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The concentration of atmospheric carbon dioxide at the Japanese Antarctic Station, Syowa

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ABSTRACT

Precise and continuous measurements of the atmospheric CO_2 concentration have been made at Syowa Station, Antarctica since February 1984. The 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 especially large in 1987, which may be related to the 1986/1987 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 early in October, respectively, and its peak-to-peak amplitude was about 1.1 ppmv. The measured seasonal cycle was variable from year to year, but there was no indication of a long-term increase of the amplitude. It was found that irregular CO_2 variations with amplitudes of 0.2 ppmv at most and periods of a few weeks show high correlation with airmass exchange by synoptic scale weather disturbances. The results from Syowa are compared with those from the South Pole and Cape Grim, Tasmania.

1. Introduction

Since the Antarctica is largely free from local and regional effects due to vegetated lands and industrial areas, it is expected that detailed information on temporal variations of the atmospheric CO_2 concentration such as the secular CO_2 trend and its small year-to-year fluctuations can be detected precisely. Systematic measurements of the atmospheric CO_2 were therefore taken for the first time by Keeling at the South Pole in 1957 (Keeling et al., 1976). At present, 5 ground-fixed stations are operating in the antarctic region, either continuous sampling with an in situ analyzer or by discrete flask sampling with subsequent laboratory analysis (Komhyr et al., 1985; Beardsmore and Pearman, 1987a; Tanaka et al., 1987a; Conway et al., 1988).

In situ continuous CO_2 measurements initiated at the Japanese antarctic station, Syowa (69°00′S, 39°35′E) in February 1984 have been continued up to the present. We have suggested, from inspection of the data taken for the first one year of the program (Tanaka et al., 1987a), that Syowa Station is a site suitable for monitoring background values of the atmospheric CO_2 concentration, because no regular diurnal CO_2 variation is observable and day-to-day CO_2 variations are also extremely small.

In this paper, we report the results of measurements for the period from February 1984 to January 1989, especially in terms of the secular trend, the seasonal cycle and irregular variations of the CO_2 concentration. The results are also compared with those at the South Pole and Cape Grim, Tasmania.

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2. Sampling site and experimental procedures

Detailed descriptions of our sampling site and 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 on East Ongul Island (69°00′S, 39°35′E) in Lützow-Holm Bay, being away from the Antarctic Continent by about 4 km. The surface of the island is composed of naked rock and is covered with snow except in summer. Annual mean values of air temperature and wind speed are −11°C and 6 m s^{-1}, respectively. Prevailing winds are north-northeasterly, north-easterly or easterly for more than 70% of the windy condition. The calm condition occurs for about 14% of the year.

The measurement system was installed in an air-conditioned laboratory at the station. The air intake was mounted at the top of a 8 m-high mast at the coast line of the island, being away from the laboratory by about 30 m and facing into the prevailing winds. Air samples were introduced into the system by pumping through an annealed copper tube from the intake. Water vapor was removed from air samples by a glass trap cooled at −60°C by an electric refrigerator, and aerosol particles larger than 1 μm were also removed by glass and membrane filters. The tubing of the measurement system, except for the intake tube of air sample and the water vapor trap, was made of stainless steel. The concentrations of atmospheric CO_2 were determined using a non-dispersive infrared (NDIR) CO_2 analyzer with a precision of 0.01 ppmv. Reference gas with CO_2 concentration lower by 15–20 ppmv than ambient atmospheric CO_2 levels was flowed continuously through the reference cell of the analyzer at a rate of about 15 ml min^{-1}.

Three kinds of working standard gases, high, low and check gases were prepared for this measurement. High and low gases were used for calibrating the analyzer response every 30 min, and check gas for examining a non-linear relationship between the analyzer response and the CO_2 concentration once every 10 days. The CO_2 concentration of the check gas was chosen nearly equal to those of air samples to be measured. In order to minimize the correction for the non-linear relationship, the CO_2 concentrations of high and low working gases were chosen so that they differed by about 10–12 ppmv and the air sample concentrations fell between them. Fig. 1 shows the errors due to non-linearities of the analyzer response derived from the relation,

$$C = (C_h - C_l) \times (X_c - X_l)/(X_h - X_l) + C_l - C_c, \tag{1}$$

where C is the CO_2 concentration, X the analyzer response, and suffixes h, l, and c represent high, low and check gases, respectively. The errors due to non-linearity ranged between −0.07 and

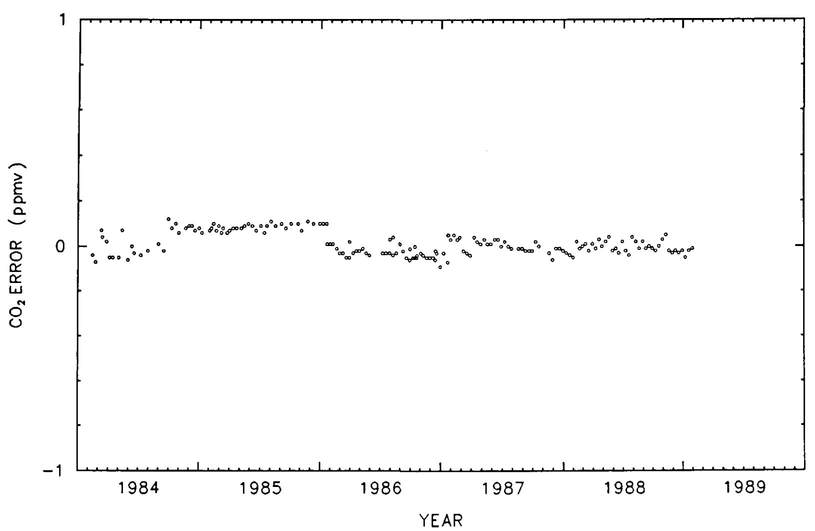

Fig. 1. Errors due to non-linear response (see text) of the NDIR analyzers used at Syowa Station.

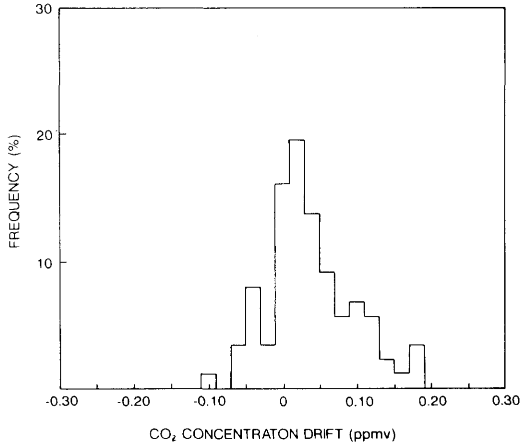

Fig. 2. Drifts in CO_2 concentration between calibrations of 87 working standard gases used at Syowa Station for the period February 1984–January 1989.

$+0.11$ ppmv for the last 5 years, but they were fairly constant for shorter period, e.g., between $+0.06$ and $+0.11$ in 1985. Discontinuous changes of the values are occasionally seen in this figure. Exchange of the analyzer is responsible for this phenomenon. In this measurement, three analyzers were used in turn, and each analyzer indicated its own non-linear response. All the CO_2 concentration data in this paper were corrected by the procedure described previously (Tanaka et al., 1987a) for these errors.

The working standard gases in 47 1-volume cylinders were shipped to the station every year to exchange for old ones. The usage of all gases was terminated at a pressure of about 3×10^6 Pa. 87 working standard gases were used for the last 5 years, and their CO_2 concentrations were determined before and after their use with a precision of 0.01 ppmv by comparing with our secondary standard gas system. Fig. 2 shows concentration differences of the working standard gases between the two calibrations. Mean value of the drifts in concentration was 0.037 ± 0.057 ppmv; slightly positive drift occurred with decrease of the pressure in the cylinders. The drifts in CO_2 concentration were within ± 0.1 ppmv for 87% of all gases, and the maximum drift was $+0.19$ ppmv. Therefore, the results of both calibrations were simply averaged to calculate the CO_2 concentration of air samples.

3. Results and discussion

The sampling rate for the equipment used at Syowa Station was 8 data points per hour (Tanaka et al., 1987a), and a total of 344,566 data points were recorded in the period from February 1984 to January 1989. Daily mean values of the CO_2 concentration calculated from all available data are plotted in Fig. 3. The seasonal cycle and secular trend of the CO_2 concentration are clearly seen in

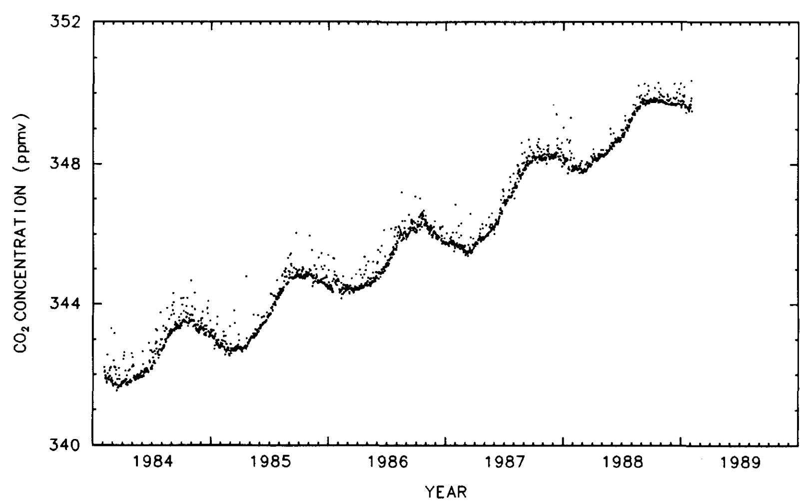

Fig. 3. Daily mean CO_2 concentrations at Syowa Station, calculated from all available data.

this figure, but values are somewhat scattered due to outliers originating presumably from station activities. To delete such locally contaminated data, a simple statistical data selection scheme was applied to the data set, assuming that a homogeneous airmass free from local contamination has small within-hour and hour-to-hour CO_2 concentration changes. We first calculated the hourly mean values from the individual concentration readings for each day and daily mean value from hourly means with the standard deviation of less than 0.1 ppmv. Then, we rejected the data deviating by more than ± 0.3 ppmv from daily mean value thus obtained. This selection scheme was applied to the data of all days when measurements were made, and 15,237 data points, corresponding to 4.4% of all available data, were rejected as outliers. The rates of rejected data in different months are shown in Fig. 4, together with the number of days with weak winds. As seen in this figure, the rejection rate increases in winter and summer and decreases in fall and spring, and it varies almost in phase with the number of calm days. This fact suggests that the CO_2 concentrations at Syowa Station are much affected by local contamination when the low wind speed prevails. It is however obvious in Fig. 4 that the phases in variations of both parameters are not always in close agreement with each other. Therefore, the wind direction and atmospheric stability may be also responsible for the occurrence of the outliers.

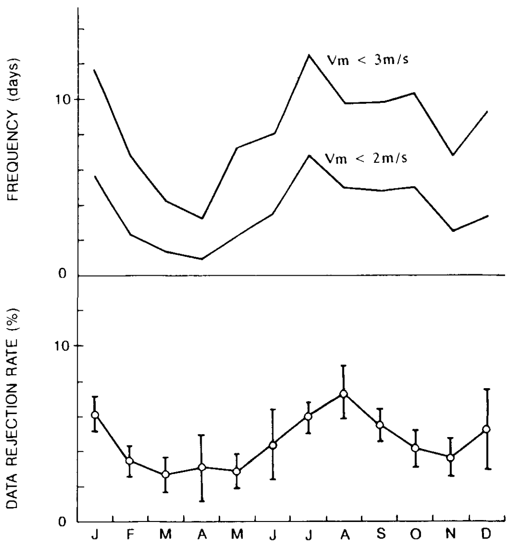

Fig. 4. Rates of CO_2 data rejected by the data selection (lower panel) and days with daily mean wind velocities less than 3 m s^{-1} and 2 m s^{-1} (upper panel) at Syowa Station. Data taken for the period February 1984–January 1989 were grouped into respective months and simply averaged. The error bars in the lower panel represent the standard deviation for average values of the data rejection rate.

Daily mean values of the CO_2 concentration calculated from the selected data are plotted in Fig. 5. The standard deviations of daily mean CO_2 concentrations ranged between 0.01 and 0.15 ppmv, an average value being 0.04 ppmv. Values in February and March 1989 are plotted for reference only, because they were obtained by averaging only two CO_2 concentrations at 0000 and 1200 LT and the re-calibration of the standard gases is not yet made. This figure shows clearly the secular trend, the seasonal cycle and irregular variations of the CO_2 concentration. To separate these components, we used a digital-filtering technique including Fourier harmonics, Reinsch-type spline and Butterworth filter. Outline of the technique has been described elsewhere (Nakazawa et al., 1991). In this case, the average seasonal CO_2 cycle was approximated by fundamental annual cycle and its first harmonics. The smoothed curve of the data and secular CO_2 trend, obtained by this filtering process, are also shown in Fig. 5. Deviations of respective data from the smoothed curve are extremely small, as shown in Fig. 6. About 88% of all concentration deviations fall within ± 0.1 ppmv. Irregular CO_2 variations may be responsible for spread tails of the histogram.

Fig. 7 shows the secular trend and the rate of annual increase of the CO_2 concentration. The average rate of annual CO_2 increase for the period from February 1984 to January 1989 was about 1.6 ppmv yr^{-1}. 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 especially large in 1987. It is well-known that these interannual variations in the growth rate of the CO_2 concentration correlate negatively with the Southern Oscillation Index (SOI), and consequently with El Niño occurrences (Bacastow, 1976; Bacastow et al., 1980; Bacastow and Keeling, 1981; Thompson et al., 1986; Tanaka et al., 1987b; Conway et al., 1988). Minimum value of 5-month running mean

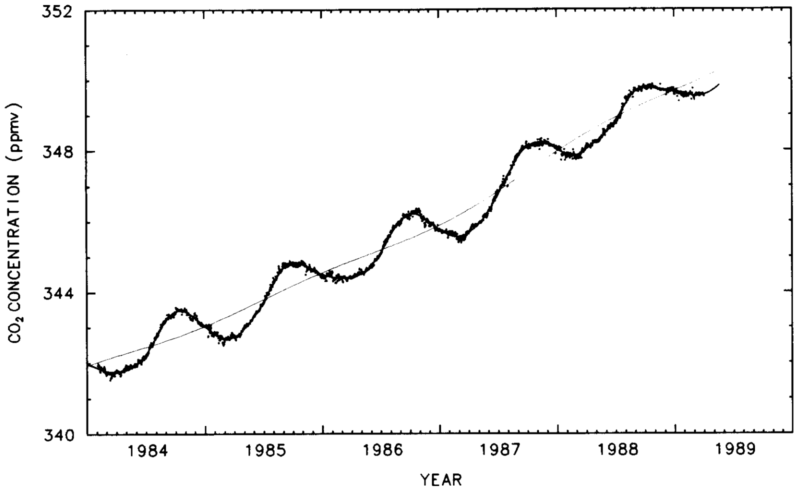

Fig. 5. Daily mean CO_2 concentrations at Syowa Station, calculated from selected data. Thick and thin lines denote the smoothed curve of the data and the secular CO_2 trend, respectively.

of the SOI in recent years appeared in May 1987, as seen in Fig. 7 (Japan Meteorological Agency, 1983–1989), and the rate of annual CO_2 increase at Syowa Station reached a maximum early in September 1987. The time lag was therefore estimated to be 3–4 months. Bacastow and 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. As compared with their result, the present

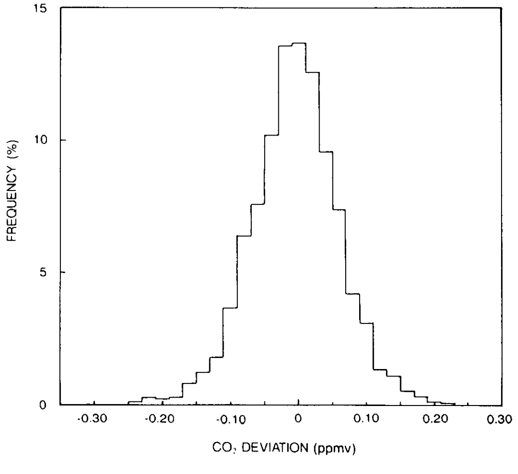

Fig. 6. Deviations of daily mean CO_2 concentrations from their smoothed curve at Syowa Station.

value is smaller by 3–2 months. The enhanced rate of increase of the CO_2 concentration was found in 1985 too when no ENSO event occurred. Such a phenomenon was also observed by our aircraft measurements over Japan (unpublished data). Therefore, changes in the growth rate of the CO_2 concentration are associated not only with ENSO event 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. 8. The computed average seasonal CO_2 cycle showed minimum and maximum concentrations in mid-April and early in October, and its peak-to-peak amplitude was 1.14 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 was not observed, but irregular CO_2 variations with amplitudes of 0.2 ppmv at most and periods of a few weeks were clearly seen at Syowa Station. Such irregular variations are compared in Fig. 9 with atmospheric temperatures at the station. Negative correlation is clearly seen in these two fluctuations. Variations of the temperature are caused by synoptic scale weather disturbances. Therefore, irregular CO_2

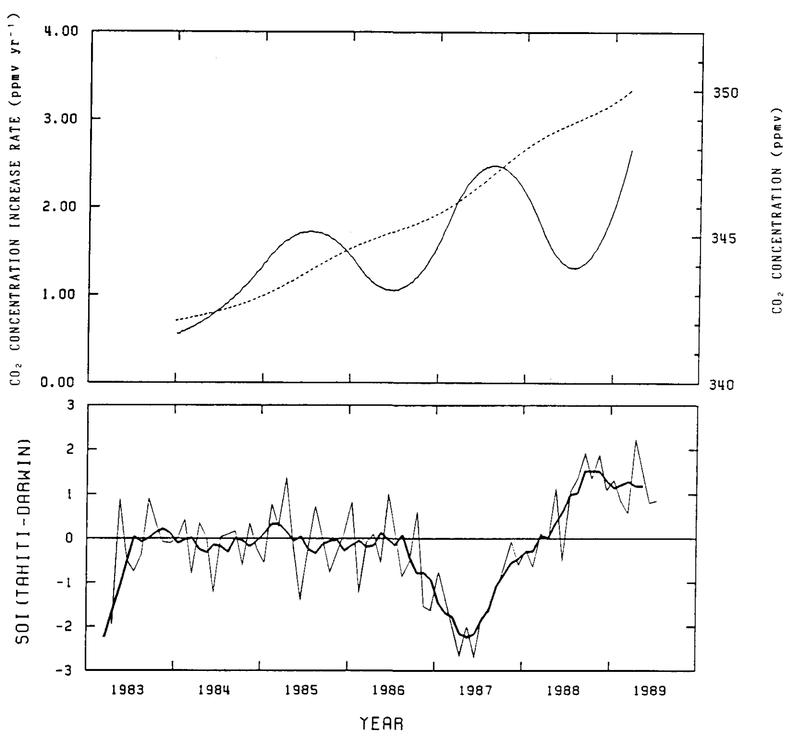

Fig. 7. Secular trend (dashed curve) and rate of annual increase (solid curve) of CO_2 concentration observed at Syowa Station and the Southern Oscillation Index. Thin and thick lines for the SOI denote monthly and 5-month running mean values, respectively.

variations are primarily attributed to exchange of different airmasses in association with such disturbances. From the fact that the CO_2 concentration is higher in the antarctic region than in mid-latitudes of the southern hemisphere throughout the year, which will be described later, it is considered that airmasses from lower latitudes decrease the CO_2 concentration at the station.

Monthly mean values of the CO_2 concentration calculated from daily means are listed in Table 1, together with standard deviations. Monthly mean CO_2 concentrations derived from the smoothed curve of daily means are also given in the table. Both values are in close agreement with each other.

To examine temporal and spatial variations of the CO_2 concentration in mid- and high latitudes of the southern hemisphere, we analyzed monthly mean CO_2 concentrations of continuous measurements at Cape Grim (Beardsmore and Pearman, 1986, 1987b, 1988, 1989), Syowa Station and the South Pole (Nickerson, 1985; Schnell, 1986, 1987; Bodhaine, 1989) from 1984 to 1987, using the above-mentioned digital-filtering technique. Annual mean values of the CO_2 concentration thus obtained are listed in Table 2. The WMO X81 scale (World Meteorological Organization 1981 mole fraction scale) and the WMO X85 scale were used to express the concentration in 1984 and after 1985, respectively, for Cape Grim and the South Pole. The concentrations at Syowa were expressed in our own scale which is entirely independent from WMO scale. Annual mean CO_2 concentrations at the South Pole and Syowa, nevertheless, agreed well with each other, values of Syowa being higher by only 0.1 ppmv, on average, than those of the South Pole. Agreement between values at both stations is excellent especially from 1985 to 1987. In 1984, annual mean CO_2 concentration was higher by 0.3 ppmv at Syowa than at the South Pole. On the other hand, annual CO_2 concentra-

Table 1. *Monthly mean values of CO_2 concentration at Syowa Station, calculated from measured daily means (Data) and their smoothed curve (Fit): N and σ represent the number of the data and standard deviations, respectively*

	1984				1985			
	Data	σ	N	Fit	Data	σ	N	Fit
Jan.				341.93	342.91	0.12	5315	342.91
Feb.	341.85	0.07	4875	341.82	342.71	0.11	4944	342.74
Mar.	341.69	0.06	5568	341.75	342.72	0.06	5734	342.70
Apr.	341.78	0.04	5388	341.77	342.80	0.09	5628	342.83
May	341.91	0.04	5746	341.87	343.13	0.08	5780	343.10
Jun.	342.08	0.06	5371	342.09	343.49	0.11	5623	343.49
Jul.	342.46	0.17	5459	342.47	343.98	0.18	5579	343.99
Aug.	343.00	0.16	5597	342.96	344.51	0.15	5546	344.48
Sep.	343.33	0.05	5329	343.35	344.78	0.05	5456	344.78
Oct.	343.50	0.04	5547	343.48	344.79	0.04	5770	344.82
Nov.	343.33	0.09	5415	343.37	344.70	0.09	5414	344.70
Dec.	343.13	0.09	5468	343.15	344.55	0.08	5614	344.56
annual	342.55			342.50	343.76			343.76
	1986				1987			
	Data	σ	N	Fit	Data	σ	N	Fit
Jan.	344.48	0.07	5211	344.46	345.69	0.04	5394	345.68
Feb.	344.38	0.06	5061	344.41	345.62	0.07	5189	345.58
Mar.	344.39	0.04	5786	344.41	345.53	0.09	5587	345.60
Apr.	344.49	0.06	5505	344.47	345.82	0.07	5647	345.77
May	344.61	0.06	5653	344.61	346.06	0.09	5776	346.07
Jun.	344.88	0.11	5338	344.91	346.52	0.19	5547	346.49
Jul.	345.38	0.16	5539	345.34	347.02	0.13	5415	347.02
Aug.	345.84	0.09	5186	345.82	347.54	0.21	5367	347.56
Sep.	346.09	0.08	5435	346.14	348.02	0.11	5397	347.96
Oct.	346.26	0.06	5636	346.20	348.13	0.04	5654	348.17
Nov.	346.03	0.12	5535	346.07	348.19	0.07	5352	348.21
Dec.	345.84	0.08	5809	345.87	348.12	0.08	5418	348.10
annual	345.22			345.23	346.86			346.86
	1988				1989			
	Data	σ	N	Fit	Data	σ	N	Fit
Jan.	347.92	0.10	5243	347.93	349.58	0.07	5417	349.61
Feb.	347.83	0.04	4995	347.84				
Mar.	347.91	0.10	5678	347.91				
Apr.	348.16	0.05	5523	348.11				
May	348.37	0.11	5795	348.34				
Jun.	348.65	0.08	5578	348.63				
Jul.	349.05	0.18	5740	349.04				
Aug.	349.55	0.12	5379	349.48				
Sep.	349.74	0.05	5480	349.71				
Oct.	349.78	0.04	5665	349.78				
Nov.	349.70	0.02	5590	349.72				
Dec.	349.67	0.04	5643	349.66				
annual	348.86			348.86				

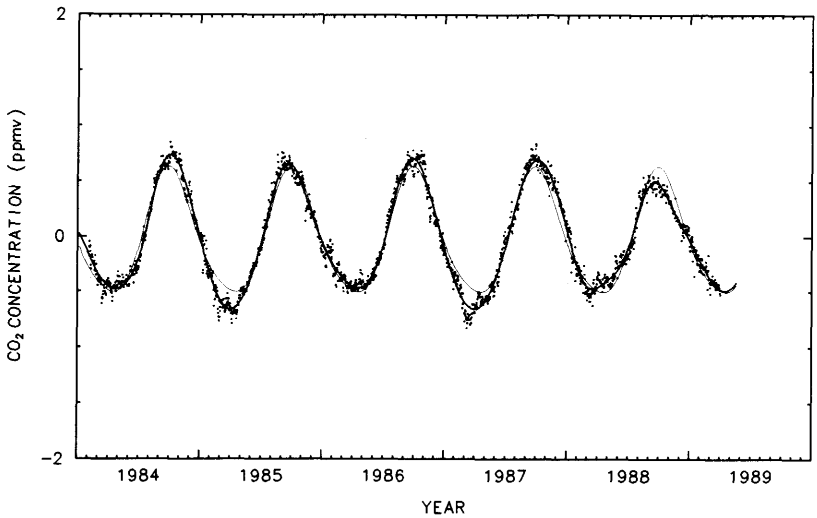

Fig. 8. Seasonal cycle of CO_2 concentration observed at Syowa Station. Thin line represents the average seasonal cycle and thick line, the measured cycle, after the secular trend has been subtracted.

tions at Cape Grim were lower by about 0.6–0.7 ppmv, on average, than those in the antarctic region. Qualitatively similar CO_2 distribution has been observed by our ship-board 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 more enhanced in 1986 and 1987 than in 1984 and 1985.

The seasonal cycles of the CO_2 concentration at three stations are shown in Fig. 10. Peak-to-peak amplitudes of the average seasonal CO_2 cycle were 1.11, 1.27 and 1.31 ppmv for Cape Grim, Syowa and the South Pole, respectively. While, minimum concentrations of the average seasonal CO_2 cycle at respective stations appeared in 93, 97 and 112 days relative to 1 January, and maximum concentrations in 253, 273 and 280 days. The seasonal

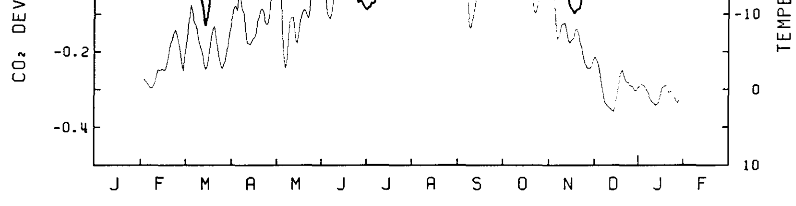

Fig. 9. Deviations from the average CO_2 concentration (thick line) and atmospheric temperature (thin line) at Syowa Station. Respective curves are 5-day running means of daily mean values of the corresponding quantities. The secular trend and the seasonal cycle were subtracted from daily mean CO_2 concentrations before smoothing.

Table 2. *Annual mean values of CO_2 concentration at Syowa Station, the South Pole and Cape Grim, calculated from measured monthly means (Data) and their smoothed curve (Fit); note that the absolute calibration scales for these data sets are not the same (see text)*

	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

CO_2 cycle is delayed gradually going southward, suggesting poleward transport of the air, but the amplitude increases from southern mid-latitudes to the antarctic region where there are no strong CO_2 sources and sinks. The measured seasonal CO_2 cycle indicated that the amplitude and phase are variable from year to year. However, the amplitudes at three stations showed a similar behavior, i.e., they were reduced in 1984 and 1986 and enhanced in 1985 and 1987.

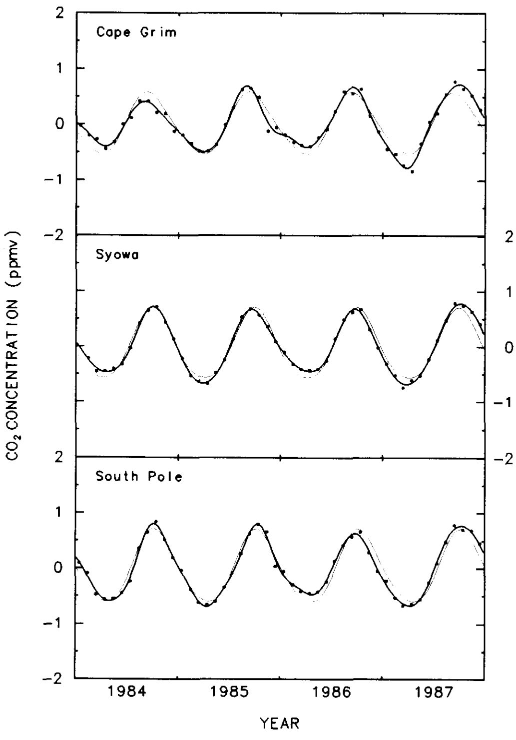

Fig. 10. Seasonal cycles of CO_2 concentration at Cape Grim, Syowa Station and the South Pole. Thick lines represent the measured seasonal cycles and thin lines, the average cycle, after their secular trends have been removed.

It is not easy to interpret variations of the atmospheric CO_2 concentration in the antarctic region, due to their smallness. Not only biospheric activity and CO_2 exchange between the atmosphere and the oceans in the southern hemishere but also dynamical process of atmospheric transport should play an important role for such variations. The southward delay of the seasonal CO_2 cycle may be partly ascribed to poleward transport of the lower tropospheric air from southern mid-latitudes, but the latitudional distribution of the amplitude and annual mean CO_2 concentration can not be explained by only such a transport process. In this connection, it is noted that there is transport from the northern hemisphere into the southern hemisphere through the upper troposphere, which shows a seasonality (Pearman and Beardsmore, 1984; Nakazawa et al., 1991). This effect has been observed in the upper troposphere at least over the Australian Continent. Downward transport of the stratospheric air in the antarctic region (Yamazaki et al., 1989) may be also responsible for the CO_2 concentrations observed there. Aircraft measurements over the antarctic region are therefore required for better understanding of variations of the CO_2 concentration in southern high latitudes.

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REFERENCES

Bacastow, R. B. 1976. Modulation of atmospheric carbon dioxide by the Southern Oscillation. *Nature 261*, 116–118.

Bacastow, R. B., Adams, J. A., Keeling, C. D., Moss, D. J. and Whorf, T. D. 1980. Atmospheric carbon dioxide, the Southern Oscillation, and weak 1975 El Niño. *Science 210*, 66–68.

Bacastow, R. B. and Keeling, C. D. 1981. Atmospheric CO_2 and the Southern Oscillations: effects associated with recent El Niño events. In: *Proceedings WMO/ICSU/UNEP Scientific Conference on Analysis and Interpretation of Atmospheric CO_2 data.* Bern. WCP 14, WMO, Geneva, 116–118.

Beardsmore, D. J. and Pearman, G. I. 1986. *Baseline Atmospheric Program (Australia) 83–84.* Department of Science/Bureau of Meteorology in cooperation with CSIRO/Division of Atmospheric Research. Cape Grim BAPS, Tasmansia, Australia, pp. 37–38.

Beardsmore, D. J. and Pearman, G. I. 1987a. Atmospheric carbon dioxide measurements in the Australian region: data from surface observatories. *Tellus 39B*, 42–66.

Beardsmore, D. J. and Pearman, G. I. 1987b. *Baseline Atmospheric Program (Australia) 1985.* Department of Science/Bureau of Meteorology in cooperation with CSIRO/Division of Atmospheric Research. Cape Grim BAPS, Tasmania, Australia, pp. 41–42.

Beardsmore, D. J. and Pearman, G. I. 1988. *Baseline Atmospheric Program (Australia) 1986.* Department of Administrative Services/Bureau of Meteorology in cooperation with CSIRO/Division of Atmospheric Research. Cape Grim BAPS, Tasmania, Australia, pp. 53–54.

Beardsmore, D. J. and Pearman, G. I. 1989. *Baseline Atmospheric Program (Australia) 1987.* Department of Administrative Services/Bureau of Meteorology in cooperation with CSIRO/Division of Atmospheric Research. Cape Grim BAPS, Tasmania, Australia, pp. 29.

Bodhaine, B. A. (Ed.). 1988. *Geophysical Monitoring for Climatic Change/Summary Report for 1987, no. 16*, ERL, NOAA, Boulder, Colorado, U. S. A., pp. 30–34.

Conway, T. J., Tans, P., Waterman, L. S., Thoning, K. W., Masarie, K. A. and Gammon, R. H. 1988. Atmospheric carbon dioxide measurements in the remote global troposphere, 1981–1984. *Tellus 40B*, 81–115.

Japan Meteorological Agency. 1983–89. *Monthly Report on Climate System 1983–89.* Long-range Forecast Division, Forecast Department, J. M. A., Tokyo, Japan.

Keeling, C. D., Adams, J. A., Jr., Ekdahl, C. A., Jr. and Guenther, P. R. 1976. Atmospheric carbon dioxide variations at the South Pole. *Tellus 28*, 552–564.

Komhyr, W. D., Gammon, R. H., Harris, T. B., Waterman, L. S., Conway, T. J., Tayler, W. R. and Thoning, K. W. 1985. Global atmospheric CO_2 distribution and variations from 1968–1982 NOAA/GMCC CO_2 flask sample data. *J. Geophys. Res. 90*, 5567–5596.

Nakazawa, T., Miyashita, K., Aoki, S. and Tanaka, M. 1991. Temporal and spatial variations of upper tropospheric and lower stratospheric carbon dioxide. *Tellus 43B*, 106–117.

Nickerson, E. C. (Ed.). 1985. Geophysical Monitoring for Climatic Change/Summary Report for 1984, no. 13, ERL, NOAA, Boulder, Colorado, U. S. A., pp. 30–50.

Pearman, G. I. and Beardsmore, D. J. 1984. Atmospheric carbon dioxide measurements in the Australian region: ten years of aircraft data. *Tellus 36B*, 1–24.

Schnell, R. C. (Ed.). 1986. *Geophysical Monitoring for Climatic Change/Summary Report for 1985, no. 14*, ERL, NOAA, Boulder, Colorado, U. S. A., pp. 37–46.

Schnell, R. C. (Ed.). 1987. *Geophysical Monitoring for Climatic Change/Summary Report for 1986, no. 15*, ERL, NOAA, Boulder, Colorado, U. S. A., pp. 41–49.

Tanaka, M., Nakazawa, T., Shiobara, M., Ohshima, H., Aoki, S., Kawaguchi, S., Yamanouchi, T., Makino, Y. and Murayama, H. 1987a. Variations of atmospheric carbon dioxide concentration at Syowa Station (69°00′S, 39°35′E), Antarctica. *Tellus 39B*, 72–79.

Tanaka, M., Nakazawa, T. and Aoki, S. 1987b. Time and space variations of tropospheric carbon dioxide over Japan. *Tellus 39B*, 3–12.

Tanaka, M., Nakazawa, T. and Aoki, S. 1987c. Seasonal and meridional variations of atmospheric carbon dioxide in the lower troposphere of the northern and southern hemispheres. *Tellus 39B*, 29–41.

Thompson, M. L., Enting, I. G., Pearman, G. I. and Hyson, P. 1986. Interannual variation of atmospheric CO_2 concentration. *J. Atmos. Chem. 4*, 125–155.

Yamazaki, K., Okada, K. and Iwasaka, Y. 1989. Where do aerosol particles in the antarctic upper troposphere come from? (a case study in January 1983). *J. Meteorol. Soc. Japan. 67*. 889–906.