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# Concentration variations of atmospheric $CO_2$ observed at Syowa Station, Antarctica from 1984 to 2000

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ABSTRACT

Systematic and continuous measurements of the atmospheric $CO_2$ concentration have been carried out at Syowa Station, Antarctica since February 1984. The measurement system was renewed in 1995, but the continuity of the data from the two systems was confirmed by operating them simultaneously. The $CO_2$ data taken for 17 years from 1984 to 2000 showed clear evidence for a seasonal cycle, a secular trend and interannual variations. The seasonal cycle was variable from year to year, with especially larger amplitudes in 1992 and 1998 and a large phase delay in 1993. A rapid increase in the $CO_2$ concentration was observed in 1987, 1994 and 1998 in association with ENSO events. The average rate of the secular $CO_2$ increase for the last 17 years was calculated to be 1.49 ppmv $yr^{-1}$. Short-term $CO_2$ variations with amplitudes of around 1.0 ppmv were found in the austral summer season of several years after 1990, probably due to an intrusion of $CO_2$-depleted air mass into the Antarctic region.

## 1. Introduction

Systematic and continuous measurements of the atmospheric $CO_2$ concentration were initiated by C. D. Keeling, Scripps Institution of Oceanography at Mauna Loa, Hawaii in 1958 and the South Pole in 1957 (Keeling et al., 1976a, b). Since then, the network for monitoring $CO_2$ concentration has been expanded globally by using a discrete flask sampling method with subsequent laboratory analysis and an in-situ continuous measurement method (WMO, 2001), to depict pictures of distributions and variations of the atmospheric $CO_2$ concentration. Based on these observed data, many model studies have been conducted to estimate geographical distributions of the $CO_2$ sources and sinks quantitatively (e.g. Tans et al., 1989; Rayner et al., 1999).

Since Antarctica is far from industrial and vegetated regions, it is expected that signals of background concentration variations of atmospheric $CO_2$ can be detected easily and monitored precisely over a long time. At present, the atmospheric $CO_2$ concentration is observed at five Antarctic stations, Amundsen–Scott (South Pole), Halley Bay, Palmer, Jubany and Syowa, as shown in Fig. 1, by operating a continuous measurement system and/or by sampling air into flasks (Nakazawa et al., 1991; Conway et al., 1994; Ciattaglia et al., 1999).

We have continued high-precision continuous measurements of the atmospheric $CO_2$ concentration at Syowa Station, Antarctica since 1984 in cooperation with the Japanese Antarctic Research Expedition teams. As we have shown in our previous papers (Tanaka et al., 1987; Nakazawa et al., 1991), Syowa Station is quite suitable for monitoring temporal variations of the background $CO_2$ concentration, since no diurnal variation is found and outliers are extremely limited. In this paper we will report the results of our measurements of the $CO_2$ concentration at Syowa for 17 years from 1984 to 2000, especially in terms of the long-term trend, the seasonal cycle and short-term variations.

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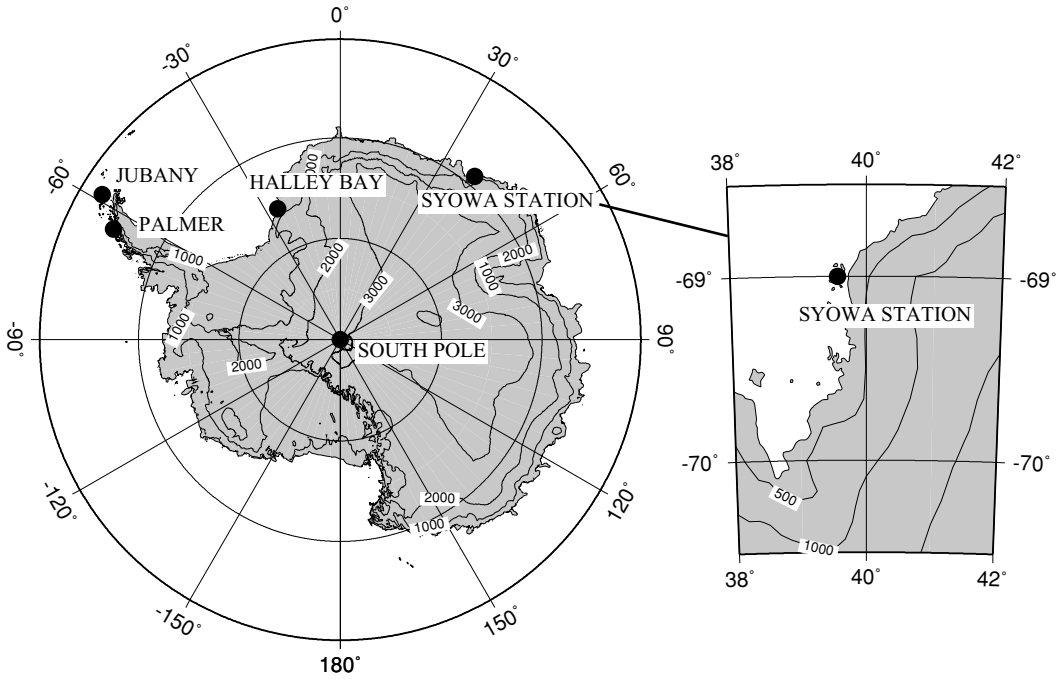


*Fig. 1.* $CO_2$ monitoring stations in Antarctica and the location of Syowa Station. Also plotted are the topographic contours of the Antarctic continent.

## 2. Observation site and measurement procedures

Since detailed descriptions of our measurement site and procedures have been given in our previous papers (Tanaka et al., 1987; Nakazawa et al., 1991), only brief and supplemental explanations will be presented here. Syowa Station (69°00′S, 39°35′E) is located on East Ongle Island, 4 km away from the coast of the Antarctic Continent (Fig. 1), and has been operated since 1957 as a wintering base for the Japanese Antarctic Research Expedition team. The island is usually surrounded by multi-year ice, and an average distance between the edge of the packed ice zone and the station is about 100 km in summer and 1000 km in winter. The surface of the island is covered with snow, except for the summer season when naked rocks are exposed by clearing snow artificially.

To observe the atmospheric $CO_2$ concentration continuously at Syowa Station, we have used two measurement systems so far. The first system was installed at the station in 1984 (Tanaka et al., 1987; Nakazawa et al., 1991), which consisted of a non-dispersive infrared analyzer (NDIR; Horiba VIA-500R), a gas handling system, a data acquisition system and three kinds of standard gas, two working and one check. The air intake was mounted at the top of an 8 m-high mast which is 30 m distant from the laboratory building, facing prevailing winds. The air samples introduced into the laboratory were dried by using a glass trap cooled at –60 °C. Aerosol particles larger than 1 $\mu$m were also removed from the air samples by a series of inline filters. The $CO_2$ concentration of the sample was measured eight times an hour with a precision of 0.01 ppmv against the working standard gases. The two working standard gases with high and low $CO_2$ concentrations were analyzed once every 30 min to calibrate the analyzer response. The $CO_2$ concentration of the check standard gas was also determined once every 10 days against the working standards to examine a non-linear response of the analyzer. The concentration of the check gas was chosen to be close to the atmospheric $CO_2$ concentrations to be measured. These standard gases were exchanged every year, and calibrated against our secondary standard system with a precision of 0.01 ppmv before shipment to Syowa Station and after being returned to Japan. It was confirmed that concentration drifts of the

standard gases during their use were usually less than 0.05 ppmv.

The second measurement system has been used at the station since 1995. The fundamental structure and performance of this new system were similar to those of the old one, but a new type of NDIR (Horiba VIA-510R) was employed. Since the length of an optical cell of the VIA-510R analyzer is shorter than that of VIA-500R, the correction for the instrumental non-linear response should be made more strictly. Therefore, the operational sequence of this system was changed so that the check gas was analyzed once every 12 h. By this change, the measurement rate of the sample air was reduced to six times per hour.

To examine the continuity of our $CO_2$ measurements at Syowa Station, the two systems were operated simultaneously five times in February, May, September and November 1995 and January 1996, which amounted to 61 days in total. Daily mean values of the $CO_2$ concentration observed by the two systems are plotted in Fig. 2(a), together with a linear line representing their one-to-one relationship. As seen in this figure, almost all the data points are distributed around the one-to-one line. Figure 2(b) shows absolute differences between the daily mean $CO_2$ concentrations obtained by the two systems for 61 days. It is clearly seen from this figure that the difference never exceed 0.10 ppmv, and those for 66% of the days are smaller than 0.05 ppmv.

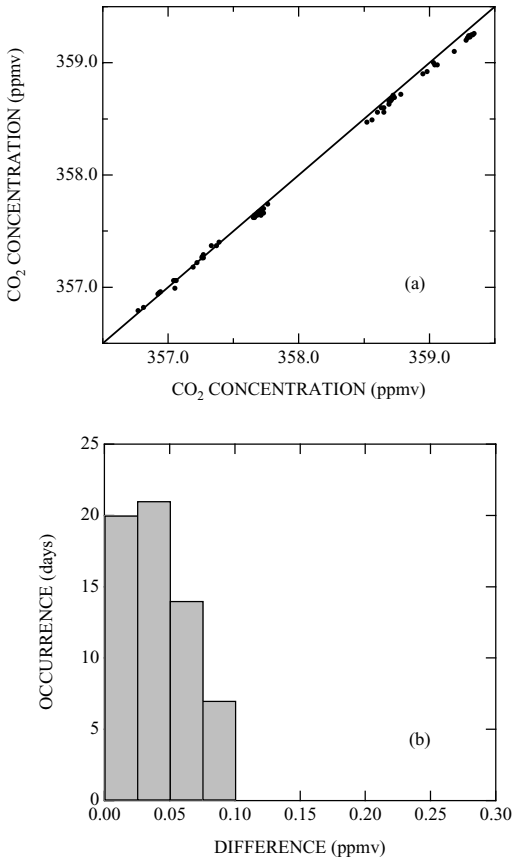


*Fig. 2.* (a) Plots of the daily mean $CO_2$ concentrations by using the two measurement systems at Syowa Station for 61 d between February 1995 and January 1996 (see text). Horizontal and vertical axes are assigned to new and old systems, respectively. The solid line represents a one-to-one relationship between the concentration values from the two systems. (b) Distribution of the absolute difference between the daily mean values of the $CO_2$ concentration observed by using the two measurement systems.

## 3. Results and discussions

A total of 1 062 556 measurements were obtained at Syowa Station from February 1984 to January 2001. To eliminate the data contaminated by station activities, a simple statistical method was applied to the raw data set (Nakazawa et al., 1991), assuming that time-to-time change of the $CO_2$ concentration is relatively small in an air mass free from human contamination. We first calculated hourly mean values of the $CO_2$ concentration using all the observed data, and then provisional daily mean concentrations only from the hourly mean values with standard deviations of less than 0.1 ppmv within a hour. After removing the raw data deviating by more than 0.3 ppmv from the provisional daily mean concentration for each day, the hourly and daily mean values of the $CO_2$ concentration were calculated again. By this selection procedure, the data of 48 609 records, corresponding to 4.6% of all available data, were rejected as outliers. The data rejection rate varied from year to year, ranging from 3.3 to 6.3%. However, no significant trend was found for the period covered by this measurement. The standard deviations of the daily mean $CO_2$ concentrations calculated from the selected data during the period 1984–2000 ranged between 0.01 and 0.23 ppmv within a day, with an average of 0.05 ppmv, as shown in Fig. 3.

In order to extract the seasonal cycle and the long-term trend from the data set obtained above, a digital-filtering technique including Fourier harmonics, linear interpolation, Reinsch-type cubic splines and a

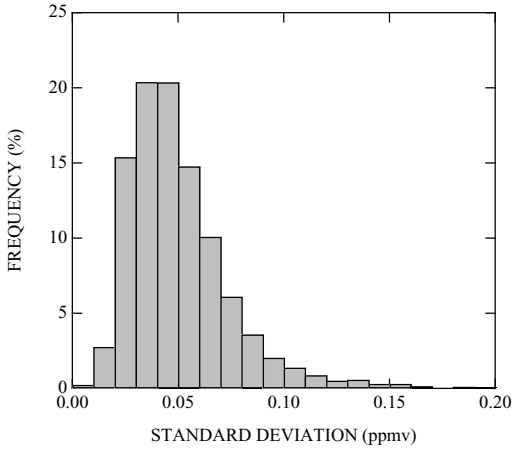


*Fig. 3.* Frequency of the standard deviation of the daily $CO_2$ concentrations observed at Syowa Station from 1984 to 2000.

Butterworth filter was applied to the daily mean $CO_2$ data. Details of this fitting procedure have been presented by Nakazawa et al. (1997a). Figure 4 shows the daily mean values of the $CO_2$ concentration observed at Syowa Station. Also shown is the long-term trend obtained by applying the above analytical method to the daily mean $CO_2$ concentrations. As seen in this figure, the $CO_2$ concentration increased secularly from about 342 ppmv in 1984 to 368 ppmv in 2000, due mainly to fossil fuel combustion. The average increase rate for the last 17 yr was estimated to be 1.49 ppmv $yr^{-1}$. It is also clearly seen in Fig. 4 that the seasonal cycle and interannual variations are superimposed on the long-term trend. The average seasonal cycle reached minimum and maximum concentrations in late March and late September, respectively, and its peak-to-peak amplitude was 1.13 ppmv.

The seasonal cycle was derived every year by subtracting the long-term trend from the best-fit curve to the observed daily mean values. As shown in Fig. 5, the seasonal cycle was variable year by year. A large seasonal amplitude was observed in 1987, 1992 and 1998, while a small amplitude was found in 1988, 1994–97 and 2000 (Fig. 5a). An average change rate of the seasonal amplitude over the period 1984–2000 was calculated to be $-0.015 \pm 0.010$ ppmv $yr^{-1}$. The negative value of the change rate could be attributable to relatively large amplitudes at the beginning of the record and small amplitudes around 1996. The seasonal minimum and maximum concentrations appeared at Julian days 61–135 and 256–293, respectively (Fig. 5b). The appearance time of the minimum value was much more variable than that of the maximum value. It is also seen that the minimum concentration was gradually advanced to appear for the period 1984–1991. It is interesting to note that the minimum value for 1994 was observed about one and a half months later than its average appearance time.

These characteristics of the seasonal cycle are thought to be caused by changes not only in its source and sink strength in southern lower latitudes but also in atmospheric transport from other latitudes to the

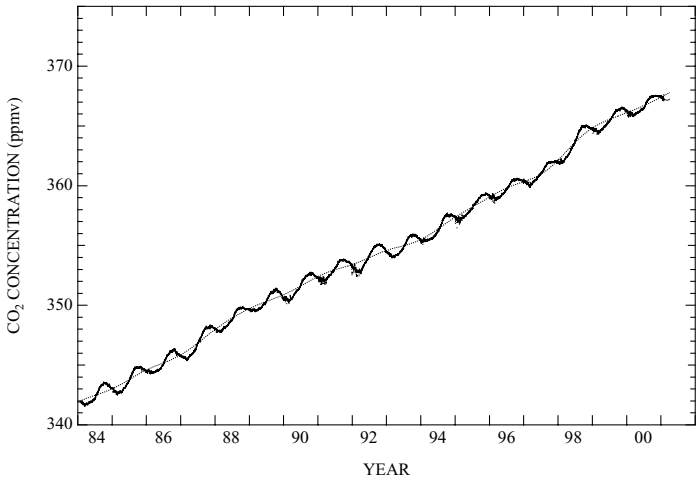


*Fig. 4.* Daily mean $CO_2$ concentrations at Syowa Station. The dotted line denotes the long-term trend fitted to the data.

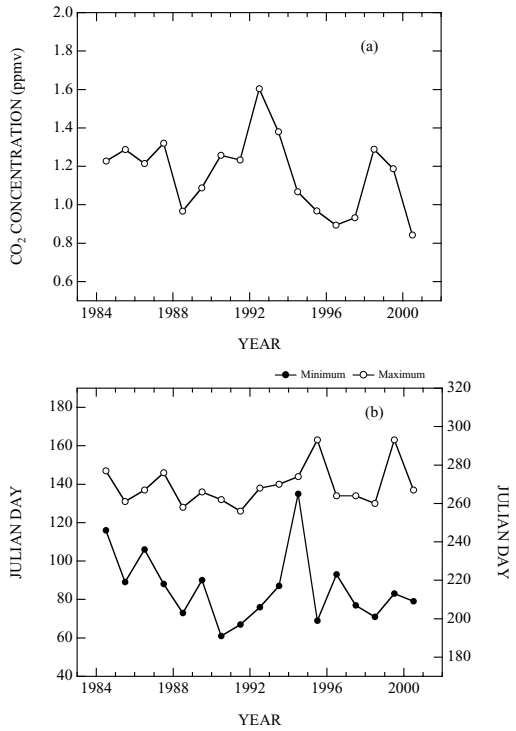


*Fig. 5.* (a) Peak-to-peak amplitudes of the $CO_2$ seasonal cycles observed at Syowa Station. and (b) appearance dates of its minimum (closed circles; left axis) and maximum (open circles; right axis) concentrations.

Antarctic region. Therefore, we tried to compare the year-by-year changes of $CO_2$ seasonal amplitude and phase with interannual variations of the $CO_2$ increase rate to be discussed below. The seasonal amplitude was also compared to Antarctic Oscillation Index (AAO) calculated by CPC/NOAA (2001) and sea ice extent around the Antarctic Continent (Japan Meteorological Agency, 2000). However, no significant correlations of the seasonal cycle with those parameters were found from these comparisons. Further detailed examinations with three-dimensional atmospheric transport models and global land/ocean biospheric models are necessary to elucidate causes of such interannual variations of the seasonal $CO_2$ cycle.

Figure 6 shows the secular trend of the $CO_2$ concentration and its annual increase rate at Syowa Station. As shown in this figure, the $CO_2$ increase was enhanced especially in 1987, 1994 and 1998, which are coincident with the occurrence of an El Niño–Southern Oscillation (ENSO) event. In particular, the increase rate exceeded 3.0 ppmv $yr^{-1}$ in 1998. Such a good correlation between the rapid $CO_2$ increase and an ENSO event has been reported from other $CO_2$ monitoring programs around the world (Bacastow, 1976; Conway et al., 1994; Nakazawa et al., 1997b). From measurements of the stable carbon isotopic ratio ($\delta^{13}C$) of atmospheric $CO_2$ (Keeling et al., 1995; Nakazawa et al., 1997b), it was found that the rapid increase of the $CO_2$ concentration was accompanied by a rapid decrease

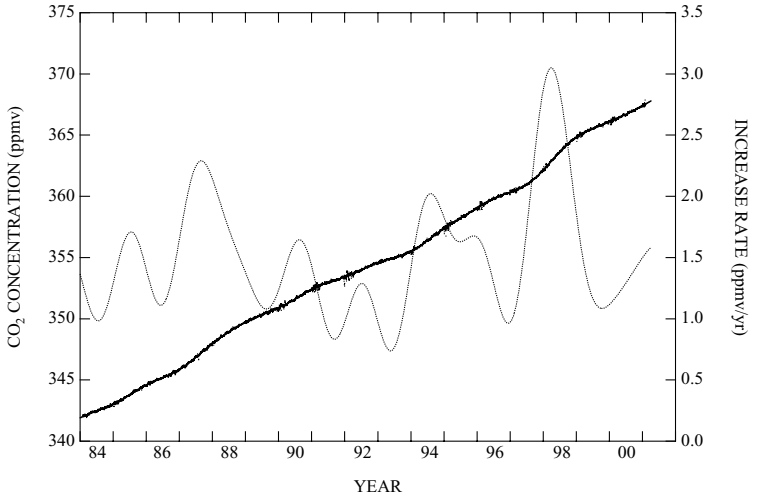


*Fig. 6.* Long-term trend (dots; left axis) and the increase rate (dotted line; right axis) of the $CO_2$ concentration at Syowa Station.

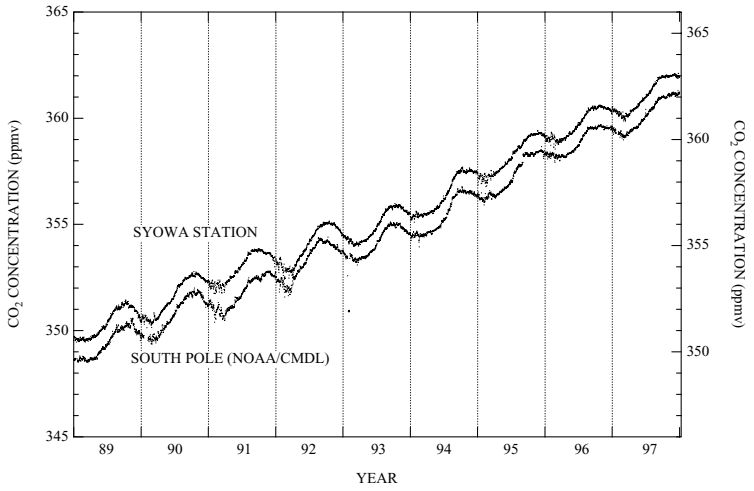


*Fig. 7.* Daily mean $CO_2$ concentrations at Syowa Station (left axis) and the South Pole (right axis).

of $\delta^{13}C$. Considering the fact that the $\delta^{13}C$ values of terrestrial biospheric $CO_2$ are lower than those of atmospheric $CO_2$ (Keeling et al., 1989), the interannual variations of the $CO_2$ increase are ascribed primarily to changes of the $CO_2$ exchange between the atmosphere and the terrestrial biosphere due to climate change in association with an ENSO event (Keeling et al., 1995; Morimoto et al., 2000). Recent biospheric model studies also showed that plant respiration and soil decomposition are enhanced in ENSO years by higher temperatures and excess precipitation, which leads to a reduction in net $CO_2$ uptake by the terrestrial biosphere from the atmosphere (Kindermann et al., 1996; Ito and Oikawa, 2000).

It has already been reported that irregular variations of the $CO_2$ concentration with amplitudes of 0.2 ppmv at most and periods of a few weeks were often observed at Syowa Station throughout the year (Nakazawa et al., 1991). From the fact that such irregular $CO_2$ variations were correlated well with atmospheric temperature at the station, it was suggested that the cause is primarily attributable to air mass exchanges in association with synoptic scale disturbances.

Short-term variations with amplitudes of more than 0.2 ppmv can be also found in Fig. 4, especially in the austral summer season after 1990. Such variations were much more prominent in the respective years from 1990 to 1992, 1995 and 1996 than in the other years. To inspect the variations more closely, the daily mean $CO_2$ concentrations at Syowa Station from 1989 to 1997 are compared in Fig. 7 with those at the South Pole (2810 m a.s.l.) observed by NOAA/CMDL. As seen from this figure, irregular variations of the $CO_2$ concentration were also clearly observed at the South Pole in 1990, 1991 and 1992, but were not very prominent in 1995 and 1996.

As examples of the comparison of the irregular $CO_2$ concentrations at Syowa Station and the South Pole in the summer season, the hourly mean $CO_2$ concentrations observed at both stations during two periods of 10–30 January 1995 and 4–24 February 1992 are shown in Figs. 8(a) and (b), respectively. It can be found in Fig. 8(a) that a remarkable decrease of the $CO_2$ concentration lasts for three days at Syowa around 19 January 1995, and that the differences between the minimum and contiguous concentrations reach about 1.0 ppmv, which is comparable to the seasonal $CO_2$ amplitude at Syowa Station, while the $CO_2$ data at the South Pole show no irregular variations during this period. On the other hand, large fluctuations with amplitudes of around 1.0 ppmv are clearly seen in both $CO_2$ records for 4–24 February 1992, but it is difficult to see a good correspondence between their fluctuations.

Distributions of 500 hPa geopotential height in the Antarctic region were composed for 19 January 1995 and 16 February 1992, using NCEP/NCAR Reanalysis data provided by the NOAA-CIRES Climate Diagnostics Center (http://www.cdc.noaa.gov/). The results for the respective dates are given in Figs. 9(a)

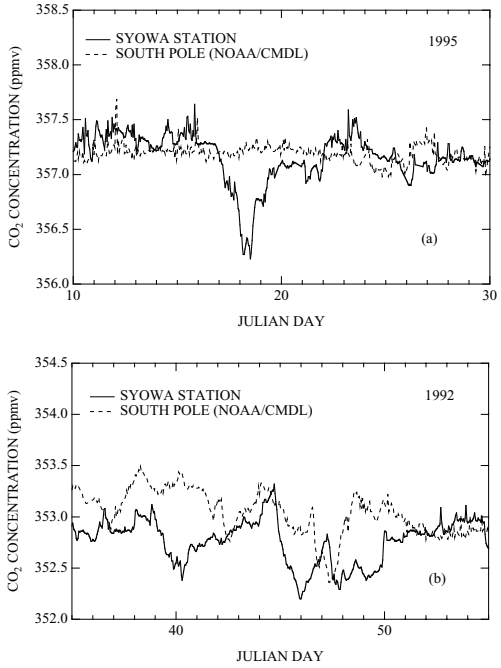


*Fig. 8.* Hourly mean values of the $CO_2$ concentration at Syowa Station (solid line) and the South Pole (broken line) during the periods (a) 10–30 January 1995 and (b) 4–24 February 1992.

and (b). A circumpolar structure of the geopotential height is clearly seen in Fig. 9(a). Also seen in this figure is an isolated low-pressure system being close to Syowa Station. This suggests that $CO_2$-depleted air mass was transported to Syowa Station by this low pressure. The results for February 1992 [Fig. 9(b)] shows that the circumpolar structure is largely skewed and air is intruded from lower latitudes into the Antarctic Continent along the meridian of 90°E. This implies that the large-scale transport of $CO_2$-depleted air mass to the Antarctic Continent occurred in association with the tongue of low pressure, by which the short-term variations of the $CO_2$ concentration on a continental scale were yielded.

It was reported that the large-scale transport of water vapor and heat flux to the Antarctic region occurred even in winter (Hirasawa et al., 2000). However, as described above, the clear short-term $CO_2$ fluctuations were observed in the Antarctic only in the summer season. The $CO_2$-depleted air masses could be originated in the terrestrial biosphere in the southern hemisphere, because its photosynthesis activity is enhanced in summer. For a more detailed interpretation of the short-term $CO_2$ variations observed in the Antarctic region, further investigation with dynamical models involving terrestrial biospheric $CO_2$ sources/sinks are required. Simultaneous observations of species such

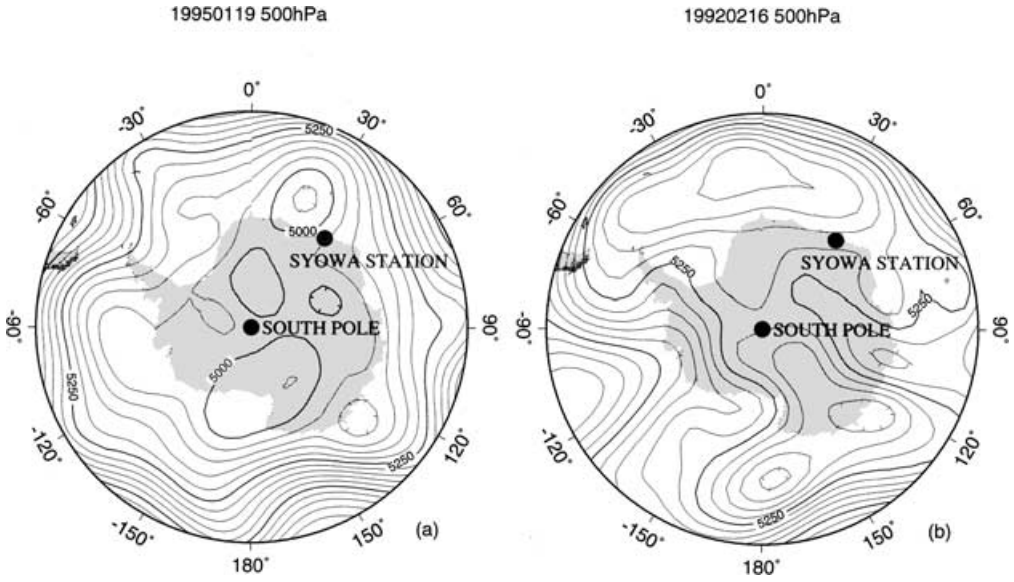


*Fig. 9.* Geopotential heights at 500 hPa on (a) 19 January 1995 and (b) 16 February 1992. Locations of Syowa Station and the South Pole are also shown.

as $CH_4$ and CO in the Antarctic region could provide a new insight into the origin of the $CO_2$-depleted air masses.

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