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Atmospheric carbon dioxide variations in the suburbs of Sendai, Japan

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ABSTRACT

The concentration of atmospheric CO_2 was measured continuously in the suburbs of Sendai, Japan for the period December 1978–June 1981. The diurnal CO_2 variation was greatest in July and August and was barely observable during the cold months from November to April. The seasonal CO_2 variation was highly irregular and a decrease of CO_2 concentration with height was found throughout the year, presumably reflecting a substantial influence of local soil respiration. Daily minimum values of CO_2 concentration, however, showed a fairly regular seasonal trend and an average rate of CO_2 increase of 1.6 ppmv yr^{-1}, which are very close to the results of our aircraft measurements in the lower troposphere for the same period.

1. Introduction

Measurements of atmospheric CO_2 concentration have been made at various places with different natural or anthropogenic situations, not only to monitor the global CO_2 increase in the atmosphere but also to elucidate the CO_2 exchange between atmosphere and biosphere or oceans. Recent measurements in areas remote from local CO_2 sources and sinks indicate a continuous increase in CO_2 concentration at the rate of 1–2 ppmv per annum (Lowe et al., 1979; Bacastow and Keeling, 1981; Bischof, 1981; Pearman, 1981; Peterson et al., 1982; Tanaka et al., 1983a). The cause is thought to be human activities such as combustion of fossil fuels and deforestation (Keeling, 1973; Bolin, 1977; Woodwell et al., 1978; Rotty, 1983). Superimposed on the secular increase is a seasonal CO_2 variation which is primarily ascribed to photosynthesis by land plants in the warm season and respiration by land plants and soil throughout the year (Pearman and Hyson, 1980). The amplitude of seasonal variation decreases and its phase lags with height through the troposphere and into the stratosphere (Bolin and Bischof, 1970; Bischof, 1973; Tanaka et al., 1983a). The amplitude also depends on latitude (Fraser et al., 1983). The concentration of atmospheric CO_2 over vegetated areas also shows a diurnal variation, especially during the growing season, in response to day-time uptake of CO_2 by photosynthesis of plants and night-time release by respiration of plants and soil. The amplitude of diurnal variation is greatest in or just above the vegetation canopy and decreases rapidly with height (Pearman and Garratt, 1973; Verma and Rosenberg, 1976).

In this paper, we report the result of measurements of CO_2 concentration made in a hilly suburban district of Sendai, Japan for the period December 1978–June 1981. The results are presented in terms of 3 characteristic variations described above.

2. Observation site and experimental procedures

Measurements were made at Aobayama (38°15′N, 140°50′E; altitude 150 m above sea level) in the suburbs of Sendai located in the northeast part of the main island of Japan (Fig. 1). Sendai is a typical commercial city with a population of about 650,000. There are urban and rice-producing areas between the station and the

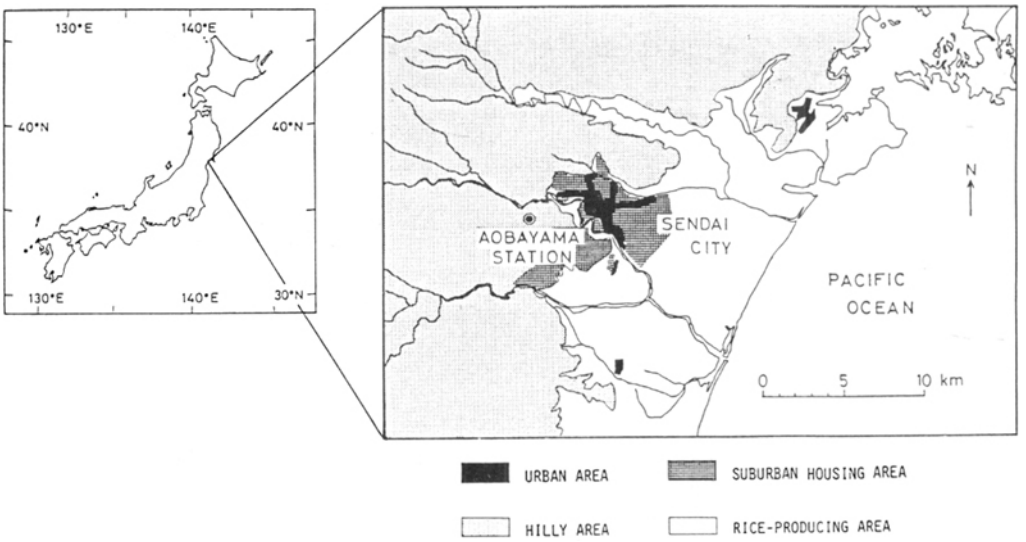

Fig. 1. Location of the Aobayama atmospheric CO_2 sampling site and land use of the region around the station.

Pacific Ocean. The area in the other direction from the station is a hilly district, the ground surface being moderately rolling. The vegetation in the vicinity consists mostly of deciduous shrubs and partly of evergreen needle-leaf trees, such as pine. Several laboratory buildings are scattered near the station and a roadway with little traffic passes through the site. Seasonal prevailing winds are northwesterly or westerly in winter and southerly in summer. However, the wind in summer is usually very weak and often shows a regular diurnal variation, i.e. alternation from sea breeze to land breeze and vice versa. Monthly-averaged air temperatures reach a minimum of 0 °C in January and a maximum of 24 °C in August.

Details of our CO_2 measurement have been published (Tanaka et al., 1983b). Therefore, only a brief description is given here. The concentration of atmospheric CO_2 was measured by a non-dispersive infrared analyzer manufactured by Hitachi-Horiba Co., Japan and improved by ourselves to attain a precision of better than ± 0.1 ppmv. The inlet of the analyzer was separated into 12 channels by solenoid valves; 4 channels were allotted to standard gases and the remaining to air samples. Solenoid valves were switched successively once every 3 min, allowing a flow of air sample or standard gas of 500 ml min^{-1} through the analyzer. Air samples were taken at 2 heights. The 1st was at approximately 10 m above the rooftop of a laboratory building of 20 m height, i.e. at a height of 30 m above the ground. The second was at a height of 0.5 m above a naked field about 50 m distant from the building. Water vapor was removed from air samples by two glass traps cooled at 0 °C and −30 °C. Because our analyzer utilized only the 4.3 μm CO_2 band by inserting interference filters, optical contaminations due to residual water vapor were negligibly small. Scaling of the concentration of CO_2 in ppm by volume of dry air would be affected by about 0.1 ppmv by the remaining water vapor.

Standard gases used were mixtures of CO_2 in air with concentrations of approximately 300, 350, 400 and 450 ppmv, calibrated with uncertainties of ± 0.1 ppmv against our secondary standard gases. The secondary standard gases were calibrated against the primary standard gases prepared by the gravimetric method. The absolute accuracy of our standard gas system was estimated to be ± 0.3 ppmv. The CO_2 concentration of each air sample was determined from analyzer responses for the air sample and standard gases by Lagrange's interpolation formula.

Concurrent measurements of air temperature and wind velocity and direction were also made by using a shielded and aspirated thermistor–thermometer and a sonic anemometer, respectively. The

output signals of the CO_2 analyzer, together with those of meteorological instruments, were recorded digitally on the paper tape as well as on the stripchart serving as back-up.

3. Results and discussion

As shown in Fig. 2, the diurnal CO_2 variation is enhanced in the warm season, especially in July and August and only small variations are found during the period of November to April, i.e. the cold season with monthly-averaged air temperature of lower than 10 °C. In the warm season, the diurnal CO_2 variation has its minimum in the afternoon and maximum in the early morning, reflecting day-time uptake of CO_2 by photosynthesis of plants and night-time release through plant and soil respiration. The situation in the cold season, on the other hand, is somewhat different from that in the warm season; weak maximums (or minimums) of the CO_2 concentration are found twice a day, just after sunset and before noon (or in the afternoon and before sunrise). The fact that the land near the observation site had recently been cleared for constructing laboratory buildings appears to be important for the explanation of such a phenomenon. In general, soil respiration is activated with soil temperature. Therefore, the release of CO_2 by soil respiration is more enhanced in the day-time than in the night-time, but photosynthetic fixation of CO_2 by plants exceeds the effect of soil respiration in the afternoon. A slightly low concentration in the night-time may be attributed to the transport of air free from such local soil respiration. The night-time airmass near the foot of the hill often ascends by atmospheric convection after sunrise, when seasonal prevailing winds calm down. This phenomenon may also be responsible for the high concentration before noon.

Monthly mean values of the CO_2 concentration measured in this study are shown in Fig. 3, together with corresponding values of aircraft measurements in the lower troposphere over the station for the same period (Tanaka et al., 1983a). Variations in the CO_2 concentration near the ground are highly irregular and their phases are opposite to that in the lower troposphere. It is also seen that CO_2 concentrations at ground levels are always higher than in the lower troposphere. This is inconsistent with results of our aircraft measurements, indicating that the ground surface generally acts as a sink of atmospheric CO_2 for the period from June to September. The cause of this discrepancy should be ascribed to local sources of CO_2. In this respect, it is noted that the present observation site is not sufficiently remote from urban and suburban areas of Sendai; the distance between the site and the closest housing area is only 3 km. To examine the influence of anthropogenic sources of CO_2 in these housing areas on the measured values of CO_2 concentration, the data

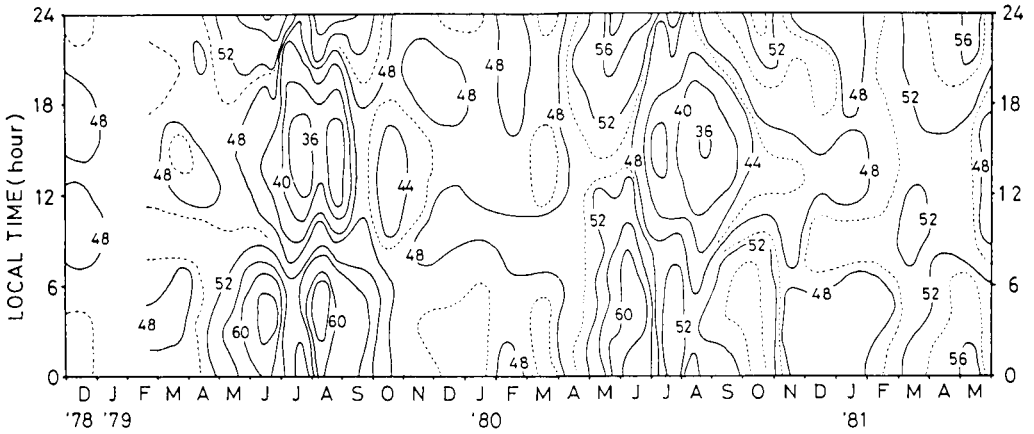

Fig. 2. Diurnal CO_2 variation at a height of 30 m above the ground. Values for the CO_2 concentration are shown as deviations from 300 p.p.m.v. The data used to prepare the diagram are half-month means of hourly mean CO_2 concentrations.

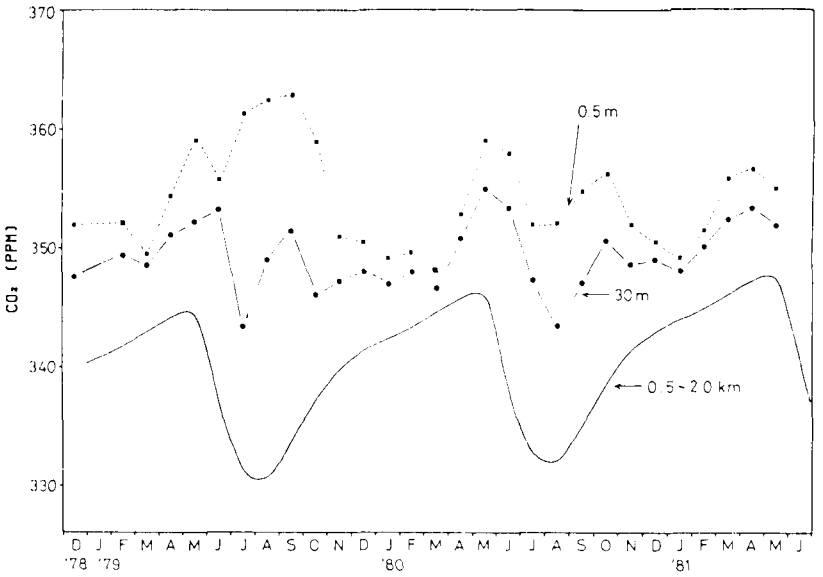

Fig. 3. Monthly mean CO_2 concentrations (p.p.m.v.) at heights of 0.5 m (solid squares) and 30 m (solid circles) above the ground. Also shown is an average CO_2 variation in the lower troposphere over this region (solid curve).

obtained at the 30 m height were also classified according to the wind direction as carried out by Woodwell et al. (1973) for Long Island CO_2 data. However, no clear evidence was found for systematic dependence of the CO_2 concentration upon the wind direction. This result suggests that the variability of CO_2 concentration is affected mainly by extremely local sources very near the station. From the facts that the maximum concentration of CO_2 occurred in summer and that CO_2 concentrations were always higher at ground level than at the 30 m height, excess soil respiration due to reclamation of woodland is strongly suggested as a possible cause of such local contamination. The concentration dip in the summer of 1980 may be attributed to inactive soil respiration due to abnormally cool weather. Monthly-averaged air temperatures in July and August 1980 were lower by almost 5 °C than those in normal years. The influence of such a local effect decreases with increasing the wind velocity, as seen in Fig. 4. However, the amplitude of the seasonal CO_2 variation for mean wind velocities 5–7 ms^{-1} is still smaller by about 2 ppmv, and the corresponding annual mean value of the CO_2 concentration is higher by about 7 ppmv, as compared with the results of aircraft measurements.

Daily minimum values of the CO_2 concentration measured at the 30 m height are plotted in Fig. 5. The day-to-day variation is still of considerable extent in the warm season, though its magnitude is greatly reduced as compared with that for all available data. It is also seen that the increasing trend of CO_2 from the summer minimum to the spring maximum temporarily remains in December and January. This phenomenon is often seen in the middle and high latitudes of the northern hemisphere and is attributed to inactive respiration of plants and soil in these coldest months (Ajtay et al., 1979).

As mentioned before, the air near the station is rich in CO_2 throughout the year due to a substantial influence of extremely local sources of CO_2. Taking account of this fact, daily minimum values of CO_2 concentration are expected to closely represent the CO_2 level in the surrounding region free from the local contamination. We therefore fitted the daily minimum values with a time-dependent function including a linear and Fourier-harmonic terms for respective contributions of the secular increase and the seasonal variation:

$$X(t) = C_1 \sin 2\pi t + C_2 \cos 2\pi t + C_3 \sin 4\pi t + C_4 \cos 4\pi t + C_5 + C_6 t, \quad (1)$$

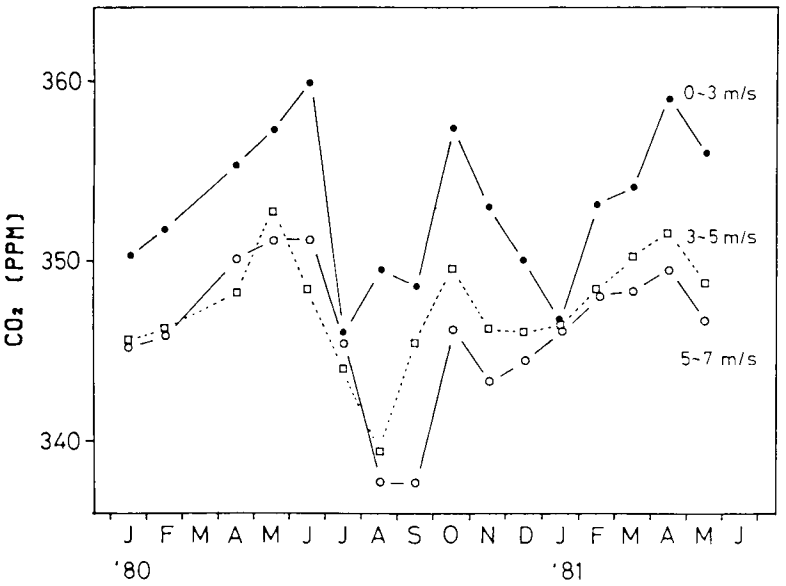

Fig. 4. Monthly mean CO_2 concentrations (p.p.m.v.) at a height of 30 m above the ground as classified according to the value of 10-min mean wind velocity.

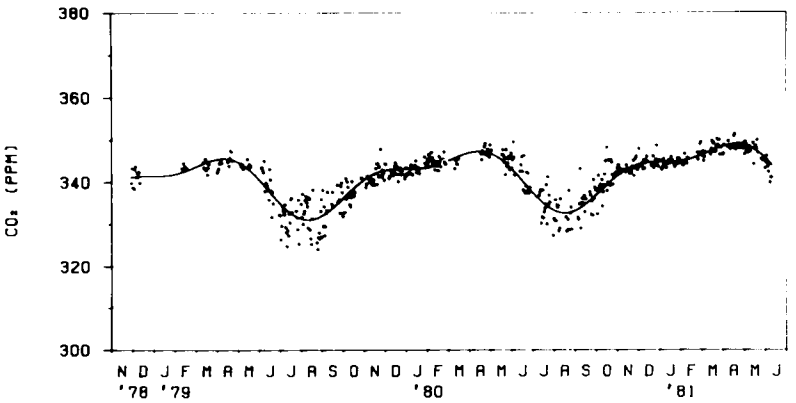

Fig. 5. Daily minimum CO_2 concentrations (p.p.m.v.) at a height of 30 m above the ground (dots). Solid curve represents a least square fit of eq. (1) to observed daily minima.

where X denotes the CO_2 concentration in ppmv and t is the elapsed time (in years) relative to December 1, 1978. The harmonic frequencies in the above equation were estimated from a spectral analysis of daily minimum values for the period June 1979–June 1981 by the maximum entropy method (Burg, 1967). Since the algorithm required equally spaced data, lack of observation was supplemented by linear interpolation from contiguous data. As seen in Fig. 6, the harmonics significantly contributing to the seasonal CO_2 variation were only the fundamental annual cycle and its first harmonics. A least-square fit of eq. (1) to the daily minimum values yielded the coefficients: $C_1 = 6.21$, $C_2 = 0.71$, $C_3 = -2.31$, $C_4 = 1.71$, $C_5 = 338.69$ ppmv and $C_6 = 1.62$ ppmv yr^{-1}, with standard deviation of 2.38 ppmv. An average rate of increase in atmospheric CO_2 concentration during this study was therefore approximately 1.6 ppmv yr^{-1}, which is very close

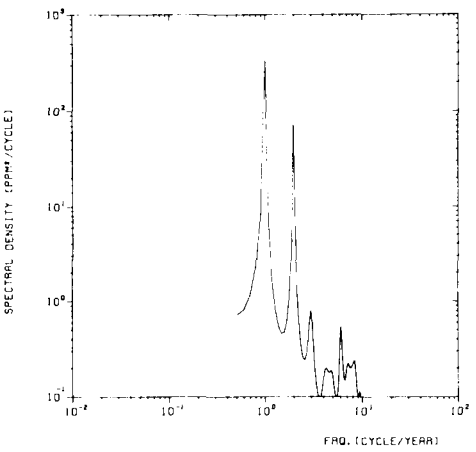

Fig. 6. Power spectrum of daily minimum CO_2 concentrations observed at a height of 30 m the ground for the period June 1979–June 1981.

to the value of 1.5 ppmv yr^{-1} obtained from aircraft measurements for the same period (Tanaka et al., 1983a). The seasonal CO_2 variation was also nearly consistent with that in the lower troposphere over this region; the amplitude is about 15 ppmv, and the maximum and minimum concentrations occur in mid-April and in early August, respectively. The data adjusted to the datum of January 1, 1979 indicated an annual mean concentration of 338.8 ppmv, which is higher by 0.9 ppmv than the corresponding value of the lower troposphere.

4. Conclusions

Continuous measurements of atmospheric CO_2 were carried out at a hilly suburban district of Sendai, Japan for the period December 1978–June 1981. The temporal variability of CO_2 concentration was found to be much larger than baseline measurements, reflecting strong influences of local sources of CO_2 as well as CO_2 exchange between atmosphere and vegetation cover. The diurnal variation was noticeable during the growing months from May to October and was barely observable out of this season. The daily maximum and minimum concentrations of CO_2 during the growing season occurred early in the morning and in the afternoon, respectively. These features are those typical for continental sites. The seasonal variation was highly irregular; the annual cycle of the CO_2 concentration varied considerably year after year and its phase was opposite to that in the lower troposphere over the station. In addition, monthly mean values of the CO_2 concentration were largest at ground level, decreasing with height into the lower troposphere, even for the growing months. These features were attributed to local contamination due presumably to excess soil respiration very near the station. Of interest is the fact, in spite of the considerable daily and seasonal variabilities, that daily minimum values of the CO_2 concentration showed fairly reasonable seasonal cycle and long-term trend values which are very close to the result of aircraft measurements in the lower troposphere.

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