Tellus (1988), *40B*, 16–22

Aircraft measurements of tropospheric carbon dioxide over the Japanese islands

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(Manuscript received 9 October, 1986; in final form 5 February, 1987)

ABSTRACT

To elucidate spatial and temporal variations of the tropospheric CO_2 concentrations over the Japanese Islands, air samples were collected between 26°N and 38°N latitude during the period from June 1982 to February 1985 aboard commercial jet airliners. The amplitude of the seasonal variation of upper tropospheric CO_2 diminished gradually going southward with a phase delay of approximately half a month. Seasonally adjusted concentrations increased gradually in 1982, rapidly in 1983 and rather slightly in 1984 for all latitudes, and annual mean values were nearly the same for all latitudes in both 1983 and 1984.

Over the southernmost part of Japan, the phase of the seasonal variation in the lower troposphere, preceded by about 15 days, those variations within the middle and upper levels of the troposphere. The peak-to-peak amplitude decreased slightly with increasing height. Annual mean values also decreased with increasing height; the concentration difference between the lowest and highest layers sampled was about 2 ppmv. The secular trend of the CO_2 concentration was almost the same as at the higher latitudes.

1. Introduction

Systematic measurements of atmospheric CO_2 levels were taken for the first time by Keeling at the South Pole and Mauna Loa, Hawaii (Keeling et al., 19767a, b). In recent years, the number of collection sites has increased greatly with a growing concern about the potential impact of CO_2 on global climate. An extensive CO_2 monitoring network is important in obtaining a detailed description of the global distribution of atmospheric CO_2. The data from a comprehensive network are indispensable for developing and validating a global carbon cycle model for use in estimating the distribution and exchange of anthropogenically produced CO_2 between the atmosphere, the oceans and the biosphere (Bolin and Keeling, 1963; Pearman and Hyson, 1980, 1986; Fung et al., 1983; Heimann and Keeling, 1986; Keeling and Heimann, 1986). Air samples collected from aircraft are especially useful for this purpose, since they are relatively free from local and regional effects of sources and sinks of CO_2 at the earth's surface. Programs aimed at long-term aircraft measurements have operated only over the polar region of the northern hemisphere, the Australian region and Japan (Bolin and Bischof, 1970; Bischof, 1981; Pearman and Garratt, 1973; Pearman and Beardsmore, 1984; Tanaka et al., 1983a, 1987a). The Swedish program over the polar northern hemisphere has now been discontinued.

In our aircraft program, initiated in 1979, most of the air samples were collected at latitudes 34°N to 38°N for the middle and upper troposphere and around 38°N for the lower troposphere. To examine temporal and spatial variations of the tropospheric CO_2 concentration over a wider geographical area, collection of air samples was also made by using commercial jet airliners between Sendai (38°N) and Okinawa

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(26° N) for the period from June 1982 to February 1985. In this paper, we show variations of upper tropospheric CO_2 over the Japanese Islands and of tropospheric CO_2 over Okinawa, the southernmost part of Japan.

2. Air sampling and analysis

Details of our experimental procedures have been published previously (Tanaka et al., 1983a, b, 1987a, b). A brief description of the procedures follows:

The air sampling was made once per month on a round-trip flight between Sendai and Okinawa, with the cooperative support of All Nippon Airways. The aircraft used was a Boeing B737, and its flight routes are shown in Fig. 1. The normal route was over the Pacific side of Japan, but an alternative route over the west coast of Japan was occasionally adopted depending on the weather conditions. Air samples were collected at 12 positions with nearly equal latitude intervals along the flight route from altitudes between 8 and 10 km and at 2 positions from altitudes of about 5.2 and 0.6 km over Okinawa. Each air sample was pumped from the cabin ventilation outlets into a 550 ml Pyrex glass flask to an overpressure of about 2 atm. All flasks were heated and evacuated prior to use. The flasks filled with air samples were stored in the dark inside of a cardboard box and returned to our laboratory for analysis.

The CO_2 concentration of each flask sample was determined using a nondispersive infrared analyzer against our CO_2-in-air standard gases. This was done within 3 days after collection. Water vapor was removed from the samples by two glass traps cooled at −78 °C. The response of the analyzer was determined by introducing three or four working standard gases into the sample cell once per hour. The CO_2 concentrations of the standard gases were distributed over a range of about 30 ppmv including the concentration of the air sample. The CO_2 concentration of the air sample (ppm by volume of dry air) was obtained from analyzer responses for the sample and standard gases, assuming a quadratic relationship between the CO_2 concentration and the analyzer response. The concentrations of working standard gases were determined before and after their use with a precision of ±0.01 ppmv by comparing them with our secondary standard gas system to confirm that any drifts in concentration were less than ±0.1 ppmv. The secondary standard gases were determined at least twice each year using the primary standards. The primary standards were prepared gravimetrically with an uncertainty of ±0.13 ppmv. The overall precision of our flask analyses was ±0.1 ppmv.

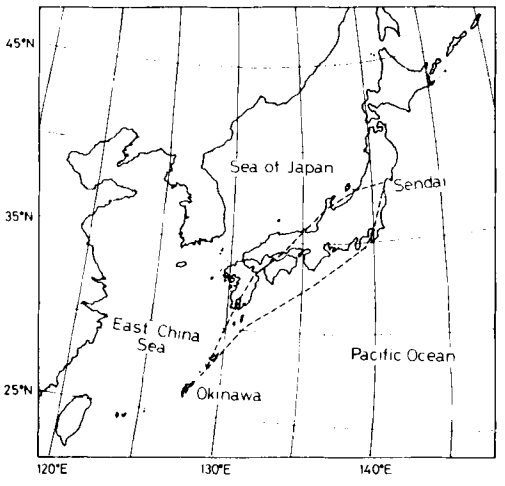

Fig. 1. Flight routes of the B737 aircraft used for the collection of air samples.

3. Results and discussion

To examine the variations of the upper tropospheric CO_2 for different latitudes, the data collected at altitudes between 8 and 10 km were averaged after being grouped into 3 latitude intervals of 26°–30°, 30°–34° and 34°–38°N. Some anomalous data with unexpectedly low CO_2 concentrations, as seen in Fig. 2, have been excluded. Such data were sometimes observed, especially over the northern part of Japan in winter, as a result of an intrusion of the stratospheric air through the tropopause gap near the jet stream. A similar phenomenon was also found by Shapiro (1980) from measurements of atmospheric O_3 and condensation nuclei. The average values of the CO_2 concentration thus obtained are plotted in Fig. 3.

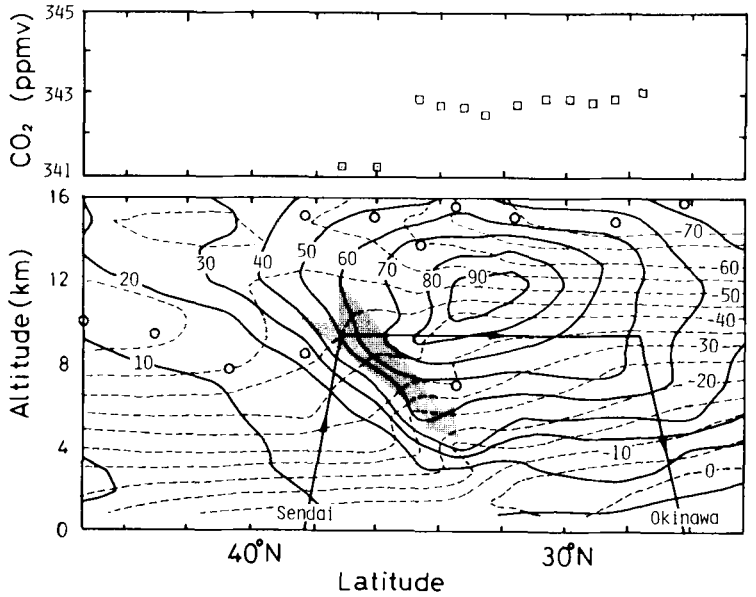

Fig. 2. Horizontal distribution of the upper tropospheric CO_2 concentrations on 29 January 1984 over the Japanese Islands (upper panel) and cross-sectional representation of wind speed and temperature at 0000 GMT (lower panel). Squares represent individual flask values, solid lines the wind speed (m s^{-1}), dashed lines the temperature (°C), solid line with arrows the flight level and circles the tropopause heights defined thermally. Air samples were taken between 0050 and 0320 GMT.

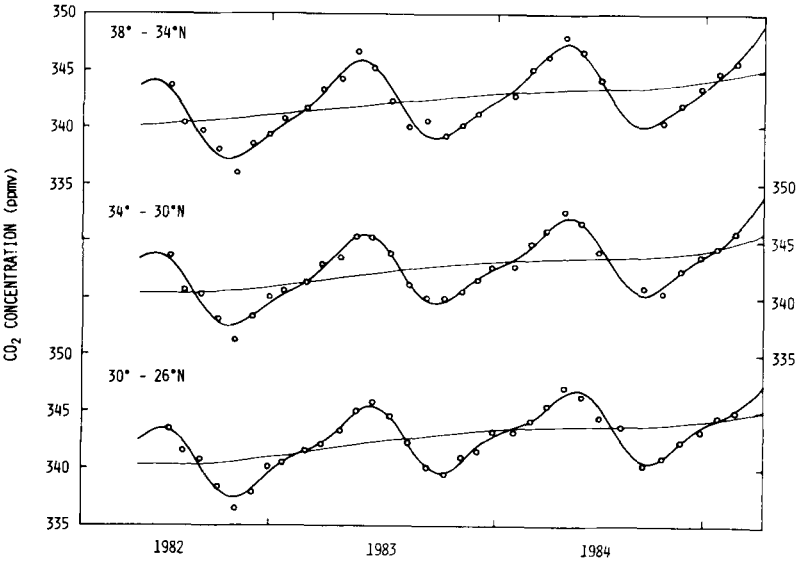

Fig. 3. Variations of the upper tropospheric CO_2 concentrations over the Japanese Islands. Circles represent average values of the measured concentrations, thick lines the best fit curves to the data and thin lines the seasonally adjusted values. Average monthly standard deviations of the data are 0.37, 0.45 and 0.46 ppmv for latitudes 26°–30°, 30°–34° and 34°–38° N, respectively.

Fig. 3 shows clearly the seasonal variation and the trend of secular increase of the CO_2 concentration. To separate these components, we fitted the observed values to the sum of Fourier harmonics and cubic splines with 12-month nodes by an iterative procedure, as

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

where t is the elapsed time (in years) relative to January 1, 1982, C_i's are parameters to be determined and $\tau(t)$ is the spline function. The harmonic component and spline were fit alternately, first one and then the other until the minimum residual was obtained. To examine for possible end effects of this type of spline fit (Enting, 1986), the present results were compared with those of the Reinsch-type spline (Reinsch, 1967; Bacastow, 1976). Results of this comparison showed very good agreement, with the largest differences being ± 0.1 ppmv over the 1 or 2 data points at the ends of the record.

The results thus obtained showed that the seasonally adjusted CO_2 concentration increased gradually in 1982, rapidly in 1983 and rather slightly in 1984 for all latitudes, as shown in Fig. 3. Similar behavior was also observed in the lower troposphere over the Pacific Ocean and in the Antarctic region (Tanaka et al., 1987b, c). This fluctuation in the rate of annual increase is thought to be a global phenomenon, and it may be related to the El Niño event which occurred between 1982 and 1983 (Bacastow, 1976; Bacastow et al., 1980; Bacastow and Keeling, 1981; Thompson et al., 1986).

Annual mean values of the CO_2 concentration measured for the latitudes of 26°–30°, 30°–34° and 34°–38° N were respectively 342.5, 342.3 and 342.3 ppmv in 1983 and 343.8, 343.7 and 343.6 ppmv, in 1984, showing little dependence on the latitude. As shown in Table 1, these values are also in good agreement with the results of our aircraft measurements over the Japanese main island (Tanaka et al., 1987a), where the annual mean values found were 342.1 ppmv in 1983 and 343.6 ppmv in 1984.

The average seasonal variations of CO_2 in the upper troposphere over the Japanese Islands are shown in Fig. 4 in latitude intervals as deviations from annual mean values. The seasonal variation in the northern latitudes is larger and its phase

Table 1. *Annual mean CO_2 concentrations (ppmv) over the Japanese Islands in 1983 and 1984*

Location	Altitude	1983	1984
38°–34° N	8–10 km	342.3	343.6
34°–30° N	8–10 km	342.3	343.7
30°–26° N	8–10 km	342.5	343.8
Over the Japanese main island	8 km-tropopause	342.1	343.6
	8–10 km	342.4	343.9
Over Okinawa	~5.2 km	342.8	344.4
	~0.6 km	344.2	346.0

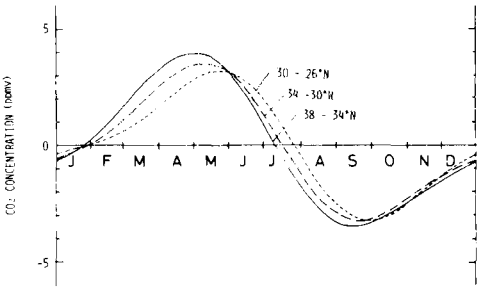

Fig. 4. Average seasonal variations of the upper tropospheric CO_2 concentration over the Japanese Islands.

leads as compared with those in the southern latitudes, reflecting the biospheric activities in the mid and high latitudes of the northern hemisphere. The maximum and minimum concentrations appear in early May and in mid-September, respectively, at latitude 34°–38° N and late May and late September at latitude 26°–30° N. The peak-to-peak amplitude decreases gradually from 7.5 to 6.5 ppmv with decreasing latitude. The present seasonal variation in latitude interval, 34°–38° N, is also in excellent agreement with that obtained over the Japanese main island as an average for the last 6 years (Tanaka et al., 1987a).

Fig. 5 shows the variation of the tropospheric CO_2 concentration over Okinawa. The values for the altitude of 8–10 km are averages of all data taken around 27° N, and those for the altitudes of 5.2 and 0.6 km were obtained by averaging the two samples collected at each altitude on the round-trip flight. In a few cases, concentration differences of more than 2 ppmv were found

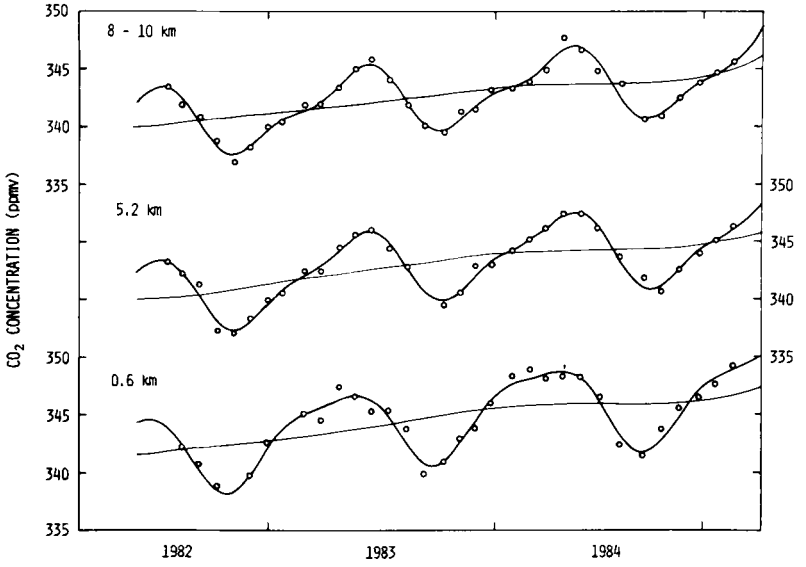

Fig. 5. Variations of the tropospheric CO_2 concentrations over Okinawa, Japan. Circles represent average values of the measured concentrations, thick lines the best fit curves to the data and thin lines the seasonally adjusted values. Average monthly standard deviations of the data are 0.47, 0.36 and 0.27 ppmv for altitudes 0.6, 5.2 and 8–10 km, respectively.

between two values for a given altitude. In such cases, the value closer to a fit through adjacent data was selected.

The seasonally adjusted CO_2 concentrations were derived using the same fitting procedure as before and are shown in Fig. 5. The trends of secular increase for the respective heights coincide closely with each other, and with those in the upper troposphere over the Japanese Islands mentioned before. Annual mean values of the CO_2 concentration in 1983 were found to be 342.4, 342.8 and 344.2 ppmv for the upper, middle and lower troposphere, respectively. Corresponding values in 1984 were 343.9, 344.4 and 346.0 ppmv. These values are also summarized in Table 1. The vertical profile of the annual mean CO_2 concentration was almost the same in these two years. The lower tropospheric value is higher than the middle by about 1.5 ppmv and higher than the upper tropospheric values by about 2 ppmv. Such a profile is quite similar to that found previously over the Japanese main island (Tanaka et al., 1983a, 1987a), but is in contrast to that in the southern hemisphere (Pearman and Garrett, 1973; Pearman and Beardsmore, 1984).

Present values in the lower troposphere are higher by about 0.5 ppmv than those measured in latitude 25°N on the Pacific Ocean aboard a container ship (Tanaka et al., 1987c). The cause may be attributed to the difference in prevailing air masses. According to surface wind analysis by Wyrtki and Meyers (1975), the air over Okinawa comes from the Chinese Continent or the Japanese main island for the period September to May and from the low latitudes for the remaining periods. Air masses are transported over Okinawa from latitudes with higher CO_2 concentration for both periods (Komhyr et al., 1985; Tanaka et al., 1987b). On the other hand, the location where the ship measurements were made is covered with air masses coming zonally from the eastern part of the North Pacific Ocean for 8 months of the year, and with those originating in the Chinese Continent or the Japanese Islands only for the period December–March.

The average seasonal variations of the tropospheric CO_2 concentration over Okinawa are shown in Fig. 6, as deviations from the annual mean values for the respective heights. The seasonal variation in the lower troposphere reaches a maximum in late April and a minimum in mid-

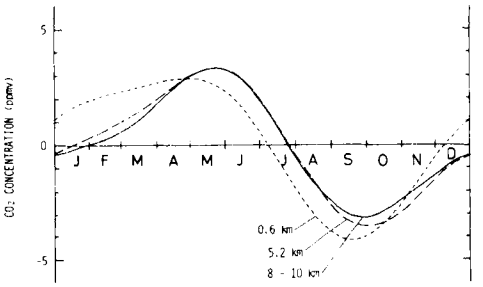

Fig. 6. Average seasonal variations of the tropospheric CO_2 concentration over Okinawa, Japan.

September, and its phase is advanced by 15 days more than those in the middle and upper troposphere. The peak-to-peak amplitude decreases slightly with increasing height, i.e., from 7 to 6.5 ppmv. The seasonality in the upper tropospheric CO_2 concentration is consistent with that in latitude interval 26°–30° N mentioned before.

Taking into account the vertical profile of the annual mean CO_2 concentration, it is obvious that the CO_2 concentration always decreases upward, but such a vertical gradient almost disappears for the period from June to September.

We have shown from our aircraft measurements over the Japanese main island (Tanaka et al., 1987a) that the seasonal variation of the tropospheric CO_2 decreases in amplitude from 14.5 to 7.8 ppmv with increasing height, the phase difference between the upper and lower troposphere is about 1 month, and the CO_2 concentration increases upward for the period from June to September and decreases during the rest of the year. A comparison of these results shows that variations of the CO_2 over Okinawa are considerably different, especially in the lower troposphere. This difference may be attributed to the difference in biospheric activities between the temperate and subtropical zones. The transport of air from other latitudes plays a much more important rôle in the temporal variations of tropospheric CO_2 over Okinawa, where the seasonality of biospheric activities is rather weak and alternation of air masses is enhanced strongly by the monsoonal activity.

4. Acknowledgements

We express our gratitude to many crew and ground staffs of the All Nippon Airways, Japan for their cooperation in the collection of air samples. This work was supported by the Grant in Aid of Scientific Research from the Ministry of Education, Culture and Science, Japan.

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