Tellus (1987), *39B*, 29–41

Seasonal and meridional variations of atmospheric carbon dioxide in the lower troposphere of the northern and southern hemispheres

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(Manuscript received November 4, 1985; in final form June 24, 1986)

ABSTRACT

Systematic collection of air samples over the Pacific Ocean was begun in March 1982 on board a container ship sailing between Japan and Australia. A current picture of seasonal and meridional variations of lower tropospheric CO_2 was derived from the measurement of these samples and supplementary information from several other observational programs. It was concluded that: (1) the amplitude of the seasonal variation was about 15 ppmv in high and mid-latitudes of the northern hemisphere and decreased southward to low values of about 1 ppmv in the southern hemisphere; (2) the maximum and minimum concentrations of the seasonal variation in the mid-latitudes of the northern hemisphere appeared early in April and in mid-August, respectively, and their occurrences were delayed gradually southward and northward from that latitude; (3) the annual mean CO_2 concentration was high in the mid-northern hemisphere, decreased gradually southward to low values in the mid-southern hemisphere and increased slightly again in the Antarctic region, the concentration difference between the mid-northern hemisphere and the Antarctic region being about 3 ppmv; (4) the year-to-year changes of annual mean CO_2 concentrations in all latitudes covered by this measurement were 1.3 and 1.7 ppmv yr^{-1}, for 1982–1983 and 1983–1984, respectively.

1. Introduction

An accurate knowledge of spatial and temporal distributions of atmospheric CO_2 on the globe is indispensable for validating the global carbon cycle models (Bolin and Keeling, 1963; Hyson et al., 1980; Pearman and Hyson, 1980; Pearman et al., 1983; Fung et al., 1983; Keeling, Heimann, Mook, 1985, pers. comm.). Substantial effort has been devoted to establishing a global station network for monitoring the concentration of the atmospheric CO_2 systematically; approximately 40 stations are currently operating around the world, including both in situ analyzer and flask-sampling measurements (Pearman, 1980). The global distribution of atmospheric CO_2 was described for the first time by Bolin and Keeling (1963) gathering many data from various sources, and in recent years by Fraser et al. (1983) and Komhyr et al. (1985) using the extensive data from the above network.

We began the systematic collection of air samples on the Pacific Ocean in March 1982 to elucidate spatial and temporal distributions of atmospheric CO_2 over an extensive geographical area. Since maritime airmasses are fairly free from the influence of local and regional effects, the representativeness of the data is expected to be greater in time and space scales than that of land-fixed measurements. In this paper, we report seasonal and meridional variations of lower tropospheric CO_2 in the northern and southern hemispheres obtained mainly from these measurements.

2. Experimental procedures

Details of our experimental procedures will be

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found elsewhere (Tanaka et al., 1983, 1987a). Only a general description of the procedures is given here. Air samples were collected at 16 positions at 33° N, at every 5° between 30° N and 35°S, and at 39°S on board a container ship "Hyogo Maru", Nippon Yusen Kaisha, Japan. A round trip cruise was repeated approximately every 30 days between Yokohama (35° N), Japan and Melbourne (38°S), Australia. The approximate location of the cruise tracks of Hyogo Maru during this measurement program is shown in Fig. 1. The air sampling was made by trained personnel at the bridge, about 22 m above the sea surface, facing the air intake to windward. Air samples were collected into 550 ml Pyrex glass flasks with greaseless stopcocks fitted at both ends and pressurized up to about 3 atm by an electric diaphragm pump (Tanaka et al., 1983). The flasks were sufficiently washed, heated and evacuated before sampling, and were stored in the dark inside of a thick paper box after protection with a shock absorbing material. Air samples collected were returned to our laboratory and their CO_2 concentrations were determined by a non-dispersive infrared analyzer against our air-based standard gases with an imprecision (one standard deviation) of ± 0.13 ppmv (Tanaka et al., 1987a). Water vapor was removed from air samples by two glass traps cooled at -78 °C. The lapse in time between sampling and subsequent laboratory analysis was 35 days at maximum. The possible deterioration of air samples stored in the flasks was corrected in the light of laboratory experiments with dry standard gases (Tanaka et al., 1983, 1987a). The maximum correction amounted to 0.4 ppmv. The overall imprecision of our flask analyses was ± 0.1 ppmv.

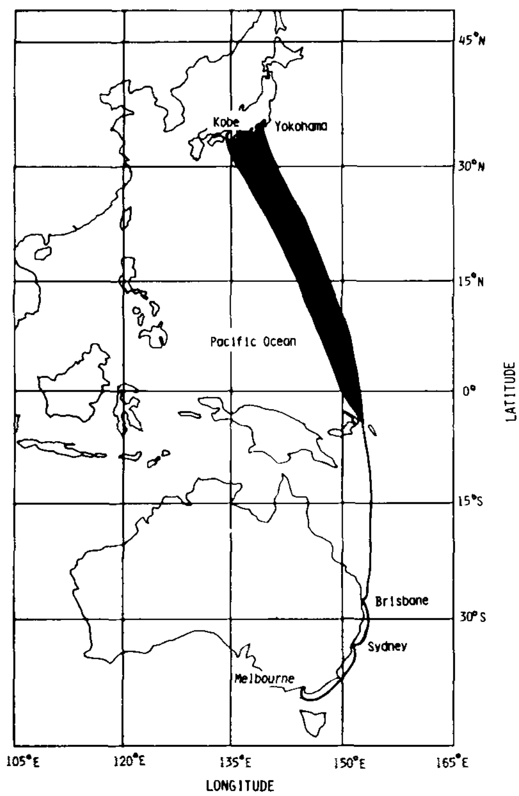

Fig. 1. Approximate locations of cruise tracks of Hyogo Maru during this measurement program.

3. Results and discussion

During the last 3 years, about 60 single flask samples were obtained for each latitude. The data with considerably higher CO_2 concentration, which were occasionally found especially near the Japanese Islands and the Australian Continent, were excluded from the analysis. The results for the respective latitudes are shown in Figs. 2a–c and in Table 1. In general, the variability of the CO_2 concentration is enhanced in mid-latitudes of the northern hemisphere, reflecting the high biospheric and human activities, and is reduced gradually southward excepting for low latitudes of the southern hemisphere where the South Pacific Convergence Zone (SPCZ) appears (Rasmusson and Carpenter, 1982). The concentration of atmospheric CO_2 often changes discontinuously near the SPCZ in February to July when the CO_2 concentration is higher in low latitudes of the northern hemisphere than in the southern hemisphere, as shown in Fig. 3. Such a phenomenon was also found by Keeling et al. (1984) and Komhyr et al. (1985) near the Intertropical Convergence Zone. The SPCZ appears usually at latitudes between 5° and 10°S on the cruise track of Hyogo Maru, but its location and activity are highly variable. Therefore, the variability of the CO_2 concentration in low latitudes of the southern hemisphere is enhanced by the alternation and mixing of air from both hemispheres.

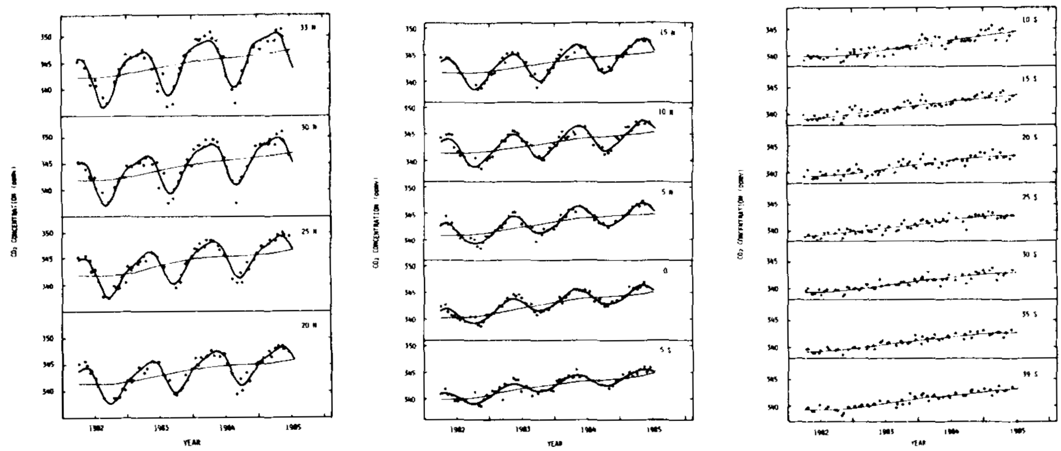

Fig. 2. (a) CO_2 concentrations at respective latitudes between 33° and 20°N over the Pacific Ocean. Circles indicate single measured values, thick lines the best fit to the data and thin lines seasonally adjusted values. (b) The same as in (a), but for latitudes between 15°N and 5°S. (c) The same as in (a), but for latitudes between 10°S and 39°S.

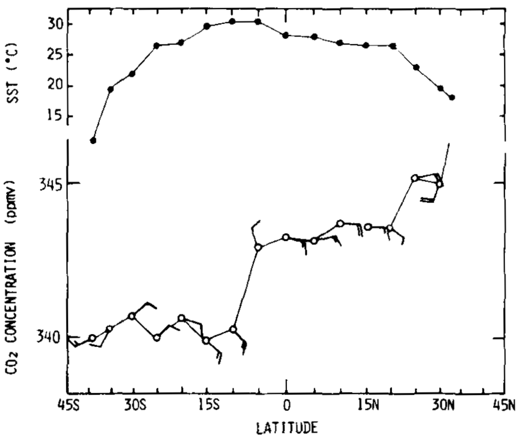

Fig. 3. Latitudinal distribution of both CO_2 concentration and sea surface temperature (SST) for the period from late in March to early in April 1983. Symbol attached to each concentration indicates the wind direction (north; upward) and wind speed. Half and full barbs correspond to 2.5 and 5 m s^{-1}, respectively. The South Pacific Convergence Zone was lcoated between 5° and 10°S on March 31, 1983 when Hyogu Maru passed 5°S.

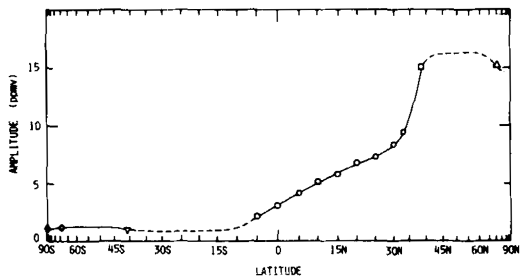

Fig. 4. Latitudinal distribution of the amplitude of the seasonal CO_2 variation: △, Point Barrow, Alaska; □, aircraft measurement for 0–1 km height; ○, this measurement: ▽, Baring Head, New Zealand; ⊕, Syowa Station, Antarctica; ◇, South Pole.

To separate the average seasonal variation and the secular increase of the CO_2 concentration from observed time-series of each latitude, we fitted the Fourier harmonics,

$$S(t) = C_1 \sin 2\pi t + C_2 \cos 2\pi t + C_3 \sin 4\pi t + C_4 \cos 4\pi t, \quad (1)$$

and cubic splines with 20-month knots, which represent the respective contributions, to the observed data by using an iterative procedure. Here, t is the elapsed time (years) relative to January 1, 1982 and C_i's are parameters determined by the fitting. However, only a cubic spline fitting was applied to the data of latitudes south of 10°S to detect the secular increase, because no regular seasonal CO_2 variation was recognized from a visual inspection of the data, merging into the data variability. Characteristic features of the average seasonal variation, thus obtained, are shown in Figs. 4 and 5, together with the results of several other measurements (Keeling et al., 1976; Lowe et al., 1979; Peterson

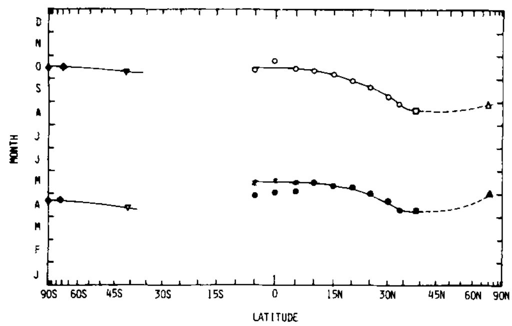

Fig. 5. Occurrence of the maximum (closed symbol) and minimum (open symbol) concentrations of the seasonal CO_2 variation as a function of latitude. Symbols have the same meaning as in Fig. 4, but asterisks represent the results obtained by excluding the data in 1982.

et al., 1982; Tanaka et al., 1987a, b). As is well-known (Bolin and Keeling, 1963; Fraser et al., 1983; Komhyr et al., 1985), the seasonal variation is larger in the northern hemisphere than in the southern hemisphere, reflecting the greater extent of boreal as compared with austral vegetated lands. The peak-to-peak amplitude of the seasonal variation is about 15 ppmv in high and mid-latitudes of the northern hemisphere and decreases southward to low values of about 1 ppmv in the southern hemisphere. The decrease is rather sudden between 38° and 30°N and around 10°S and gradual at other latitudes. The sudden change of the amplitude near 35°N is probably caused by the difference in prevailing airmasses, i.e., either continental or maritime, because the zonal mean wind in the lower troposphere varies from westerly to easterly near the latitude (Newell et al., 1972). In this respect, it is noted that the seasonal CO_2 variations at midocean stations P (50°N, 45°W), C (54°N, 35°W) and M (66°N, 20°E) and at Azores (39°N, 27°W) show lower amplitudes than those at continental and coastal sites (Wong et al., 1984; Keeling et al., 1985; Komhyr et al., 1985). The change near 10°S is attributed to the poorer meridional transport at the latitudes of the SPCZ than at higher latitudes.

The maximum and minimum concentrations of the seasonal CO_2 variation appear early in April and in mid-August, respectively, at 38°N, and their occurrences are delayed gradually southward and slightly northward, from that latitude, as seen in Fig. 5. The phase shift in low latitudes may be attributed to the transport of air from high and mid-latitudes of the northern hemisphere, and that in high latitudes to a delay of the summer season as well as the transport of air from mid-latitudes. The phase shift in low latitudes, however, are larger for the minimum concentration than for the maximum concentration by about a half month. Such a phenomenon may be ascribed to the northward transport of the southern hemispheric air in summer and early autumn (Wyrtki and Meyers, 1975). It is also seen from Fig. 5 that the maximum concentration at latitudes of 5°N to 5°S occurs late in April or early in May, earlier by about a half month than expected from the results of higher latitudes of the northern hemisphere. The cause is attributed to the fact that the southern hemispheric air with low CO_2 concentrations intruded into these latitudes from the Indian Ocean during the period May–July 1982. Our sampling area from 5°N to 5°S, where the wind is fairly weak (Wyrtki and Meyers, 1975), are normally covered with the northern hemispheric air in that period of the year, but the westerly wind anomalies originated in the Indian Ocean were enhanced in 1982 (Rasmussen, 1982). If such low values are excluded from the data set, the occurrence of the maximum concentration is delayed to mid-May. On the other hand, the seasonal CO_2 variations observed in the southern hemisphere are nearly consistent with each other, at least for high latitudes; the minimum concentration appears in mid- or late April and the maximum concentration in mid- or late October.

The seasonally adjusted CO_2 concentration increased slightly in 1982, rapidly in 1983 and gradually in 1984 for all latitudes covered by these measurements, as seen in Fig. 2. A similar trend is also found in the results obtained at Syowa Station, Antarctica and over Japan (Tanaka et al., 1987a, b). Such a fluctuation of the rate of annual increase may be related to the El Niño event occurred in 1982 to 1983 (Bacastow, 1976; Bacastow et al., 1980; Bacastow and Keeling, 1981; Newell et al., 1978).

Fig. 6 shows latitudinal distributions of the annual mean value of the CO_2 concentration. The values in 1982 of this measurement were obtained by supplementing the CO_2 concentrations of January to March by an extrapolation.

Table 1. *CO_2 concentrations at respective latitudes between 33° N and 39° S*

Sampling Date	CO_2 (ppmv)	Sampling Date	CO_2 (ppmv)	Sampling Date	CO_2 (ppmv)
33° N		Nov. 6, 1984	345.14	Mar. 17, 1984	349.75
		Dec. 22, 1984	348.03	Apr. 18, 1984	348.76
Mar. 31, 1982	345.44	Jan. 22, 1985	347.61	Apr. 26, 1984	349.60
May 6, 1982	345.65	Jan. 27, 1985	349.25	May 26, 1984	349.19
May 13, 1982	344.16	Mar. 7, 1985	349.19	Jun. 2, 1984	347.17
Jun. 10, 1982	342.57	Apr. 11, 1985	349.19	Jul. 3, 1984	346.15
Jun. 15, 1982	340.88	Apr. 16, 1985	351.22	Jul. 10, 1984	345.03
Jul. 12, 1982	341.90	May 18, 1985	351.35	Aug. 12, 1984	341.96
Jul. 17, 1982	340.72	May 23, 1985	350.08	Aug. 31, 1984	336.51
Aug. 23, 1982	338.63	Jun. 24, 1985	347.24	Sep. 28, 1984	342.00
Sep. 17, 1982	337.52			Oct. 6, 1984	343.06
Oct. 26, 1982	342.03	30° N		Nov. 5, 1984	344.68
Nov. 21, 1982	343.99			Dec. 22, 1984	347.27
Nov. 27, 1982	342.75	Apr. 1, 1982	345.44	Jan. 21, 1985	347.72
Dec. 23, 1982	344.75	May 6, 1982	345.19	Jan. 28, 1985	347.66
Dec. 29, 1982	346.75	May 13, 1982	344.02	Mar. 1, 1985	348.99
Jan. 25, 1983	345.95	Jun. 10, 1982	342.63	Mar. 8, 1985	350.00
Jan. 30, 1983	346.15	Jun. 16, 1982	342.60	Apr. 11, 1985	348.74
Mar. 4, 1983	346.56	Jul. 12, 1982	342.60	Apr. 17, 1985	350.79
Mar. 9, 1983	346.81	Jul. 18, 1982	340.53	May 17, 1985	351.16
Apr. 8, 1983	347.67	Aug. 23, 1982	339.49	May 24, 1985	349.48
Apr. 14, 1983	346.12	Sep. 17, 1982	337.52	Jun. 23, 1985	346.89
May 18, 1983	346.10	Oct. 27, 1982	340.67		
May 23, 1983	343.90	Nov. 20, 1982	341.59	25° N	
Jun. 23, 1983	341.22	Nov. 28, 1982	342.30		
Jun. 28, 1983	340.10	Dec. 23, 1982	342.42	Apr. 2, 1982	345.36
Aug. 1, 1983	343.11	Dec. 30, 1982	344.84	May 5, 1982	345.04
Aug. 23, 1983	336.81	Jan. 25, 1983	344.63	May 14, 1982	345.42
Sep. 20, 1983	337.21	Mar. 4, 1983	345.34	Jun. 9, 1982	344.72
Sep. 25, 1983	340.64	Mar. 10, 1983	345.69	Jun. 16, 1982	343.78
Oct. 26, 1983	342.63	Apr. 8, 1983	344.97	Jul. 11, 1982	342.90
Oct. 31, 1983	344.02	Apr. 15, 1983	346.15	Jul. 19, 1982	340.88
Nov. 28, 1983	346.44	May 17, 1983	346.26	Aug. 22, 1982	339.10
Dec. 4, 1983	346.91	May 23, 1983	345.07	Sep. 18, 1982	338.82
Jan. 3, 1984	347.59	Jun. 22, 1983	345.26	Oct. 20, 1982	340.06
Feb. 5, 1984	349.64	Jun. 29, 1983	340.49	Oct. 28, 1982	339.70
Feb. 10, 1984	349.37	Aug. 1, 1983	343.29	Nov. 20, 1982	339.23
Mar. 11, 1984	349.54	Aug. 23, 1983	337.52	Nov. 28, 1982	341.52
Mar. 17, 1984	350.21	Sep. 19, 1983	338.46	Dec. 22, 1982	340.59
Apr. 19, 1984	350.92	Sep. 25, 1983	340.37	Dec. 30, 1982	343.62
Apr. 26, 1984	349.70	Oct. 25, 1983	341.59	Jan. 24, 1983	343.11
May 27, 1984	349.36	Oct. 31, 1983	343.31	Feb. 1, 1983	343.38
Jun. 1, 1984	349.76	Nov. 28, 1983	344.82	Mar. 3, 1983	343.99
Jul. 4, 1984	346.35	Dec. 4, 1983	346.05	Mar. 11, 1983	344.59
Jul. 9, 1984	342.60	Jan. 3, 1984	344.70	Apr. 7, 1983	345.27
Aug. 13, 1984	339.97	Jan. 9, 1984	347.67	Apr. 16, 1983	344.48
Aug. 30, 1984	337.52	Feb. 5, 1984	348.58	May 16, 1983	346.18
Sep. 28, 1984	341.43	Feb. 11, 1984	348.67	May 24, 1983	346.01
Oct. 5, 1984	343.61	Mar. 10, 1984	348.18	Jun. 21, 1983	345.22

Table 1 (*continued*)

Sampling Date	CO_2 (ppmv)	Sampling Date	CO_2 (ppmv)	Sampling Date	CO_2 (ppmv)
Jul. 31, 1983	343.48	Nov. 19, 1982	339.10	Jun. 22, 1985	347.55
Sep. 18, 1983	340.39	Nov. 29, 1982	340.89		
Sep. 26, 1983	339.55	Dec. 21, 1982	340.44	15° N	
Oct. 24, 1983	340.46	Dec. 31, 1982	342.28		
Nov. 1, 1983	342.08	Jan. 23, 1983	342.09	Apr. 3, 1982	344.36
Nov. 27, 1983	344.11	Feb. 1, 1983	342.50	May 4, 1982	344.67
Dec. 5, 1983	344.54	Mar. 2, 1983	344.66	May 15, 1982	344.79
Jan. 1, 1984	345.34	Mar. 12, 1983	344.17	Jun. 8, 1982	343.93
Jan. 10, 1984	346.99	Apr. 6, 1983	343.43	Jun. 18, 1982	343.54
Feb. 4, 1984	346.96	Apr. 17, 1983	344.28	Jul. 10, 1982	342.59
Feb. 12, 1984	348.11	May 16, 1983	345.82	Jul. 20, 1982	341.52
Mar. 9, 1984	347.15	May 25, 1983	345.47	Aug. 21, 1982	340.63
Mar. 18, 1984	348.83	Jun. 20, 1983	345.42	Oct. 18, 1982	339.36
Apr. 18, 1984	348.73	Jul. 30, 1983	343.09	Oct. 29, 1982	338.54
Apr. 27, 1984	348.37	Aug. 25, 1983	342.36	Nov. 18, 1982	338.99
May 25, 1984	349.40	Sep. 18, 1983	339.65	Nov. 30, 1982	340.05
Jun. 3, 1984	346.86	Sep. 27, 1983	339.43	Dec. 21, 1982	340.42
Jul. 2, 1984	345.79	Oct. 24, 1983	340.37	Jan. 1, 1983	341.44
Jul. 11, 1984	345.34	Nov. 2, 1983	340.92	Jan. 22, 1983	341.27
Aug. 11, 1984	341.14	Nov. 26, 1983	343.31	Feb. 2, 1983	341.55
Sep. 1, 1984	339.55	Dec. 6, 1983	342.28	Mar. 1, 1983	343.97
Sep. 27, 1984	342.41	Jan. 1, 1984	344.33	Mar. 12, 1983	344.72
Oct. 6, 1984	340.49	Jan. 11, 1984	346.39	Apr. 5, 1983	343.62
Nov. 3, 1984	344.28	Feb. 3, 1984	345.12	Apr. 17, 1983	345.40
Nov. 11, 1984	343.08	Feb. 13, 1984	346.59	May 15, 1983	345.69
Dec. 16, 1984	344.60	Mar. 9, 1984	346.61	May 25, 1983	345.44
Dec. 23, 1984	346.08	Mar. 19, 1984	346.97	Jun. 19, 1983	345.39
Jan. 20, 1985	347.53	Apr. 17, 1984	347.98	Jul. 29, 1983	343.71
Jan. 28, 1985	347.23	Apr. 28, 1984	346.83	Aug. 25, 1983	341.02
Mar. 1, 1985	348.08	May 24, 1984	347.42	Sep. 17, 1983	341.37
Mar. 8, 1985	348.87	Jun. 3, 1984	346.69	Sep. 28, 1983	339.08
Apr. 10, 1985	348.52	Jul. 1, 1984	347.18	Oct. 23, 1983	340.25
Apr. 17, 1985	349.80	Jul. 11, 1984	345.12	Nov. 3, 1983	340.44
May 17, 1985	350.43	Aug. 11, 1984	343.27	Nov. 25, 1983	342.20
May 25, 1985	348.69	Sep. 1, 1984	339.55	Dec. 7, 1983	341.99
Jun. 23, 1985	347.37	Sep. 26, 1984	342.50	Dec. 31, 1983	343.70
		Oct. 17, 1984	340.17	Jan. 11, 1984	344.43
20° N		Nov. 2, 1984	343.51	Feb. 2, 1984	345.17
		Nov. 13, 1984	342.04	Feb. 13, 1984	346.13
Apr. 2, 1982	345.20	Dec. 15, 1984	345.12	Mar. 8, 1984	344.77
May 5, 1982	345.88	Dec. 24, 1984	345.27	Mar. 20, 1984	345.02
May 14, 1982	345.04	Jan. 19, 1985	345.44	Apr. 16, 1984	346.74
Jun. 9, 1982	344.09	Jan. 29, 1985	346.41	Apr. 29, 1984	345.53
Jun. 17, 1982	344.04	Feb. 28, 1985	347.78	May 24, 1984	346.97
Jul. 10, 1982	342.60	Mar. 9, 1985	346.56	Jun. 4, 1984	346.42
Jul. 19, 1982	341.18	Apr. 9, 1985	348.18	Jun. 30, 1984	346.55
Aug. 21, 1982	338.94	Apr. 18, 1985	348.79	Jul. 12, 1984	345.34
Oct. 19, 1982	339.10	May 16, 1985	348.75	Aug. 10, 1984	343.31
Oct. 28, 1982	338.84	May 26, 1985	348.09	Sep. 2, 1984	342.15

Table 1 (*continued*)

Sampling Date	CO_2 (ppmv)	Sampling Date	CO_2 (ppmv)	Sampling Date	CO_2 (ppmv)
Sep. 26, 1984	342.50	Nov. 25, 1983	341.93	Jan. 20, 1983	341.34
Oct. 7, 1984	341.85	Dec. 7, 1983	342.48	Feb. 4, 1983	341.94
Nov. 2, 1984	342.91	Dec. 30, 1983	343.26	Feb. 27, 1983	342.70
Nov. 14, 1984	342.15	Jan. 12, 1984	343.11	Mar. 14, 1983	342.37
Dec. 15, 1984	344.73	Feb. 2, 1984	344.52	Apr. 2, 1983	343.17
Dec. 25, 1984	344.85	Feb. 14, 1984	345.44	Apr. 19, 1983	344.69
Jan. 19, 1985	344.89	Mar. 6, 1984	344.16	May 14, 1983	345.18
Jan. 30, 1985	345.65	Mar. 20, 1984	344.68	May 27, 1983	345.33
Feb. 27, 1985	346.95	Apr. 15, 1984	345.55	Jun. 17, 1983	344.35
Mar. 10, 1985	346.66	Apr. 30, 1984	345.08	Jul. 3, 1983	343.13
Apr. 8, 1985	348.01	May 23, 1984	346.61	Jul. 27, 1983	342.67
Apr. 19, 1985	347.90	Jun. 5, 1984	346.31	Aug. 27, 1983	342.69
May 15, 1985	348.01	Jun. 28, 1984	346.71	Sep. 15, 1983	341.72
May 26, 1985	347.67	Jul. 13, 1984	345.24	Sep. 29, 1983	339.89
Jun. 21, 1985	347.37	Aug. 9, 1984	343.00	Oct. 21, 1983	341.26
		Sep. 3, 1984	342.96	Nov. 4, 1983	342.25
10° N		Sep. 25, 1984	342.56	Nov. 24, 1983	341.99
		Oct. 9, 1984	341.27	Dec. 8, 1983	342.15
Apr. 4, 1982	344.41	Nov. 1, 1984	341.57	Dec. 29, 1983	342.33
May 3, 1982	345.04	Nov. 15, 1984	342.09	Jan. 13, 1984	343.11
May 16, 1982	345.09	Dec. 14, 1984	344.42	Feb. 1, 1984	343.86
Jun. 7, 1982	345.10	Dec. 26, 1984	344.33	Feb. 15, 1984	344.86
Jun. 18, 1982	342.46	Jan. 19, 1985	344.66	Mar. 5, 1984	344.15
Jul. 9, 1982	341.83	Jan. 31, 1985	346.37	Mar. 21, 1984	345.56
Jul. 21, 1982	341.12	Feb. 26, 1985	346.30	Apr. 14, 1984	345.79
Aug. 20, 1982	340.70	Mar. 11, 1985	345.73	May 1, 1984	345.24
Sep. 20, 1982	339.23	Apr. 8, 1985	347.47	May 22, 1984	346.61
Oct. 18, 1982	340.47	Apr. 20, 1985	347.07	Jun. 6, 1984	346.19
Oct. 30, 1982	339.05	May 14, 1985	347.78	Jun. 27, 1984	345.89
Nov. 18, 1982	338.60	May 27, 1985	347.07	Jul. 14, 1984	345.16
Dec. 1, 1982	340.27	Jun. 20, 1985	347.24	Aug. 8, 1984	343.71
Dec. 20, 1982	340.15			Sep. 4, 1984	343.31
Jan. 1, 1983	340.53	5° N		Sep. 24, 1984	343.04
Jan. 21, 1983	340.76			Oct. 10, 1984	343.27
Feb. 3, 1983	342.03	Apr. 5, 1982	342.99	Oct. 31, 1984	342.24
Feb. 28, 1983	342.96	May 2, 1982	344.43	Dec. 13, 1984	343.74
Mar. 13, 1983	343.94	May 17, 1982	343.11	Jan. 17, 1985	344.20
Apr. 4, 1983	343.73	Jun. 6, 1982	343.27	Feb. 1, 1985	344.58
Apr. 18, 1983	345.04	Jun. 19, 1982	342.23	Feb. 25, 1985	345.56
May 14, 1983	345.69	Jul. 8, 1982	341.08	Mar. 12, 1985	346.37
May 26, 1983	345.44	Jul. 21, 1982	340.28	Apr. 7, 1985	347.01
Jun. 18, 1983	345.14	Aug. 19, 1982	339.61	Apr. 20, 1985	346.42
Jul. 2, 1983	343.96	Sep. 20, 1982	340.55	May 13, 1985	347.48
Jul. 28, 1983	343.40	Oct. 17, 1982	340.37	May 28, 1985	346.78
Aug. 26, 1983	342.09	Oct. 30, 1982	338.84	Jun. 20, 1985	346.36
Sep. 16, 1983	341.12	Nov. 17, 1982	338.53		
Sep. 28, 1983	341.04	Dec. 1, 1982	339.40	0°	
Oct. 22, 1983	340.33	Dec. 19, 1982	340.96		
Nov. 3, 1983	340.24	Jan. 2, 1983	340.79	Apr. 6, 1982	342.40

Table 1 (*continued*)

Sampling Date	CO_2 (ppmv)	Sampling Date	CO_2 (ppmv)	Sampling Date	CO_2 (ppmv)
May 1, 1982	342.71	Nov. 17, 1984	343.39	Mar. 4, 1984	344.11
May 17, 1982	341.26	Dec. 12, 1984	343.74	Mar. 23, 1984	344.63
Jun. 6, 1982	340.87	Jan. 16, 1985	344.21	Apr. 13, 1984	344.02
Jun. 20, 1982	340.67	Feb. 2, 1985	343.43	May 2, 1984	345.61
Jul. 8, 1982	340.30	Feb. 24, 1985	346.15	May 21, 1984	344.06
Jul. 22, 1982	339.88	Mar. 13, 1985	345.94	Jun. 7, 1984	344.07
Aug. 19, 1982	339.80	Apr. 6, 1985	345.33	Jun. 26, 1984	344.13
Sep. 21, 1982	340.57	Apr. 22, 1985	346.04	Jul. 16, 1984	343.44
Oct. 17, 1982	340.50	May 12, 1985	347.07	Aug. 6, 1984	343.63
Oct. 31, 1982	339.01	May 29, 1985	345.97	sep. 5, 1984	343.62
Nov. 17, 1982	338.74			Sep. 23, 1984	342.71
Dec. 2, 1982	339.41	5° S		Oct. 11, 1984	342.68
Dec. 19, 1982	340.96			Oct. 29, 1984	342.07
Jan. 3, 1983	340.60	Apr. 7, 1982	341.08	Nov. 18, 1984	342.75
Jan. 19, 1983	341.16	Apr. 30, 1982	341.89	Dec. 12, 1984	343.56
Feb. 5, 1983	341.30	May 18, 1982	340.76	Jan. 15, 1985	344.82
Feb. 27, 1983	342.46	Jun. 5, 1982	340.87	Feb. 3, 1985	344.10
Mar. 15, 1983	342.30	Jun. 21, 1982	339.65	Feb. 23, 1985	345.14
Apr. 1, 1983	343.26	Jul. 7, 1982	339.63	Mar. 14, 1985	344.13
Apr. 20, 1983	344.06	Jul. 23, 1982	339.81	Apr. 6, 1985	344.83
May 13, 1983	344.74	Aug. 18, 1982	339.83	Apr. 22, 1985	345.78
May 28, 1983	344.29	Oct. 16, 1982	341.28	May 11, 1985	346.15
Jun. 16, 1983	343.38	Nov. 1, 1982	338.94	May 30, 1985	345.06
Jul. 4, 1983	343.92	Nov. 16, 1982	338.84	Jun. 18, 1985	346.05
Jul. 26, 1983	342.59	Dec. 3, 1982	340.12		
Aug. 28, 1983	342.94	Dec. 18, 1982	340.88	10° S	
Sep. 15, 1983	341.41	Jan. 3, 1983	340.57		
Sep. 30, 1983	340.60	Jan. 18, 1983	341.59	Apr. 7, 1982	339.25
Oct. 20, 1983	342.07	Feb. 6, 1983	341.28	Apr. 30, 1982	341.19
Nov. 5, 1983	341.79	Feb. 26, 1983	342.23	May 19, 1982	339.61
Nov. 23, 1983	342.11	Mar. 15, 1983	339.89	Jun. 5, 1982	340.12
Dec. 9, 1983	342.00	Mar. 31, 1983	342.98	Jun. 21, 1982	339.13
Dec. 28, 1983	342.59	Apr. 21, 1983	341.76	Jul. 6, 1982	339.76
Jan. 14, 1984	343.31	May 12, 1983	343.94	Jul. 24, 1982	339.52
Jan. 31, 1984	344.22	May 28, 1983	343.74	Aug. 17 1982	339.92
Feb. 16, 1984	342.98	Jun. 15, 1983	343.68	Oct. 15, 1982	341.39
Mar. 4, 1984	344.18	Jul. 5, 1983	341.28	Nov. 1, 1982	338.85
Mar. 22, 1984	344.64	Jul. 26, 1983	342.47	Nov. 15, 1982	339.04
Apr. 13, 1984	345.77	Aug. 29, 1983	340.61	Dec. 3, 1982	340.06
May 1, 1984	345.36	Sep. 14, 1983	342.11	Dec. 17, 1982	340.87
May 21, 1984	345.18	Oct. 1, 1983	341.08	Jan. 4, 1983	341.46
Jun. 7, 1984	345.38	Oct. 20, 1983	341.74	Feb. 6, 1983	340.09
Jun. 26, 1984	345.63	Nov. 5, 1983	341.71	Feb. 25, 1983	341.37
Jul. 15, 1984	345.14	Nov. 22, 1983	342.09	Mar. 16, 1983	339.79
Aug. 8, 1984	343.21	Dec. 10, 1983	341.69	Mar. 31, 1983	340.27
Sep. 5, 1984	343.85	Dec. 28, 1983	341.49	Apr. 21, 1983	341.86
Sep. 24, 1984	343.05	Jan. 15, 1984	343.43	May 12, 1983	341.94
Oct. 11, 1984	342.46	Jan. 31, 1984	343.75	May 29, 1983	340.21
Oct. 30, 1984	342.67	Feb. 17, 1984	343.79	Jun. 14, 1983	341.80

Table 1 (*continued*)

Sampling Date	CO_2 (ppmv)	Sampling Date	CO_2 (ppmv)	Sampling Date	CO_2 (ppmv)
Jul. 6, 1983	339.94	Sep. 23, 1982	339.15	Apr. 4, 1985	344.17
Jul. 25, 1983	341.48	Oct. 15, 1982	340.67	Apr. 24, 1985	344.68
Aug. 30, 1983	340.45	Nov. 2, 1982	338.31	May 10, 1985	342.75
Sep. 14, 1983	341.49	Nov. 15, 1982	339.43	May 31, 1985	342.94
Oct. 1, 1983	341.43	Dec. 4, 1982	339.95	Jun. 17, 1985	343.82
Oct. 19, 1983	341.64	Dec. 17, 1982	341.45		
Nov. 6, 1983	341.69	Jan. 5, 1983	341.08	20° S	
Nov. 22, 1983	341.99	Jan. 17, 1983	341.59		
Dec. 11, 1983	341.36	Feb. 7, 1983	339.64	Apr. 9, 1982	339.41
Dec. 27, 1983	341.45	Feb. 24, 1983	340.79	Apr. 28, 1982	340.65
Jan. 15, 1984	343.00	Mar. 17, 1983	339.65	May 20, 1982	338.94
Jan. 30, 1984	344.11	Mar. 30, 1983	339.83	Jun. 4, 1982	339.04
Feb. 17, 1984	343.35	Apr. 22, 1983	340.92	Jun. 23, 1982	339.08
Mar. 3, 1984	343.10	May 11, 1983	340.43	Jul. 5, 1982	340.14
Mar. 24, 1984	341.97	May 30, 1983	340.28	Jul. 26, 1982	339.65
Apr. 12, 1984	343.62	Jun. 13, 1983	341.08	Aug. 16, 1982	339.74
May 3, 1984	343.49	Jul. 7, 1983	340.61	Sep. 23, 1982	339.69
May 20, 1984	342.04	Jul. 24, 1983	340.78	Oct. 14, 1982	340.37
Jun. 8, 1984	341.27	Aug. 30, 1983	341.02	Nov. 2, 1982	338.71
Jun. 25, 1984	342.50	Sep. 13, 1983	341.52	Nov. 14, 1982	339.45
Jul. 16, 1984	342.60	Oct. 2, 1983	341.24	Dec. 5, 1982	340.57
Aug. 6, 1984	343.68	Oct. 18, 1983	342.40	Dec. 16, 1982	340.66
Sep. 6, 1984	342.81	Nov. 7, 1983	342.48	Jan. 5, 1983	339.95
Sep. 22, 1984	342.60	Nov. 21, 1983	342.24	Jan. 16, 1983	341.68
Oct. 12, 1984	343.05	Dec. 12, 1983	341.32	Feb. 8, 1983	339.61
Oct. 28, 1984	342.56	Dec. 26, 1983	341.75	Feb. 23, 1983	340.15
Nov. 19, 1984	342.56	Jan. 16, 1984	342.81	Mar. 18, 1983	339.12
Dec. 11, 1984	343.87	Jan. 29, 1984	343.93	Mar. 29, 1983	340.61
Dec. 29, 1984	345.06	Feb. 18, 1984	342.40	Apr. 23, 1983	339.58
Jan. 14, 1985	344.53	Mar. 2, 1984	341.27	May 10, 1983	340.33
Feb. 3, 1985	344.92	Mar. 24, 1984	341.98	May 31, 1983	339.64
Feb. 22, 1985	345.70	Apr. 11, 1984	341.83	Jun. 12, 1983	340.35
Mar. 14, 1985	342.90	May 4, 1984	341.92	Jul. 8, 1983	340.37
Apr. 5, 1985	344.96	May 19, 1984	341.46	Jul. 23, 1983	341.40
Apr. 23, 1985	345.24	Jun. 9, 1984	341.80	Aug. 31, 1983	340.06
May 11, 1985	342.84	Jun. 24, 1984	341.85	Sep. 12, 1983	341.98
May 30, 1985	343.92	Jul. 17, 1984	342.41	Oct. 3, 1983	341.38
Jun. 17, 1985	344.62	Aug. 5, 1984	342.91	Oct. 17, 1983	342.41
		Sep. 7, 1984	342.93	Nov. 8, 1983	341.69
15° S		Sep. 22, 1984	342.24	Nov. 20, 1983	341.95
		Oct. 13, 1984	342.70	Dec. 12, 1983	341.15
Apr. 8, 1982	339.21	Oct. 28, 1984	341.81	Dec. 25, 1983	340.99
Apr. 29, 1982	339.07	Nov. 19, 1984	343.42	Jan. 17, 1984	342.60
May 19, 1982	339.30	Dec. 11, 1984	343.86	Jan. 28, 1984	343.44
Jun. 4, 1982	339.92	Dec. 30, 1984	344.18	Feb. 19, 1984	341.41
Jun. 22, 1982	339.05	Jan. 14, 1985	343.26	Mar. 1, 1984	341.70
Jul. 6, 1982	339.52	Feb. 4, 1985	342.70	Mar. 25, 1984	341.61
Jul. 25, 1982	339.47	Feb. 22, 1985	344.05	Apr. 10, 1984	342.76
Aug. 17, 1982	339.93	Mar. 15, 1985	342.56	May 4, 1984	341.02

Table 1 (*continued*)

Sampling Date	CO_2 (ppmv)	Sampling Date	CO_2 (ppmv)	Sampling Date	CO_2 (ppmv)
May 19, 1984	341.58	Jul. 23, 1983	341.04	Nov. 10, 1982	339.05
Jun. 10, 1984	341.36	Sep. 1, 1983	340.09	Dec. 6, 1982	340.41
Jun. 23, 1984	342.33	Sep. 12, 1983	340.36	Dec. 14, 1982	340.27
Jul. 18, 1984	342.37	Oct. 4, 1983	341.30	Jan. 6, 1983	340.08
Aug. 4, 1984	342.33	Oct. 17, 1983	342.15	Jan. 14, 1983	340.06
Sep. 8, 1984	342.45	Nov. 8, 1983	340.90	Feb. 10, 1983	339.96
Sep. 21, 1984	341.17	Nov. 20, 1983	340.69	Feb. 20, 1983	340.24
Oct. 14, 1984	342.45	Dec. 13, 1983	341.49	Mar. 19, 1983	340.90
Oct. 27, 1984	343.13	Dec. 25, 1983	341.08	Mar. 26, 1983	340.69
Nov. 20, 1984	343.19	Jan. 18, 1984	342.20	Apr. 25, 1983	340.16
Dec. 10, 1984	343.82	Jan. 28, 1984	342.36	May 8, 1983	340.06
Dec. 30, 1984	343.92	Feb. 20, 1984	342.02	Jun. 1, 1983	341.90
Jan. 13, 1985	342.42	Mar. 1, 1984	341.60	Jun. 10, 1983	341.37
Feb. 5, 1985	342.48	Mar. 26, 1984	341.04	Jul. 10, 1983	340.83
Feb. 21, 1985	342.37	Apr. 10, 1984	342.20	Jul. 20, 1983	340.98
Mar. 16, 1985	342.62	May 5, 1984	341.71	Sep. 1, 1983	340.96
Apr. 4, 1985	343.81	May 18, 1984	342.42	Sep. 10, 1983	340.96
Apr. 25, 1985	343.11	Jun. 10, 1984	341.97	Oct. 4, 1983	341.28
May 9, 1985	343.02	Jun. 22, 1984	343.58	Oct. 15, 1983	341.23
Jun. 1, 1985	342.70	Aug. 3, 1984	342.50	Nov. 9, 1983	340.77
Jun. 16, 1985	343.36	Sep. 9, 1984	341.68	Nov. 17, 1983	340.67
		Sep. 20, 1984	340.40	Dec. 14, 1983	341.89
25° S		Oct. 15, 1984	342.60	Dec. 23, 1983	341.18
		Oct. 26, 1984	342.52	Jan. 19, 1984	341.81
Apr. 10, 1982	339.00	Nov. 21, 1984	343.28	Jan. 26, 1984	342.33
Apr. 27, 1982	340.46	Dec. 9, 1984	343.10	Feb. 21, 1984	341.70
May 21, 1982	338.64	Dec. 31, 1984	343.44	Feb. 28, 1984	343.19
Jun. 3, 1982	339.05	Jan. 12, 1985	342.94	Mar. 27, 1984	341.48
Jun. 23, 1982	338.13	Feb. 6, 1985	343.95	Apr. 6, 1984	341.75
Jul. 4, 1982	338.55	Feb. 20, 1985	343.79	May 6, 1984	340.55
Jul. 27, 1982	339.79	Mar. 17, 1985	342.56	May 15, 1984	341.89
Aug. 15, 1982	339.75	Apr. 3, 1985	342.76	Jun. 12, 1984	342.00
Sep. 24, 1982	339.60	Apr. 26, 1985	342.39	Jun. 20, 1984	342.68
Oct. 14, 1982	340.39	May 7, 1985	342.94	Aug. 1, 1984	342.60
Nov. 3, 1982	338.74	Jun. 15, 1985	343.40	Sep. 9, 1984	342.62
Nov. 13, 1982	339.54			Sep. 20, 1984	341.00
Dec. 5, 1982	340.47	30° S		Oct. 15, 1984	342.70
Dec. 15, 1982	340.47			Oct. 23, 1984	342.09
Jan. 6, 1983	340.06	Apr. 11, 1982	339.68	Nov. 22, 1984	343.21
Jan. 19, 1983	339.58	Apr. 26, 1982	340.16	Dec. 6, 1984	343.11
Feb. 9, 1983	339.94	May 21, 1982	339.10	Jan. 1, 1985	343.31
Feb. 23, 1983	339.63	May 30, 1982	339.15	Jan. 10, 1985	342.91
Mar. 18, 1983	341.06	Jun. 24, 1982	339.83	Feb. 6, 1985	343.65
Mar. 28, 1983	339.94	Jul. 3, 1982	338.85	Feb. 17, 1985	344.05
Apr. 24, 1983	339.82	Jul. 27, 1982	339.52	Mar. 18, 1985	341.36
May 10, 1983	340.53	Aug. 13, 1982	339.84	Mar. 30, 1985	342.75
May 31, 1983	341.23	Sep. 24, 1982	339.76	Apr. 27, 1985	342.60
Jun. 12, 1983	339.22	Oct. 12, 1982	339.78	May 5, 1985	342.99
Jul. 9, 1983	341.02	Nov. 4, 1982	338.73	Jun. 13, 1985	343.21

Table 1 (*continued*)

Sampling Date	CO_2 (ppmv)	Sampling Date	CO_2 (ppmv)	Sampling Date	CO_2 (ppmv)
35° S		Oct. 23, 1984	341.59	Apr. 5, 1984	342.09
		Dec. 4, 1984	343.01	May 8, 1984	341.49
Apr. 19, 1982	339.58	Jan. 4, 1985	343.21	May 14, 1984	341.80
Apr. 25, 1982	339.86	Feb. 9, 1985	342.31	Jun. 14, 1984	341.99
May 23, 1982	339.06	Feb. 15, 1985	342.60	Jun. 19, 1984	341.80
May 29, 1982	339.05	Mar. 21, 1985	342.55	Jul. 30, 1984	342.60
Jun. 26, 1982	339.09	Mar. 29, 1985	342.81	Sep. 13, 1984	342.10
Jul. 2, 1982	339.55	Apr. 30, 1985	342.00	Sep. 19, 1984	341.94
Aug. 6, 1982	340.16	May 5, 1985	343.01	Oct. 19, 1984	343.01
Aug. 12, 1982	339.76	Jun. 12, 1985	343.41	Oct. 22, 1984	342.09
Sep. 27, 1982	339.55			Dec. 4, 1984	342.72
Oct. 11, 1982	339.60	39° S		Jan. 5, 1985	343.15
Nov. 9, 1982	338.59			Feb. 9, 1985	342.60
Dec. 8, 1982	339.62	Apr. 20, 1982	339.55	Feb. 15, 1985	341.83
Dec. 13, 1982	340.10	Apr. 24, 1982	339.55	Mar. 21, 1985	342.60
Jan. 8, 1983	340.06	May 24, 1982	339.03	Mar. 29, 1985	343.80
Jan. 13, 1983	340.34	May 28, 1982	339.12	May 1, 1985	343.03
Feb. 13, 1983	340.01	Jun. 27, 1982	340.18	May 4, 1985	343.21
Feb. 19, 1983	339.77	Aug. 7, 1982	339.55	Jun. 11, 1985	343.38
Mar. 21, 1983	339.49	Aug. 12, 1982	339.86		
Mar. 26, 1983	340.27	Sep. 27, 1982	339.40		
Apr. 27, 1983	340.52	Oct. 11, 1982	339.29		
May 4, 1983	339.66	Nov. 6, 1982	338.18		
Jun. 5, 1983	341.16	Nov. 8, 1982	338.54		
Jun. 9, 1983	341.46	Dec. 8, 1982	339.88		
Jul. 15, 1983	340.88	Dec. 12, 1982	339.42		
Jul. 19, 1983	340.88	Jan. 9, 1983	339.96		
Sep. 3, 1983	340.37	Jan. 12, 1983	340.06		
Sep. 8, 1983	340.29	Feb. 13, 1983	339.96		
Oct. 7, 1983	341.25	Feb. 19, 1983	340.25		
Oct. 12, 1983	340.85	Mar. 22, 1983	340.38		
Nov. 11, 1983	340.64	Mar. 25, 1983	339.94		
Nov. 16, 1983	341.08	Apr. 28, 1983	340.55		
Dec. 17, 1983	342.32	May 3, 1983	340.27		
Dec. 22, 1983	341.43	Jun. 5, 1983	341.08		
Jan. 21, 1984	340.77	Jul. 18, 1983	340.80		
Jan. 25, 1984	342.30	Sep. 3, 1983	339.85		
Feb. 23, 1984	341.80	Sep. 7, 1983	340.57		
Feb. 27, 1984	341.18	Oct. 8, 1983	341.08		
Mar. 29, 1984	341.90	Oct. 11, 1983	340.06		
Apr. 5, 1984	342.50	Nov. 12, 1983	340.57		
May 7, 1984	341.46	Nov. 16, 1983	342.28		
May 14, 1984	341.79	Dec. 17, 1983	342.01		
Jun. 14, 1984	342.21	Dec. 21, 1983	341.37		
Jun. 19, 1984	341.99	Jan. 21, 1984	342.07		
Jul. 31, 1984	342.66	Jan. 24, 1984	342.36		
Sep. 12, 1984	342.59	Feb. 23, 1984	341.69		
Sep. 19, 1984	342.41	Feb. 26, 1984	341.05		
Oct. 18, 1984	342.94	Mar. 30, 1984	341.89		

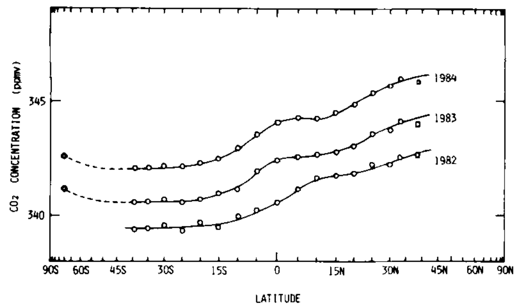

Fig. 6. Latitudinal distribution of annual mean CO_2 concentration in 1982 to 1984. Symbols have the same meanings as in Fig. 4.

The annual mean value is high in the mid-northern hemisphere, decreases gradually southward to low values in the mid-southern hemisphere, and increases slightly again in the Antarctic region for all years, but a concentration hump due primarily to the ocean upwelling source (Bolin and Keeling, 1963) is observed around the equator excepting for 1982. The hump is not obvious in 1982 due to low CO_2 concentrations in May to July of that year. The suppression of the hump was also found by Komhyr et al. (1985). The fact that the annual mean CO_2 concentration is higher in the Antarctic region than in the mid-southern hemisphere by about 0.4 ppmv is due probably to the air transport from the northern hemisphere through the stratosphere or the upper troposphere as suggested by Pearman and Beardsmore (1984). The concentration difference between the mid-northern hemisphere and the Antarctic region is about 3 ppmv for recent years, which is compatible with the results of Komhyr et al. (1985) and Fraser et al. (1983), and is expanded as compared with that in 1962 (Bolin and Keeling, 1963). This fact suggests that the current increase of the atmospheric CO_2 concentration results mainly from human activities in high and mid-latitudes of the northern hemisphere. An expansion of the north-south gradient in CO_2 concentration was discussed by Keeling (1983) using measured data, and by Pearman et al. (1983) and Keeling and Heimann (1985, pers. comm.) using global carbon cycle models.

The year-to-year changes of annual mean CO_2 concentrations were nearly the same for all latitudes covered by this measurement, i.e. 1.3 and 1.7 ppmv yr^{-1} for 1982–1983 and 1983–1984, respectively.

4. Acknowledgements

The authors express their gratitude to the staff of Hyogo Maru, Nippon Yusen Kaisha, Japan, who carefully collected the air samples over a long time for this study.

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