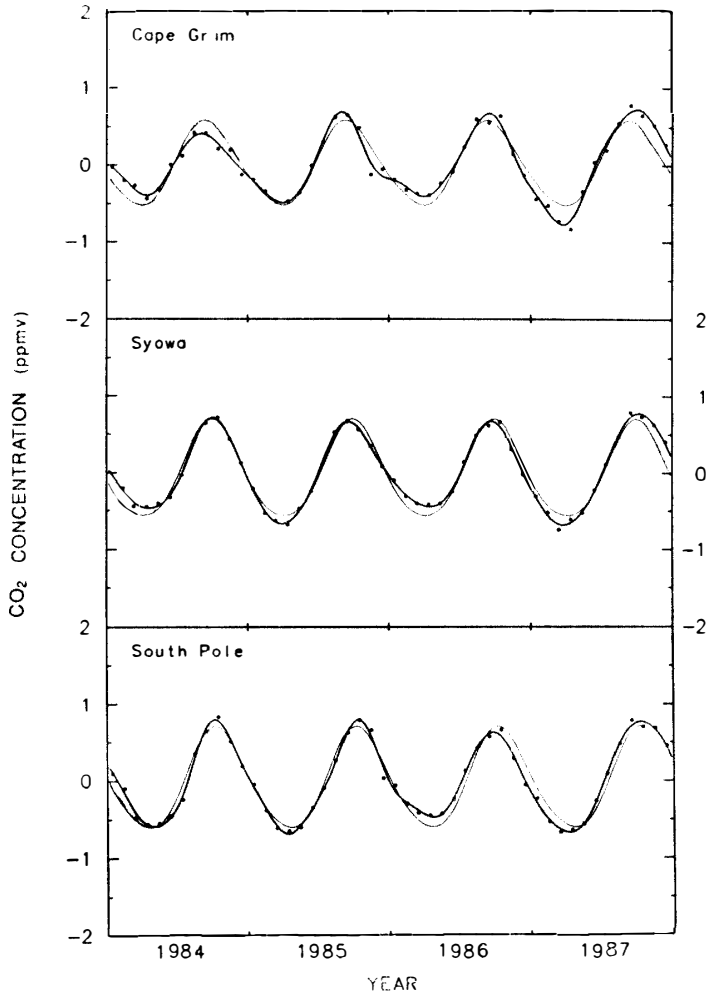

Fig. 6. Seasonal variations of CO_2 concentration at Cape Grim (40°41'S, 144°41'E), Syowa Station (69°00'E, 39°35'E) and South Pole (90°S). Thick lines denote seasonal variations including interannual variation part and thin lines denote mean seasonal variations.

and sinks. This fact cannot be explained only by a simple transport process. There is a seasonal transport from the northern hemisphere to the southern hemisphere through the upper troposphere (PEARMAN and BEARDSMORE, 1984; NAKAZAWA *et al.*, 1991); this upper tropospheric transport and the downward motion of air over the Antarctic continent may also play an important role in variations of atmospheric CO_2 concentration in the Antarctic region.

Figure 6 also shows the seasonal cycle including interannual variation components. Amplitudes of the seasonal cycle varied from year to year. But the changes of amplitudes of each station correlate well: comparatively small amplitudes appeared in 1984 and 1986, and comparatively large amplitudes in 1985 and 1987. These variations may be related to the interannual difference of CO_2 exchange between the atmosphere and the oceans and/or that of atmospheric transport of CO_2.

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