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Longitudinally different variations of lower tropospheric carbon dioxide concentrations over the North Pacific Ocean

By TAKAKIYO NAKAZAWA, SHOHEI MURAYAMA, KOHJI MIYASHITA*, SHUHJI AOKI** and MASAYUKI TANAKA, *Center for Atmospheric and Oceanic Studies, Tohoku University, Sendai 980, Japan*

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ABSTRACT

To elucidate temporal and spatial variations of the atmospheric CO_2 concentration over the North Pacific Ocean, air samples have been collected systematically using 4 container ships for 3 years from 1984 to 1986. The seasonal CO_2 cycle was most enhanced at high latitudes and decreased gradually going southward with a phase delay. North of 30° N, the seasonal amplitude was larger in the western part than in the eastern part; however, to the south the situation was reversed. The southward phase shift of the seasonal CO_2 cycle was much reduced in the eastern part, as compared with that in the western part. In the western part, the annual mean values of the CO_2 concentration in respective years were high at middle latitudes and decreased going southward and northward; those in the eastern part were rather constant at middle and high latitudes, but increased slightly with decreasing latitude. As a result, yearly mean CO_2 concentrations between 50° and 25° N were always higher in the western part than in the eastern part and those at lower latitudes showed the opposite distribution. Differences of the CO_2 concentration between the eastern and western parts depended on season and latitude.

1. Introduction

Systematic measurements of the atmospheric CO_2 concentration were begun by C. D. Keeling at Mauna Loa, Hawaii in 1958 and the South Pole in 1957 (Keeling et al., 1976a, b), and have been extended to many places around the world during the last 34 years. The data from these measurements have established a rapid increase of the atmospheric CO_2 concentration due to fossil fuel combustion in the developed countries in the northern hemisphere and deforestation mainly in the tropical region (Houghton and Woodwell, 1989). However, respective contributions to the present CO_2 increase are not yet quantitatively well understood, which makes it difficult to predict future levels of the atmospheric CO_2 concentration. To solve this problem, it is necessary to elucidate the carbon cycle on the earth's surface. For this purpose, a knowledge of atmospheric CO_2 variations is indispensable (Pearman and Hyson, 1980, 1986; Fung et al., 1983; Gillette and Box, 1986; Heimann and Keeling, 1986, 1989; Keeling and Heimann, 1986; Tans et al., 1989, 1990; Keeling et al., 1989a, b; Heimann et al., 1989; Enting and Mansbridge, 1991), and the establishment of a comprehensive and close-knit station network for background monitoring of the atmospheric CO_2 concentration is needed. The present network consists mainly of fixed stations on land. Further measurements, especially with ships and aircraft, are therefore required for painting a more detailed global picture of the atmospheric CO_2 variations.

We have started a systematic collection of air samples on board a commercial container ship between Yokohama, Japan and Melbourne, Australia in 1982 (Tanaka et al., 1987a). In addition to this measurement, air samples were also collected over the North Pacific Ocean using

* Present affiliation: Japan Weather Association, Kita 4-Nishi 23–260, Chuoh, Sapporo 064, Japan.

** Present affiliation: National Institute of Polar Research, 1–9–10 Kaga, Itabashi, Tokyo 173, Japan.

3 container ships sailing between Tokyo, Japan and Seattle or San Francisco, USA, and between Tokyo and New York, USA for the period of 1984 to 1986.

In this paper, we will report the results of these shipboard measurements and discuss temporal and spatial variations of the lower tropospheric CO_2 concentration over the North Pacific Ocean.

2. Measurements

In this measurement, 4 container ships (Hyogo-Maru, Hakone-Maru, Kiso-Maru and Kurobe-Maru) were used for the collection of air samples over the North Pacific Ocean, and their typical cruise tracks are shown in Fig. 1. Details of the air sampling on board Hyogo-Maru, which sailed repeatedly between Yokohama and Melbourne, have been described by Tanaka et al. (1987a). In this study, observations taken at 33°N and every 5 degrees between 30° and 10°N once every 2 weeks or so were used to derive the CO_2 concentration variations in the western part of the North Pacific Ocean. Hakone-Maru repeated a round trip approximately every 25 days between Tokyo and Seattle from April 1984 to March 1986, and between Tokyo and San Francisco for the remaining period. Kiso-Maru and Kurobe-Maru sailed approximately every 50 days between Tokyo and New York. Air samples were obtained at latitudes of 40°, 45° and 50°N in the western hemisphere and at longitudes of every 10 degrees between 170°W and 130°E on board Hakone-Maru, and at every 5 degrees between 40° and 10°N in the eastern hemisphere on board Kiso-Maru and Kurobe-Maru. The numbers of air samples collected and analyzed for the period of 1984–1986 were 328, 454, 161 and 158 for Hyogo-Maru, Hakone-Maru, Kiso-Maru and Kurobe-Maru, respectively.

Air samples were brought into the cabin from the intake set on the windward side of the bridge, approximately 25 m above the sea surface, and filled into 550 ml Pyrex glass flasks at an over-pressure of 2.0×10^5 Pa by using an electric diaphragm pump. The flasks were washed sufficiently in an ultra-sonic bath with purified water, dried by passing N_2 gas through them and then evacuated to lower than 1.3×10^{-1} Pa at approximately 100°C for 3 h before their use. The flasks filled with air samples were returned to our laboratory, and their CO_2 concentrations were determined using a non-dispersive infrared

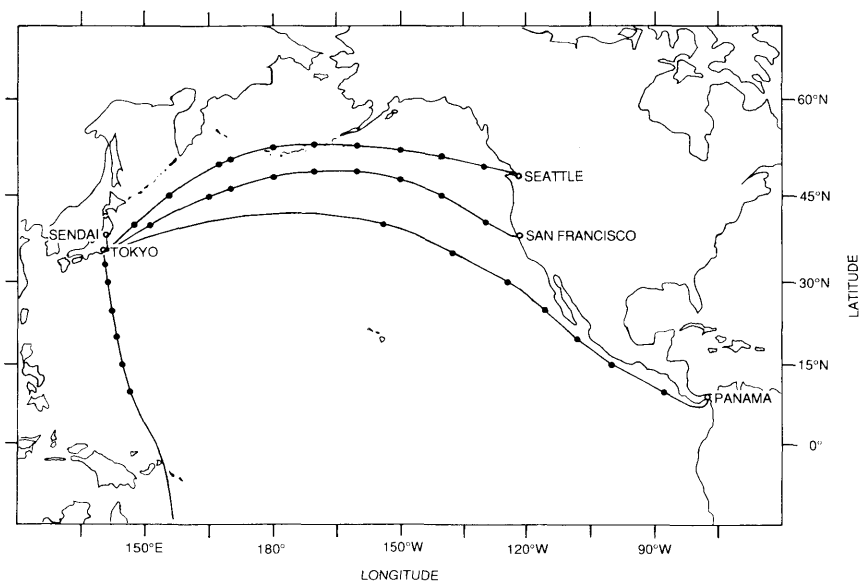

Fig. 1. Typical cruise tracks of Hakone-Maru, Kiso-Maru, Kurobe-Maru and Hyogo-Maru. Solid circles represent the approximate locations where air samples were collected.

analyzer with a precision of 0.01 ppmv and 3 or 4 working standard gases. The CO_2 concentrations of the working standard gases were chosen such as to span the entire range of the air sample concentrations. Water vapor was removed from the air samples by 2 glass traps cooled at $-78°C$. As a result of laboratory experiment with dry standard gases (Tanaka et al., 1987b), the measured values of the CO_2 concentration were corrected for the possible deterioration of the air samples stored in the flasks between sampling and subsequent analysis. The correction ranged between 0.2 and 0.4 ppmv.

The CO_2 concentrations of the working standard gases were calibrated with the above-mentioned analyzer against our secondary standard gas system at least before and after their use. The secondary standard gases were calibrated once or twice a year, using our primary standards prepared gravimetrically with uncertainties of 0.13 ppmv (Tanaka et al., 1987b). By these calibration procedures, we confirmed that any concentration drifts of the working standard gases used for this measurement were less than 0.05 ppmv. Our concentration scale of the standard gases was developed independent of the WMO mole-fraction scale, which is widely used in measurements of the atmospheric CO_2 concentration. In 1987, 4 standard gases with different CO_2 concentrations of approximately 331, 339, 351 and 366 ppmv were calibrated by using the manometric system installed at Scripps Institution of Oceanography, University of California, San Diego, and it was confirmed that their determined values agree with ours within 0.1 ppmv.

3. Results and discussion

The CO_2 measurements from the ship cruises are plotted in Fig. 2, together with those from our aircraft measurements in the height interval of 0–1 km above the Pacific Ocean off the coast of Sendai, as well as monthly values of the CO_2 concentration at Pt. Barrow, Alaska for the same period (Tanaka et al., 1987c; Schnell, 1987). Since Hakone-Maru sailed between 45° and 55°N in the northern part of the Pacific Ocean, depending on weather conditions, the data in these latitudes were grouped into two longitude intervals of 160°W–160°E and 160°–130°E to examine longitudinally different behavior of the atmospheric CO_2 concentration in this region. Kiso-Maru and Hakone-Maru sometimes reached 40°N in the western hemisphere. Therefore, the data at 40°N to the east of 160°E and those at 35°N are plotted as 38°N in Fig. 2. The data taken aboard Hakone-Maru off the coast of San Francisco for the period of April–December 1986 also supplement this data set. Several air samples collected at 10°N in the eastern part of the Pacific Ocean showed remarkably low CO_2 concentrations, especially in winter and spring when the CO_2 concentration at low latitudes is higher in the northern hemisphere than in the southern hemisphere, as seen in Fig. 2. The Intertropical Convergence Zone (ITCZ) is usually located at 5°N in this region and moves northward and southward with season (Oort, 1983). Since rapid air exchange between the northern and southern hemispheres is hindered by ITCZ, these low CO_2 concentration values can probably be attributed to outbreaks of southern hemispheric air. Therefore, we excluded such samples from the data set. The same phenomenon was also observed by Tanaka et al. (1987a) near the South Pacific Convergence Zone (SPCZ) in the western part of the Pacific Ocean.

A digital-filtering technique was used to separate the respective contributions of the seasonal cycle and the increasing trend of the CO_2 concentration from the observed data. The technique has been outlined by Nakazawa et al. (1991a). However, the technique was somewhat modified in this study; in iterative procedures, linear interpolation was used instead of the Reinsch-type cubic spline to calculate daily mean values of the CO_2 concentration from the data, in order to avoid overfitting to a noisy record with low data density. The average seasonal CO_2 cycle was first approximated by an annual cycle consisting of the fundamental and its first and second harmonics, and then smoothed by the Butterworth filter with a cutoff period of 4 months at which a signal is attenuated by 50%. In this way signals with higher frequencies than before are included in the average seasonal cycle. In the analysis of the Barrow data, a third harmonic was included in approximating the average seasonal CO_2 cycle, and the Butterworth filter with a cutoff period of 3 months was then used to obtain the best fit curve to monthly mean CO_2 concentrations.

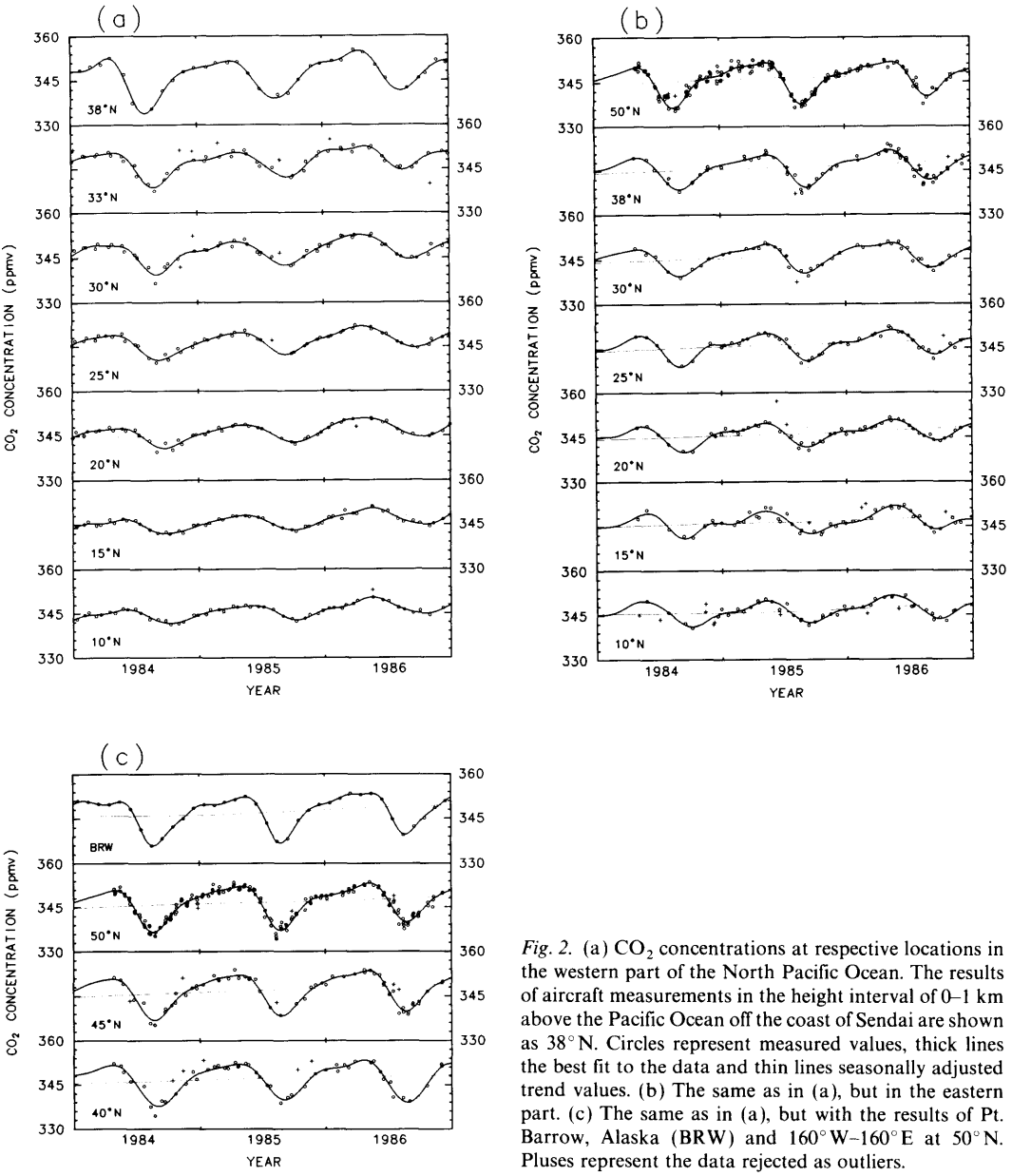

Fig. 2. (a) CO_2 concentrations at respective locations in the western part of the North Pacific Ocean. The results of aircraft measurements in the height interval of 0–1 km above the Pacific Ocean off the coast of Sendai are shown as 38°N. Circles represent measured values, thick lines the best fit to the data and thin lines seasonally adjusted trend values. (b) The same as in (a), but in the eastern part. (c) The same as in (a), but with the results of Pt. Barrow, Alaska (BRW) and 160°W–160°E at 50°N. Pluses represent the data rejected as outliers.

This filtering technique was applied to the time series of measured CO_2 concentrations. Data lying outside 3 standard deviations of the fitted curve were regarded as outliers and rejected from the data set. The procedure was repeated few times for each data set until no further outliers were identified. Several data rejected by this procedure were not used for any further statistical analysis. The smoothed curves to the data and the CO_2 trends, thus obtained, are also shown in Fig. 2.

The average seasonal CO_2 cycles at respective locations are shown in Fig. 3. The seasonal CO_2 cycle is most enhanced at high latitudes and decreases with a phase delay going southward.

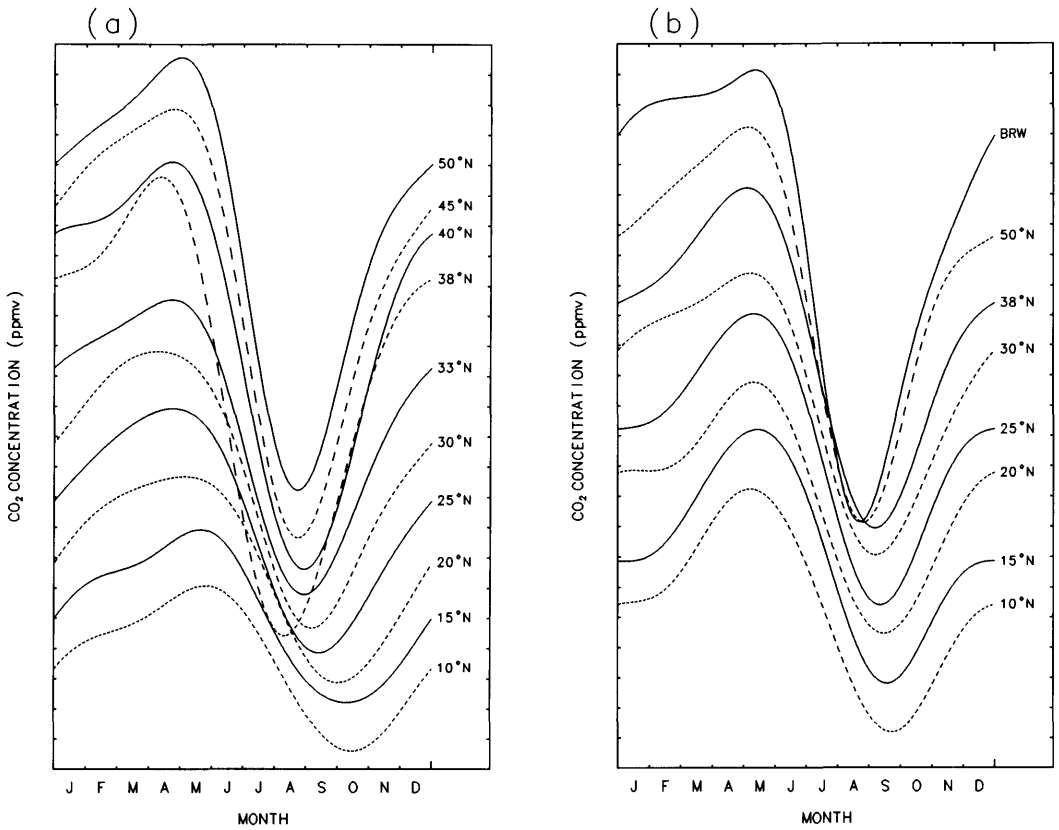

Fig. 3. (a) Average seasonal CO_2 cycles at respective locations in the western part of the North Pacific Ocean. (b) The same as in (a), but for the eastern part. The cycle at Pt. Barrow, Alaska (BRW) is also shown. One division of the ordinate corresponds to 1 ppmv.

Peak-to-peak amplitudes of these cycles are plotted against latitude in Fig. 4. The amplitude is about 15 ppmv at Barrow, and north of 30°N, it is larger in the western part than in the eastern part of the Pacific Ocean; the situation is reversed south of that latitude. Longitudinally different amplitudes are also observed at 50°N, the value being larger by 1.2 ppmv in 160°W–160°E than in 160°–130°E. Such a distribution of the amplitudes could arise from different air transport at the respective sampling locations and their different distances from land. At northern high and middle latitudes, westerly, northwesterly and northerly winds usually prevail, putting the Asian Continent and Japan on the windward side of our sampling locations. This situation is reversed in the summer when the prevailing wind is predominately southerly. The amplitude in the interval 160°–130°E is however somewhat smaller than the average value obtained from measurements at Ocean Weather Station P (50°N, 145°W) for 1969–1981 (Keeling et al., 1985). In this connection, it may be noted that Keeling et al. approximated the average seasonal CO_2 cycle by 4 harmonics. The seasonal amplitude observed near Sendai is apparently larger than those at contiguous latitudes. As seen in Fig. 2, the enhanced decrease of the CO_2 concentration in the summer of 1984 is responsible for the large amplitude at Sendai. Our aircraft measurements over the last 12 years show an average seasonal amplitude of almost 14 ppmv, which is smaller than the above value by about 1 ppmv.

At low latitudes of the western part of the Pacific

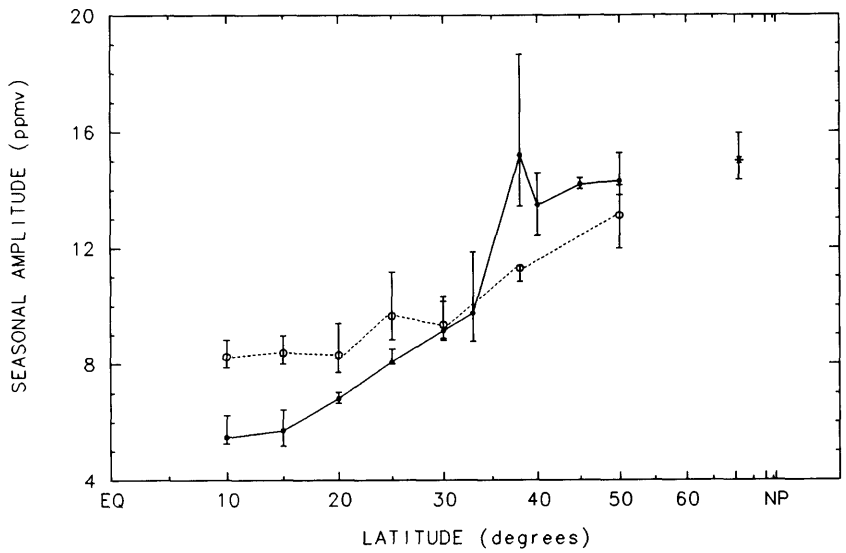

Fig. 4. Latitudinal distributions of the peak-to-peak amplitude of the average seasonal CO_2 cycle in the western (small closed circles with solid line) and eastern parts (open circles with dashed line) of the North Pacific Ocean. The value of the cycle at Pt. Barrow, Alaska (*) is also shown. Vertical bars represent maximum and minimum peak-to-peak amplitudes for 3 years of 1984–1986.

Ocean, maritime air is usually brought in by the easterly trade wind, with the southern hemispheric air with very small CO_2 seasonality intruding for the period of May–November when a monsoon circulation occurs in Southeast Asia (Oort, 1983). Due to the mixing of air from higher latitudes with that from low latitudes, the seasonal CO_2 cycle diminishes with decreasing latitude in this region. On the other hand, the seasonal CO_2 cycle in the eastern part is not reduced as much as in the western part. This can be primarily ascribed to the rapid transport of air from northern high latitudes where the cycle is much larger. Wind directions observed when the air samples were collected on board Kiso-Maru, Kurobe-Maru and Hakone-Maru at respective latitudes between 40° and 10° N for 3 years are shown in Fig. 5. It is seen from this figure that the prevailing wind is almost northerly, especially between 30° and 15° N, due to atmospheric circulation around the high pressure system in the Pacific Ocean off the coast of North America (Oort, 1983). The air originating from Central America may be partly responsible for the fairly large seasonal CO_2 cycles at low latitudes where the easterly wind also occurs regularly.

In the western part of the Pacific Ocean, a discontinuous change of the seasonal CO_2 cycle was

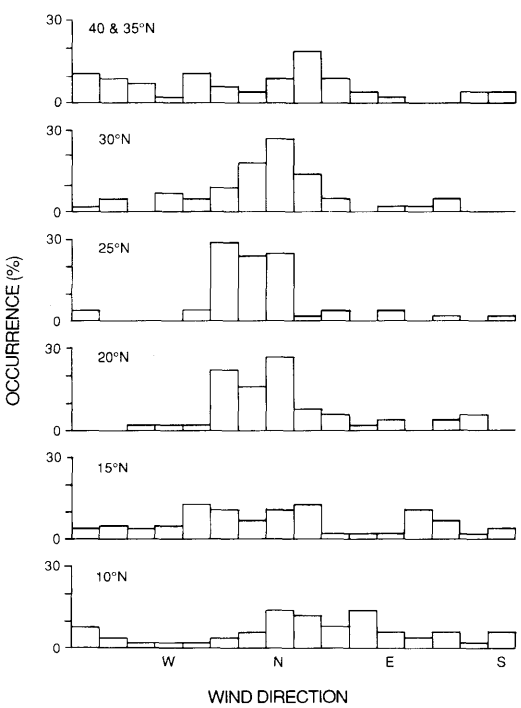

Fig. 5. Occurrence of wind directions observed at respective latitudes in the eastern part of the North Pacific Ocean for the period of 1984–1986.

observed between 5° and 10°S due to the suppression of southward air transport by the SPCZ (Tanaka et al., 1987a). As stated before, the ITCZ in the eastern part of the Pacific Ocean is situated, on average, at 5°N. Therefore, the same change is expected to be observed near that latitude in this region.

The occurrence of maximum and minimum concentrations of the seasonal CO_2 cycle at respective locations are shown in Fig. 6. In the western part of the Pacific Ocean, the maximum concentration appears in mid-April at middle latitudes, and its occurrence is delayed gradually going both southward and northward. The phase shift at low latitudes could result from the transport of air from northern middle and high latitudes, and at high latitudes from a delay of the summer season as well as the transport of air from middle latitudes. Minimum concentrations appear at middle and high latitudes first, with a gradual delay in their occurrence with decreasing latitude due to the transport of air from higher latitudes. The minimum concentration appears in mid-August near Sendai, earlier by about half a month than those at contiguous latitudes, reflecting the fact that the air was sampled in the proximity of land. In the eastern part, the maximum concentration is found at almost the same time of the year as in the western part, i.e., in early or mid-May. This is due to rapid transport of air from northern high latitudes by the northerly prevailing wind. A similar phenomenon is also seen in the phase shift of the minimum concentration.

At 50°N, the CO_2 concentration in the interval 160°W–160°E varies seasonally in phase with that in the interval 160°–130°E. This is in agreement with the result at Station P (Keeling et al., 1985). The seasonal CO_2 cycles at this latitude are similar to that at Barrow, but the occurrence of the maximum concentration is slightly delayed at Barrow.

It is also seen from Fig. 6 that the maximum concentrations at middle latitudes appear earlier by about half a month in the western part than in the eastern part, due probably to a stronger influence of CO_2 from the Asian Continent and Japan. On the other hand, the minimum concentrations occur almost at the same time of the year, suggesting that biospheric CO_2 uptake reaches a maximum simultaneously at these latitudes. At low latitudes the situation is reversed, i.e., the occurrence of the maximum concentrations in

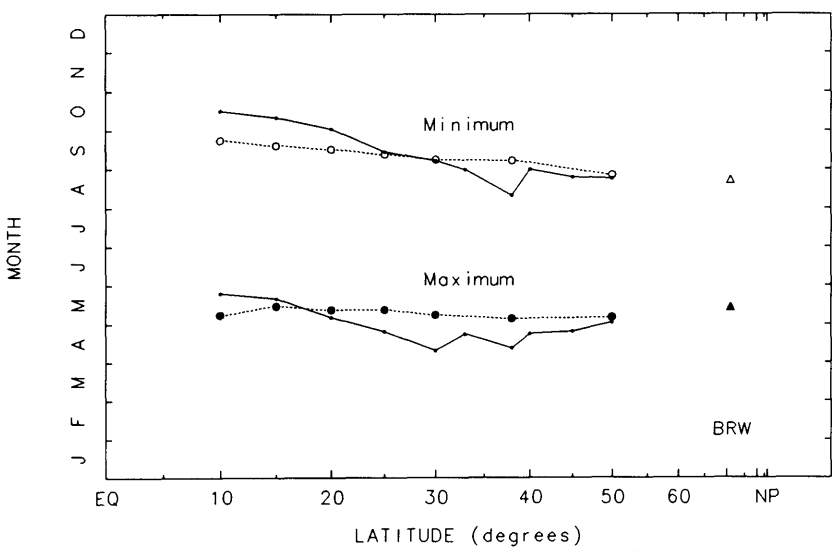

Fig. 6. Occurrence of maximum and minimum concentrations of the average seasonal CO_2 cycle at respective locations in the western (small closed circles with solid lines) and eastern (circles with dashed lines) parts of the North Pacific Ocean. BRW represents the results of Pt. Barrow, Alaska (71°N). The results in 160°W–160°E at 50°N are included in those of the western part.

both parts of the Pacific Ocean are almost coincident with each other, but the minimum concentration in the eastern part precedes the western part. Such a longitudinally different occurrence of the minimum concentration may be attributed not only to the rapid transport of air from northern high latitudes in the eastern part but also to intrusion of the southern hemispheric air with low CO_2 concentrations into northern low latitudes of the western part in summer and early fall in association with the monsoon circulation.

Latitudinal profiles of the annual mean CO_2 concentration values for the years 1984 to 1986 are listed in Table 1 and plotted in Fig. 7. These values were derived from fitted curves to the observed data. Values at Barrow, Cold Bay, Cape Meares, Cape Kumukahi, Guam (Schnell, 1987) and La Jolla (Keeling, 1991, pers. comm.), which are expressed in the WMO X85 scale (World Meteorological Organization 1985 mole fraction scale), are also plotted in Fig. 7 for comparison. The average rate of the annual CO_2 increase obtained from our values of the annual mean CO_2 concentrations for the 3-year period is 1.4 ppmv/year, which is very close to that obtained from the measurements at the Japanese Antarctic Station, Syowa (Nakazawa et al., 1991b) and from the other locations cited above. At middle and low latitudes of the western part, the increase in the CO_2 concentration from 1985 to 1986 is higher than the increase from 1984 to 1985. Such a trend is also found at low latitudes of the eastern part and at Barrow. However, the CO_2 concentrations

Table 1. *Annual mean values of the CO_2 concentration at respective locations over the North Pacific Ocean in 1984, 1985 and 1986 (ppmv), and standard deviations of curve fitting to the data (ppmv)*

	Western part				Eastern part			
	1984	1985	1986	σ	1984	1985	1986	σ
50°N	345.7	346.9	348.1	1.1	345.2	346.7	347.6	1.2
45°N	345.8	347.2	348.6	1.1				
40°N	346.1	347.5	348.1	1.1				
38°N	345.2	346.6	349.1	0.7	345.2	346.4	347.9	1.1
33°N	346.3	347.2	349.6	1.0				
30°N	345.8	347.0	349.1	0.9	345.2	346.4	347.6	0.8
25°N	345.3	346.5	348.4	0.6	345.2	346.5	347.7	0.7
20°N	344.8	345.9	347.9	0.6	345.2	346.4	347.9	0.6
15°N	344.5	345.7	347.7	0.5	345.8	346.7	348.1	1.0
10°N	344.1	345.6	347.4	0.4	346.0	346.6	348.2	0.8

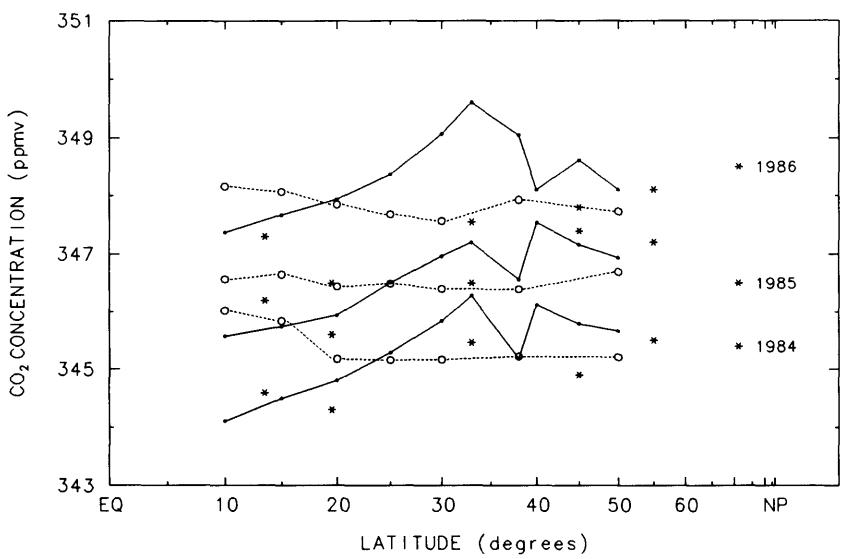

Fig. 7. Annual mean CO_2 concentrations at respective locations in the western (small closed circles with solid lines) and eastern parts (open circles with dashed lines) of the North Pacific Ocean. Values at Pt. Barrow (71°N), Cold Bay (55°N), Cape Meares (45°N), La Jolla (33°N), Cape Kumukahi (20°N) and Guam (13°N) are also indicated by asterisks.

at other locations indicate somewhat different trends from the above, due probably to different local effects in different areas.

In the western part of the Pacific Ocean, annual mean CO_2 concentrations are always high at middle latitudes, reflecting the strong influence of CO_2 released in the Asian Continent and Japan, and decreasing gradually going both southward and northward. Our value for each year at 15°N is somewhat different from that at Guam, but the average difference between both places is only 0.1 ppmv. In the eastern part, the annual mean CO_2 concentration is rather constant between 50° and 25°N, due to the rapid southward transport of air from the northern high latitudes, and it increases gradually with decreasing latitude from 25°N. The values at Cape Meares and La Jolla are in good agreement with those expected for their latitudes from our results, except for that at Cape Meares in 1985. The southward increase of the annual mean CO_2 concentration at low latitudes may be primarily ascribed to oceanic CO_2 sources in the tropical region. It is well-known (Keeling, 1968) that a large amount of CO_2 is released from the surface ocean into the atmosphere in this region, due to the upwelling of deep waters rich in CO_2, and that the supersaturation of CO_2 in equatorial surface waters is stronger in the eastern part than in the western part of the Pacific Ocean. Taking account of the prevailing winds in this region, the air originating in Central America may be partly responsible for the observed increase of the annual mean CO_2 concentration. Annual mean values in the interval 160°W–160°E at 50°N are always higher than those in the interval 160°–130°E and are in close agreement with those at Cold Bay. The annual mean CO_2 concentration at Shemya Island (53°N, 174°E) in 1986 (Schnell, 1987) is higher by 0.8–1.3 ppmv than all these values. This implies that the anual mean CO_2 concentration is longitudinally different near 50°N too, depending probably on the remoteness of the respective sampling locations from the Asian Continent situated on their windward side or depending on their own regional effects. In this connection, at northern high latitudes, the seasonally dependent CO_2 exchange between the atmosphere and the biosphere is especially active and a large amount of CO_2 is released by fossil fuel combustion (Rotty, 1983). The values at Barrow are close to those around 50°N, except for those at Shemya Island. Such an agreement could suggest fairly rapid transport of air from lower latitudes into the arctic region. Between 50° and 25°N, the annual mean CO_2 concentrations are always higher in the western part than in the eastern part, reflecting the stronger influence of CO_2 from the Asian Continent and Japan, and the situation is reversed south of 25°N, due mainly to tropical oceanic CO_2 sources in the eastern part. The values at Cape Kumukahi are clearly lower than those at 20°N in the western and eastern parts, suggesting smaller sources or larger sinks of CO_2 upwind of Kumukahi.

To examine the seasonal dependence of the longitudinal differences of the CO_2 concentration on the North Pacific Ocean, concentration deviations between the western and eastern parts were calculated using fitted curves to the observed data;

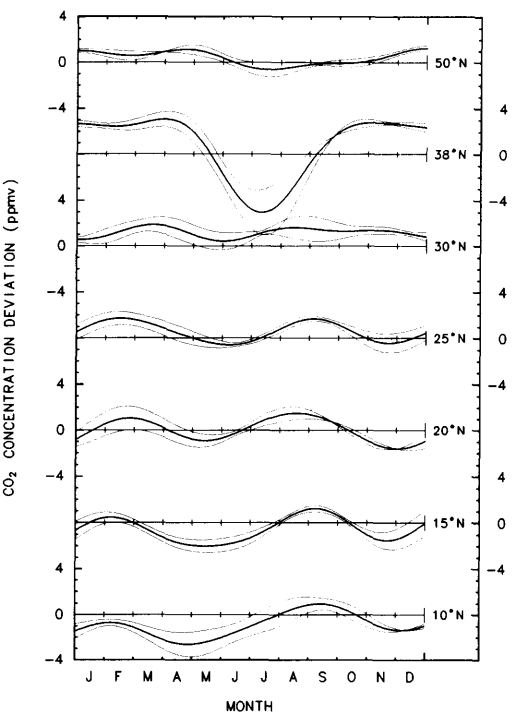

Fig. 8. Seasonal changes of the CO_2 concentration differences between the western and eastern parts of the North Pacific Ocean at respective latitudes. The result at 50°N was derived from values of 160°W–160°E and 160°–130°E. Thin lines represent one standard deviation of daily mean values of the CO_2 concentration differences.

daily values of the deviation were first grouped into each day of the year and then their values were simply averaged. The concentration differences thus obtained are shown in Fig. 8. Here, the results of 50°N were derived from deviations between values of 160°W–160°E and 160°–130°E. It is obvious from this figure that the CO_2 concentration shows a different behavior in the western and eastern parts even at the same latitude, depending on the season. At 50°N, the CO_2 concentration is higher in the interval 160°W–160°E than in the interval 160°–130°E, except for the period of June–October when the concentration difference is reversed due to substantial influence of biospheric CO_2 uptake in the Asian Continent. Such a seasonal change is found more clearly at 38°N. The enhanced seasonality of the concentration difference is attributed to the fact that the data taken near Sendai are much affected by local or regional biospheric activities. The seasonal change of the difference is largely reduced again at 30°N, but its sign is always positive, the concentration being higher in the western part than in the eastern part throughout the year. At 25°N, the CO_2 concentration in the western part is high from mid-December to late April and from early July to late October and low for remaining period of the year, as compared with that in the eastern part. Similar behavior is also found at lower latitudes. As mentioned above, the prevailing wind is almost northerly south of 30°N in the eastern part. On the other hand, the prevailing winds are northerly or northwesterly at the same latitudes in the western part from fall to spring through the winter and southerly in the summer (Oort, 1983). Taking account of these seasonally prevailing winds, the fact that the CO_2 concentration at 30°N is always decreasing going eastward could be explained by the transport of air with high CO_2 concentrations to this latitude in the western part. In this connection, the CO_2 concentration in the air transported from Japan and the Asian Continent between the fall and the spring is higher than that at lower latitudes, and the air from the tropical region in the summer, which originates mostly in the southern hemisphere, is richer in CO_2 than at northern middle and high latitudes. Such seasonally different air transport from different latitudes is also responsible for variations of the concentration differences at lower latitudes.

The results at latitudes lower than 30°N also show dips in the concentration difference between spring and early summer and between fall and early winter. These dips may be explained by the fact that the CO_2 draw-down from the maximum concentration in late spring and the CO_2 build-up from the minimum concentration in late summer occur slower in the western part than in the eastern part, due to intrusion of the southern hemispheric air with relatively high CO_2 concentrations into northern low latitudes of the western part in summer. It is also seen in Fig. 8 that the concentration difference during winter and spring is decreased with decreasing latitude, and its sign becomes negative at 10°N as a whole. Such a phenomenon can be ascribed to the influence of CO_2 from northern middle and high latitudes being gradually reduced with decreasing latitude in the western part, while it is still effective in low latitudes of the eastern part, due to rapid southward air transport. As mentioned above, the annual mean CO_2 concentration is always higher in the eastern part than in the western part. This effect may be also responsible for the distribution of the concentration difference at low latitudes.

4. Conclusions

As a result of the complicated distribution of CO_2 sources/sinks on the earth's surface and changeable atmospheric circulation, the atmospheric CO_2 concentration should be expected to indicate different variations depending not only on latitude but also on longitude. Indeed, the data from the present background CO_2 monitoring network consisting mainly of fixed stations on land suggest such a situation. For a better understanding of the longitudinal variations of the atmospheric CO_2 concentration, air samples were systematically collected using 4 container ships in the western, eastern and northern parts of the North Pacific Ocean. Conclusions obtained from this measurement are as follows:

The CO_2 concentration showed different variations at different locations, depending on local or regional effects, the distance from sources/sinks and transport of air with different CO_2 concentrations from other places. The average seasonal CO_2 cycles observed north of 30°N were larger in the western part than in the eastern part, reflecting a substantial influence of CO_2 from the Asian Conti-

nent and Japan; the situation was reversed south of that latitude due to the rapid southward air transport from high and middle latitudes by the prevailing northerly wind in the eastern part. Maximum and minimum concentrations of the seasonal CO_2 cycle appeared earlier at middle and high latitudes than at low latitudes and their occurrence was delayed going southward. The southward phase shift of the seasonal CO_2 cycle was, however, much reduced in the eastern part compared to the western part. This may be attributed to the rapid southward air transport from northern high and middle latitudes in the eastern part, as well as to an intrusion of the southern hemispheric air into northern low latitudes in association with the monsoon circulation in Southeast Asia during the summer season.

Annual mean CO_2 concentrations between 50° and 25°N were always higher in the western part than in the eastern part, reflecting the influence of CO_2 from the Asian Continent and Japan; those at latitudes lower than 25°N showed the opposite distribution due to a large amount of CO_2 released into the atmosphere from tropical surface waters in the eastern part.

As a result, variations of the lower tropospheric CO_2 concentration were clearly different in the western and eastern areas of the North Pacific Ocean, and the concentration difference between east and west parts was seasonally and latitudinally dependent.

These findings suggest that a denser network of CO_2 background monitoring is required to obtain detailed knowledge on the variations of the atmospheric CO_2 concentration. This is important for elucidating the carbon cycle on the earth's surface.

5. Acknowledgements

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