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Variation of carbon dioxide partial pressure in the western North Pacific surface water during the 1982/83 El Niño event

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ABSTRACT

To clarify the effect of oceanic condition on the pCO_2 in the surface sea water, observations of pCO_2 in the surface water of the western North Pacific were performed in January and February during the years from 1981 through 1985. An El Niño event occurred in the tropical Pacific Ocean from 1982 through 1983 and its effect was expected to appear in general oceanic conditions such as relatively low water temperatures, and high salinities in the surface sea water of the tropical and western region. Throughout the El Niño event, pCO_2 value in surface water in tropical and western region increased by up to 20 to 40 μatm above the normal values. Near the equator along the meridian of 137°E, it was found that a remarkable increase of pCO_2 was strongly correlated with the increase of salinity in the surface sea water. This finding could be related to eastward displacement of warm water and enhanced upwelling of subsurface water in this area. On the other hand, in the area from 14°N to 5.5°N along the meridian of 137°E, the pCO_2 and temperatures in the surface sea water, which were strongly correlated with each other, showed lower values than normal by up to 20 μatm and 1°C, respectively, in the year of the El Niño event. In the area from 14°N to 5.5°N, it was found that the variation of pCO_2 was stongly correlated with that of water temperatures, with a rate of about 4% pCO_2/°C.

1. Introduction

El Niño events are known as the most spectacular phenomena associated with a low Southern Oscillation Index (SOI) which is related to a large-scale atmospheric and hydrospheric fluctuation centered in the equatorial Pacific Ocean and occurs every several years (Rasmusson and Hall, 1983). El Niño events bring about large changes in oceanic conditions such as surface temperatures, salinities, ocean currents and biological activities in large areas of the Pacific. These are also expected to bring about changes in CO_2 partial pressure (pCO_2) in the surface ocean, because the magnitude of pCO_2 in surface water is strongly controlled by these oceanographical factors. It was suggested that the El Niño events would exert a significant control over variations of global atmospheric carbon dioxide (Machta et al., 1977).

It is known that the yearly increasing rate of the atmospheric CO_2 observed at the South Pole and Mauna Loa Observatory is not steady but is much greater in some years than in others. This fact could not be attributed to the increase of fossil fuel combustion which has been very steady.

Several studies have been made concerning the relationship between the atmospheric pCO_2 variation and the large-scale variation of oceanic conditions brought about by El Niño.

Bacastow (1976, 1977a, b) has shown that the

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variation of the atmospheric CO_2 is highly correlated to SOI. A high SOI with strong easterly trades and correspondingly strong southern hemisphere westerlies is found to be associated with a decrease in atmospheric CO_2. He suggested that the relationship resulted from extra uptake by the sea when the roaring forties were strong, as the exchange coefficient of CO_2 between air and sea was a strong function of wind speed (Deacon, 1981; Liss, 1983; Smethie et al., 1985).

On the other hand, Weare et al. (1976), Newell and Weare (1977) and Newell et al. (1978) reported that there was a spatial and temporal correspondence between changes in Pacific sea surface temperature (SST) and in atmospheric CO_2, after seasonal trends had been removed. They suggested that the observed atmospheric modulation of CO_2 was caused by a variation of upwelling in the tropical ocean. These authors pointed out that it was a variable source rather than a variable sink that was responsible for the observed atmospheric modulation.

Machta et al. (1977), based on the calculation of a computer model of horizontal and vertical transport of an inert tracer injected into the 0° to 10°S latitude band, interpreted the observed lag correlations in the atmospheric CO_2 modulation between Mauna Loa, Australia and the South Pole. However, Bacastow et al. (1980) made a simple equilibrium model calculation which predicted only about 50% of the observed atmospheric CO_2 modulation with the change in SST associated with the El Niño event. Bacastow et al. (1980) proposed that observations of pCO_2 in Pacific equatorial water during the whole El Niño event should be made because the biological activity might have an important rôle in the change of pCO_2 in the surface water.

Correlations between atmospheric CO_2 and SST variation in areas other than the equatorial Pacific are also reported. Hanson et al. (1981) and Schnell et al. (1981) showed that the anomalously low increase rate of atmospheric CO_2 observed at Ocean Weather Station P, and Pt. Barrow and Mauna Loa were well correlated with large negative SST anomalies in the mid-latitude area of North Pacific during the El Niño years of 1976/77. They suggested that the Northwest Pacific (20°–50°N) might have been a major sink for atmospheric CO_2 during these years.

In the case of the 1982/83 El Niño event, it is suggested by Gammon et al. (1985) that the atmospheric CO_2 response, which showed a very low or negative CO_2 growth in the atmosphere in the early stage of the event followed by a high growth in the later stage, seemed to begin with nearly simultaneous CO_2 sink at mid to high latitudes in both hemispheres.

Although these high correlations between the atmospheric CO_2 and the oceanic conditions are pointed out and several studies have been made concerning the correlations between seasonal variations of pCO_2, temperature, salinity and the upwelling in the surface sea water (Kelley, 1970; Kelley et al., 1971; Gordon et al., 1971; Takahashi et al., 1983; Weiss et al., 1982), it is poorly known how pCO_2 changes correspondingly with the large-scale variation of oceanic conditions. To clarify the variabilities of pCO_2 in the surface sea water which might occur as a result of the large-scale variation of oceanic conditions such as El Niño events, determination of pCO_2 was made in water and air near the surface over the western North Pacific Ocean. During the period of the observations, an El Niño event broke in the summer of 1982 and continued until the summer of 1983. Results of the observations of pCO_2 in the surface water before, during and after the 1982/83 El Niño event in the western North Pacific are reported.

2. Observation and experimental

Observations of pCO_2 were made continuously in the cruise in each year aboard the R/V Ryofu Maru of the Japan Meteorological Agency (JMA). The method of determination of pCO_2 in sea water was an infrared (NDIR) analysis of air which was continuously equilibrated with a surface sea water. Determination of pCO_2 both in the air and surface sea water were made by running for 25 min in every hour. The surplus 10 min in every hour were used for a calibration of the system. The apparatus used here is a slightly modified one of Miyake and Sugimura (1969). A diagram of the system is reported in by Inoue et al. (1987).

2.1. Calibration of pCO_2

Working standard gases of 250, 350 and 450 μatm CO_2 in N_2 were used for the determination

of pCO_2 on board. Gravimetrically prepared secondary standard gases of 250, 350, 450 μatm in the artificial air were used for calibration of the working standard gases. These secondary standard gases were standardized in 1981 WMO mole fraction scale by gas supplied from the Scripps Institution of Oceanography.

2.2. pCO_2 in the air

Air was taken at the bow or at the upper bridge of the vessel which was about 10 m above the sea surface. The inlet of air is projected about 1 m into the sea and the air was pumped into the laboratory on board through a PVC tubing at a flow rate of 10 l min^{-1}. An aliquot of air was introduced into the apparatus at a flow rate of 0.5 l min^{-1}. Air was dehumidified at a dew point of 1.5°C, successively through a column of anhydrous $Mg(ClO_4)_2$ (18 to 30 mesh) which made air dry at a dew point of about −70°C. A pCO_2 in dry air was determined by using a Beckman Model 315A type NDIR. As the values of pCO_2 obtained here were those in dry air, corrections for the water vapour pressure in the air on the atmospheric pCO_2 measurement were made using humidity data of the air obtained for the meteorological observations on board. The accuracy for the atmospheric pCO_2 measurement was estimated at 0.5 μatm.

2.3. pCO_2 in surface sea water

The sample water was continuously pumped up to the laboratory on board at a flow rate of 10 l min^{-1} from the bottom of the vessel which is about 4 m below the surface. In order to avoid gas exchange with the atmosphere, a debubbler was inserted in the flow. This water was sprayed into a 2 l clear plastic cylinder which served as the equilibrator. A constant level of water was maintained by a drain which is open to the atmosphere. Equal water levels in the drain and chamber ensured that the gas pressure in the latter was atmospheric. Gas/water equilibrium was obtained through exchange of CO_2 between the cylinder-air and the water droplets that sprayed into the gas. Air was continuously analyzed by circulating it in a closed loop containing the equilibrator, electromagnetic valves, a desiccant system, a diaphragm pump, a flow meter and an infrared CO_2 analyzer.

A slight rise of water temperature at the equilibrator was observed compared to SST. A correction for pCO_2 for the temperature rise was made according to the temperature effect equation on pCO_2 given by Gordon and Jones (1973). Quite similar results of temperature effect as shown by Gordon and Jones (1973) were obtained at the laboratory test, changing the water temperature in the range from 10°C to 30°C using this system of pCO_2 determination (Inoue, 1985 pers. comm.). As pCO_2 in sea water determined here were values in dry air, corrections for pCO_2 were made to values in 100% humidity air at in situ water temperature. After these corrections were made for temperature and water vapor pressure, the accuracy was estimated at a few μatm for pCO_2 in sea water.

2.4. Data selection

Data selections were made for pCO_2 both in the air and sea water to exclude the contaminated data by the air of the ship and unrepresentative data because of the problem of the system under bad weather conditions (Inoue et al., 1987). Available data are 73 to 83% of the total in each year for pCO_2 in the air and 81 to 97% for pCO_2 in the surface sea water. Data for pCO_2 in dry air used here are summarized and listed, as reported by Inoue et al. (1987).

2.5. Potential pCO_2 calculation from determinations of total carbon dioxide and pH

Vertical distributions of potential pCO_2 in deep water along the 137°E line were determined by calculation from total carbon dioxide data, pH, water temperature and salinity obtained on board during the 1984 expedition. Potential pCO_2 means pCO_2 in deep water when the deep water is brought up to the sea surface and when the water temperature is heated up to the sea surface temperature.

The content of total carbon dioxide in sea water was determined by the following method using another NDIR analyzer on board. Sample water from various depths was obtained using a 1.5 l Nansen-type sampler at a hydrocasting point at about 5° intervals from 34°N to 1°S along the 137°E meridian. Each sample water was taken in a 100 ml oxygen bottle and stored for a few hours before the analysis. A 2 ml aliquot of the sample water was injected into a gas-stripping glass bottle which contained 5 ml of 0.08% H_3PO_4

solution using a hypodermic syringe. Nitrogen gas was introduced into the solution through a hypodermic needle at a constant flow rate of 200 ml min^{-1}. Total CO_2 deliberated from the sea water was dehumidified through a column of anhydrous $Mg(ClO_4)_2$, and CO_2 in N_2 flow was determined by an NDIR analyzer. Duplicate analyses were made on each water sample and an average value was used as a datum. A calibration curve was drawn using standard solutions of Na_2CO_3. The precision of the analysis for the total carbon dioxide was 10 μM.

A sea water pH was determined on board using a Denki Kagaku Keiki Model COM-10 pH meter at room temperature near 25°C. Standard solutions of pH used here were 0.05 M potassium phthalate buffer solution for pH 4 and 0.025 M potassium dihydrogenphosphate + 0.025 M sodium phosphate buffer solution for pH 6. The precision of the pH determination was 0.01.

Potential pCO_2 was calculated using the pH value corrected to that at the sea-surface temperature at each hydrocasting location. Correction for pH at the temperature other than 25°C was made using the equation reported by Gieskes (1969). Apparent dissociation constants used here for pCO_2 calculations are those reported by Mehrbach et al. (1973) for carbonic acid and those by Edmond and Gieskes (1970) for boric acid. The CO_2 solubility of Edmond and Gieskes (1970) was used.

Meteorological and oceanographical data used here are cited from RMMOO (1982, 1983, 1984, 1985, 1986) reported by JMA. The SST's were determined continuously during the cruise at the intake of sea water for pCO_2 determination.

3. Results and discussion

3.1. SST variation in the Pacific

Fig. 1 shows the monthly mean SST in the Pacific in January from 1981 to 1984 observed by ships, buoys and satellites (OMS, 1981; 1982; 1983; 1984). The shaded area shows that the temperatures are higher than 28°C. In January 1983 when the El Niño event was seen, the high temperature area of the ocean surface extended widely to the eastern part of the Pacific. However, in the western North Pacific, this high temperature belt was narrower than that in other years. In 1983, the northern boundary of the 28°C line lay at 8°N on the 137°E meridian. In the other years when the El Niño event was not seen, this high temperature area spread up to 15°N on the meridian of 137°E. Observations of pCO_2 were made along the 137°E meridian from 34°N to 1°S and also along the returning course to Naha as shown in the thick V-line in Fig. 1.

It is known to be a characteristic feature in the equatorial region along 137°E, that the area occupied by the warmest surface water with the temperatures higher than 28°C is least in the year of El Niño event. This low temperature in the western equatorial Pacific is associated with higher SST in the central and eastern equatorial Pacific which results from the El Niño event (Masuzawa and Nagasaka, 1975).

3.2. The pCO_2 variation in the western North Pacific

Fig. 2 shows the ΔpCO_2 distribution observed in 1981. ΔpCO_2 denotes the difference in pCO_2 between the surface water and air. In this area of the ocean, ΔpCO_2 is mostly and largely negative except in the area near the equator.

In 1983, the El Niño event was still continuing, as shown in Fig. 3, pCO_2 had increased markedly especially in the area near the equator and along the western section. In these areas, pCO_2 in surface seawater was higher by 20 μatm and even more than in 1981. In 1984, when the El Niño event had terminated as shown in Fig. 4, the pCO_2 in the surface water was found to decrease again down to the same levels as that before the El Niño event.

Fig. 5 shows the meridional distributions of ΔpCO_2 in each year from 1981 to 1985 along observation lines. As reported previously by Akiyama (1968) and Miyake et al. (1974), the general feature of the pCO_2 distribution in sea water along the 137°E line is the increase from relatively low values in the temperate zone to high values in the tropical region. The pCO_2 value in the surface water is lower than that of air in the area north of about 10°N. The range of year-to-year variation of pCO_2 in this area is as large as 15 to 30 μatm during the period of observations. In the area south of 10°N, pCO_2 in the surface water is nearly equal to or higher than that of the air. The year-to-year variation of pCO_2 in this area ranged from 30 to 50 μatm.

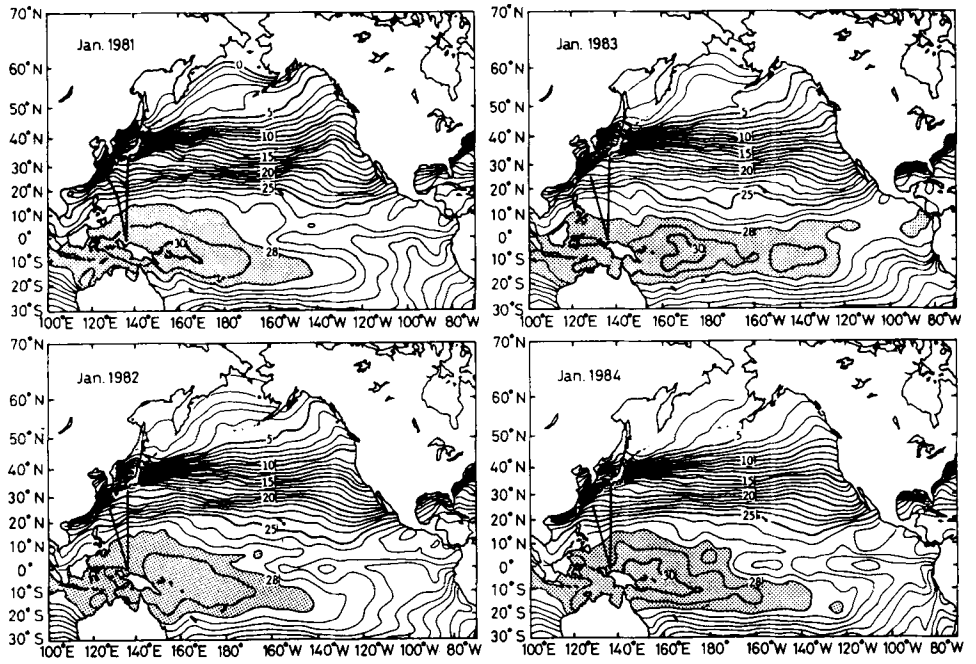

Fig. 1. Monthly mean SST's in the North Pacific modified from figures in OMS (1981, 1982, 1983, 1984). Each contour line is at 1 °C intervals. Shaded area shows where the temperatures are higher than 28 °C. The V-line in the western North Pacific shows the observation line of pCO_2.

Along the course from 1°S to Naha, the feature of the meridional distribution of pCO_2 is just like that along 137°E. However, the range of year-to-year pCO_2 variation is as large as from 30 μatm at 25°N to 50 μatm near the equator. The prominent feature of pCO_2 variation along this line is that the pCO_2 is higher by more than 20 μatm along the whole course in 1983 than that in other years.

3.3. Temperature and salinity sections at 137°E meridian

Vertical sections of water temperature and salinity along the 137°E line observed in 1981 before the El Niño event are shown in Fig. 6a. A region of upwelling is seen under the thermocline near 7°N and the northern area is thought to be a sinking area. Vertical structure of the sea is different in the area near the equator from that in the area north of about 15°N. There is a high salinity water mass in the subsurface layer near the equator.

In 1983, as shown in Fig. 6b, the thermocline in the area near the equator was not so remarkable and water colder than 28°C has covered the surface over the area down to 2.5°N. The high salinity water mass went back to the surface of the equatorial area a little, but a large mass of the high salinity water was coming up to the surface in this area.

3.4. Variation of pCO_2 and ΔpCO_2 distributions and its correlation to SST and salinity distributions

3.4.1. SST and salinity distributions. In order to compare the features of the oceanic conditions, time series data of the meridional distributions of SST and salinity along 137°E are shown in Fig. 7. In the area south of 17°N, SST in 1983, when the El Niño event was observed, was found to be lower than that in other years and the area where the temperatures were above 28°C was found only south of 2.5°N. A tendency of the lower sea surface temperature was also seen in the area south of 15°N in 1981. In 1983, salinity was higher than usual in the area south of 11°N. Especially in the area south of 5°N, it was much higher than 34.8‰. The figure shows clearly that

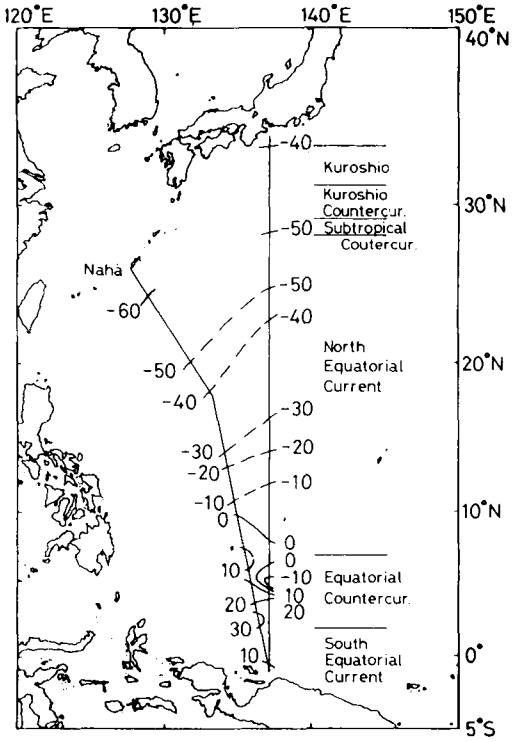

Fig. 2. The ΔpCO_2 distribution observed in January and February 1981, (μatm). Areas of current systems are estimated from geostrophic calculations in the section of 137°E.

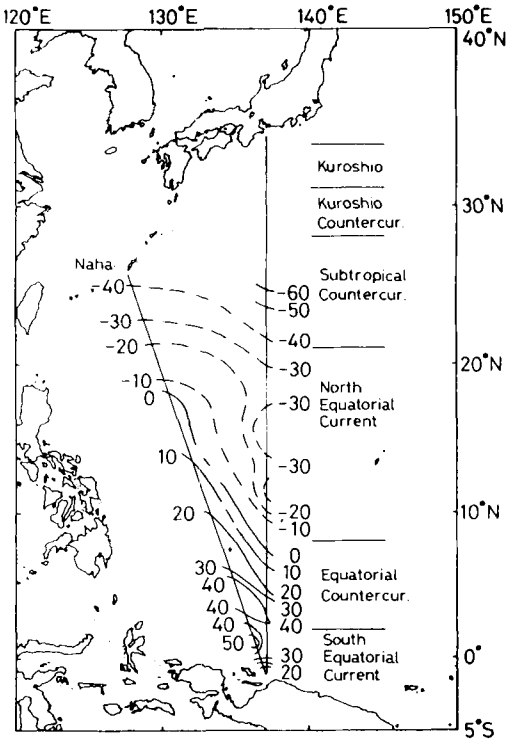

Fig. 3. The same as Fig. 2, except for 1983.

the continuation of El Niño events resulted in quite anomalous SST and salinity in 1983.

An anomalous state of temperature and salinity in the equatorial surface water at 137°E in 1972/73 El Niño event was reported by Masuzawa and Nagasaka (1975). They showed that the low temperature in the upper layer was associated with the lowest steric sea level in this western equatorial region. This finding meant that the warm surface water which had been piled up in this region was removed toward the eastern Pacific by the decline of the easterly trade winds. The lower steric sea level in the western equatorial Pacific was also observed during the 1982/83 El Niño event (PROMBMP, 1983).

3.4.2. pCO_2 and ΔpCO_2 distributions. Fig. 8 shows the time series data of pCO_2 and ΔpCO_2 measured in the surface water. The correlation between characteristic variations of pCO_2 and the variation of oceanic conditons is considered. In the area from 17°N through 5°N, pCO_2 was low in 1981 and 1983 when the sea surface temperature was low, while in the area south of 5°N, pCO was high, especially in 1983, corresponding to the high salinity in that year. In the area south of 5°N, the year-to-year variation of pCO_2 shows patterns similar to the salinity distribution given in Fig. 7.

As shown in Fig. 9, surface water sampled during the cruise from 1°S to Naha showed more conspicuous variations in pCO_2 and ΔpCO_2 than those along the 137°E line. In 1983, pCO_2 was higher than that observed in other years by 20 to 40 μatm. As pointed out previously (Miyake et al., 1974), high pCO_2 in the surface water near the equator is produced by the upwelling of CO_2-rich subsurface water which extends to the South Equatorial Current from the end of the Peruvian Current. Akiyama (1968) showed that there exists a wide area of high pCO_2 in sea surface water between the east of the Philippines and the 137°E line. The presence of an upwelling area named

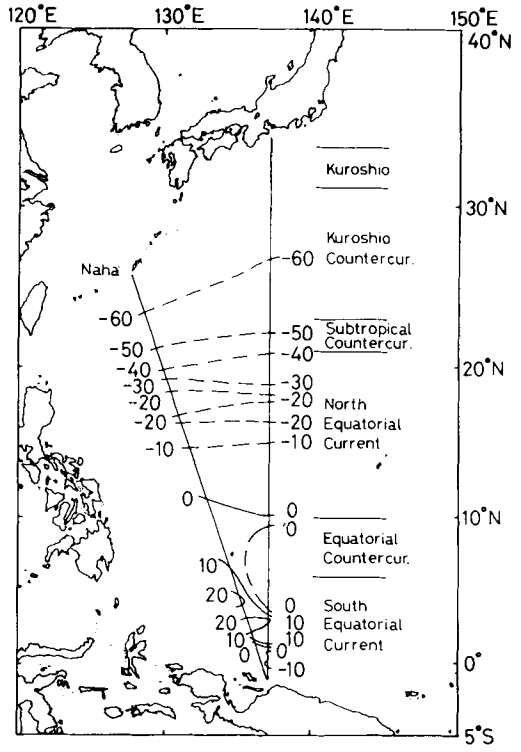

Fig. 4. The same as Fig. 2 except for 1984.

the Mindanao eddy was reported by Masuzawa (1968) in this region of the western North Pacific. This high pCO_2 areas seem to correspond to areas of the Mindanao eddy and the following Equatorial Countercurrent which brings deeper water to the surface. In the year of the El Niño event, such upswellings as the Mindanao eddy might prevail in the western North Pacific which followed the eastward displacement of warm surface water. As a result, it might be said that the high pCO_2 in the surace seawater appeared in the area near the equator and along the course from 1°S to Naha. The higher salinity than usual in the surface sea water along the course from 1°S to 15°N was also observed in 1983 (Fig. 10).

3.4.3. Correlation between pCO_2 and SST. In Fig. 11 is shown a relationship between the pCO_2 and SST observed in each year from 1981 to 1985 in the area from 14°N through 5.5°N along 137°E. Data of pCO_2 and SST plotted here are those observed at the Nansen hydrocasting locations. Values of pCO_2 in surface water observed in each year are strongly correlated with SST. The rate of variation of pCO_2 against SST in each year is estimated to be about 14 μatm/°C except in 1983 of the El Niño year when the rate increases up to about 35 μatm/°C. The large increment of the rate in 1983 which is more than twice as large as in other years might reflect the remarkable effect of the upwelling of deeper water which prevailed in the El Niño year in this area.

In this area along the 137°E line, both the pCO_2 and SST changed considerably from year to year. The range of the variation in both of them extends toward the lower values, especially in 1983, the El Niño year. Plots indicate that in

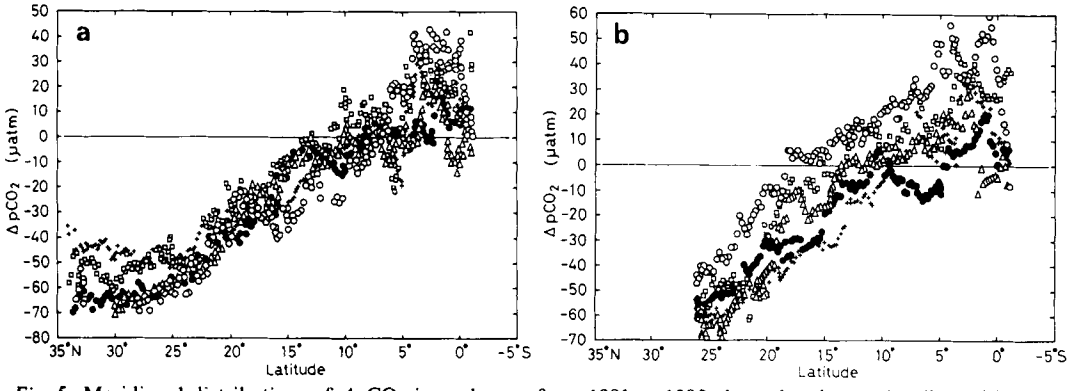

Fig. 5. Meridional distributions of ΔpCO_2 in each year from 1981 to 1985 along the observation lines. (a) along 137°E line, (b) along the course from 1°S to Naha. Symbols are: +, 1981; □, 1982; ○, 1983; △, 1984 and ●, 1985.

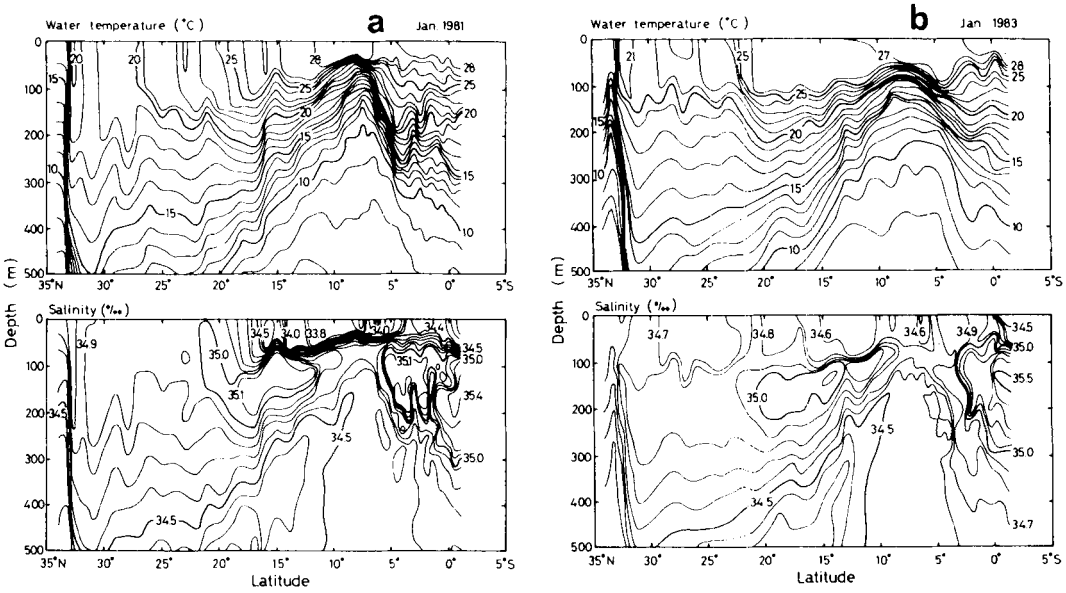

Fig. 6. Vertical sections of water temperature and salinity along the 137°E line. (a) January 1981, (b) January 1983.

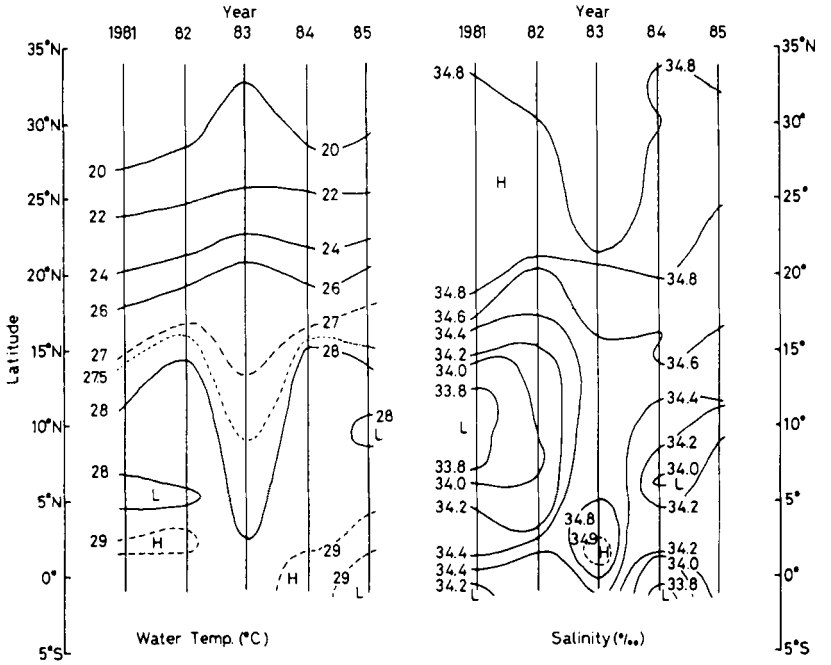

Fig. 7. Year-to-year change of meridional distributions of water temperature and salinity in the surface seawater along the 137°E line.

this area, the year-to-year variation of temperature by 1°C results in pCO_2 variations of about 14 μatm. The rate of variation of pCO_2 against temperature of about 14μatm/°C (about 4% pCO_2/°C at 330 μatm) is found to be quite similar to the rate expected from the physico-chemical

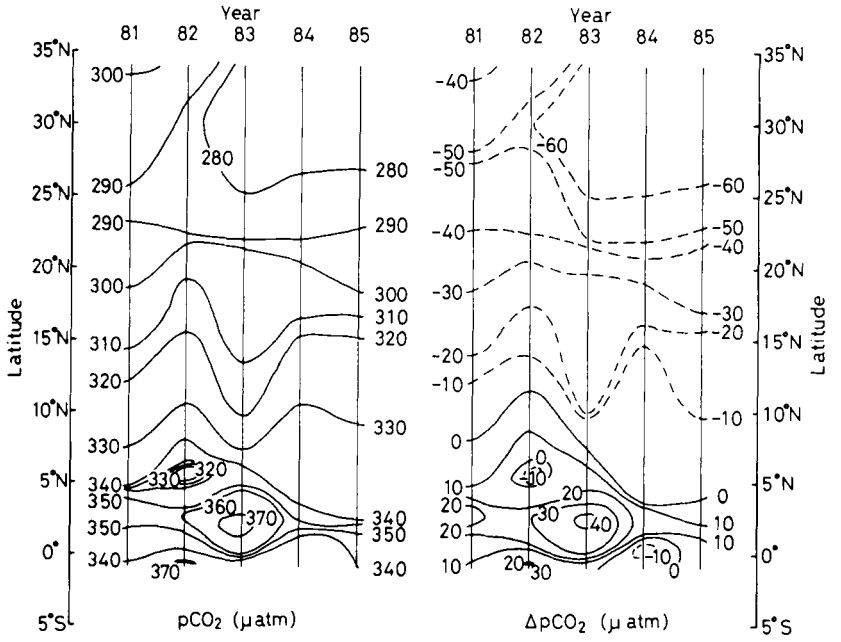

Fig. 8. The same as Fig. 7 except for pCO_2 and ΔpCO_2.

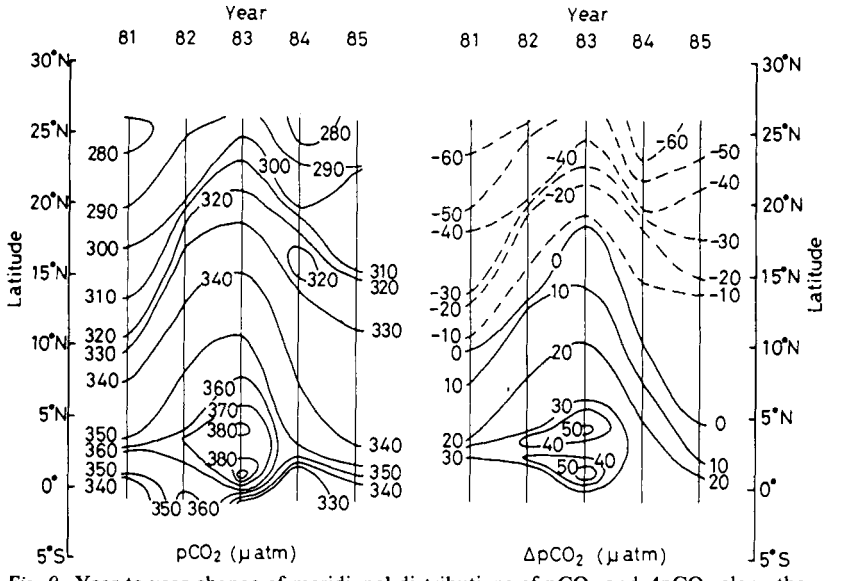

Fig. 9. Year-to-year change of meridional distributions of pCO_2 and ΔpCO_2 along the course from 1°S, 137°E to Naha.

processes in which the total dissolved inorganic carbon (TC) and the alkalinity (TA) are held constant (Kanwisher, 1960; Takahashi, 1961; Li et al., 1969; Gordon and Jones, 1973). The rate of temperature effect on pCO_2 observed here is almost the same as 4.3% pCO_2/°C observed in the Labrador Sea and the Norwegian–Greenland Sea in the North Atlantic (Takahashi et al., 1983);

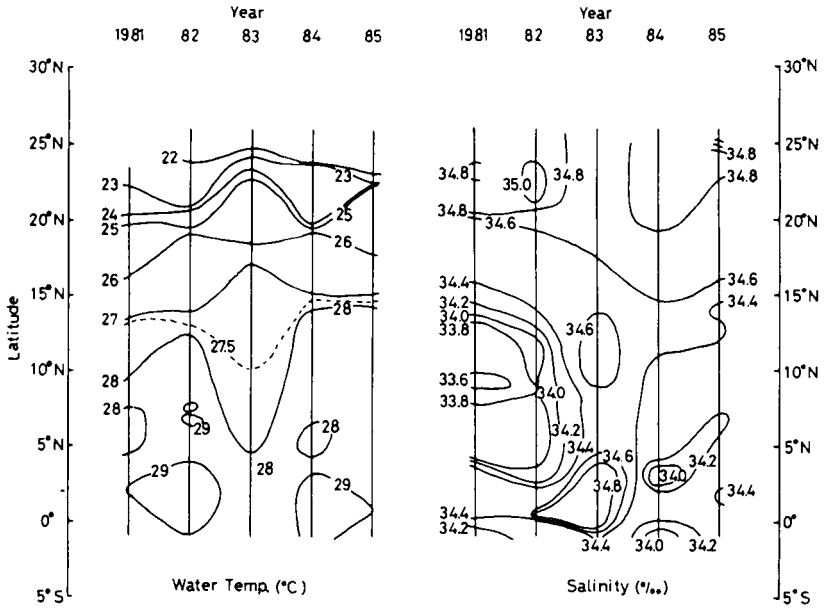

Fig. 10. The same as Fig. 9 except for SST and salinity.

however, it is larger than 1.2% pCO_2/°C observed in the temperate ocean, such as the Sargasso Gyre and the Antilles Current/Gulf Stream (Takahashi et al., 1983) and the subtropical gyres of the North and South Pacific Ocean (Weiss et al., 1982). As pointed out by MacIntyre (1978), the transfer of CO_2 between ocean and atmosphere can cause an appreciable change in TC, which results in the weakening of the temperature dependence of pCO_2. The strong temperature dependence observed in this area of the ocean might be caused by the process of temperature change progressing more rapidly compared with all other processes altering TC and TA.

In the area from 15°N to 30°N along 137°E longitude, year-to-year variation of pCO_2 and SST were not observed clearly even in the El Niño year. However, the relationship between pCO_2 and SST was observed to be almost linear in each year, which showed about 1.6% increase in pCO_2 against 1°C increase of water temperature. No distinct correlation between year-to-year variation of pCO_2 and SST was observed in the area south of 5°N.

3.4.4. Correlation between pCO_2 and salinity. In the area from 14°N through 5.5°N and in the area from 15°N to 30°N along 137°E, the correlation between an apparent pCO_2 and salinity variation was not found.

In the area south of 5°N along the 137°E line, however, a relationship between pCO_2 and salinity was observed as shown in Fig. 12. Data plotted here are all observed in the surface water at Nansen hydrocasting points. Salinities and pCO_2 of surface water were highest in the El Niño year, while the lowest in 1985. The rate of the variation of pCO_2 against salinity was about 40 μatm per 1‰ salinity. The rate of pCO_2 variation against salinity observed here is just the same as observed in the Barents Sea by Kelley (1970).

As pointed out by Takahashi (1985), the magnitude of variation of pCO_2 in the surface seawater is mostly affected by (1) the rate of temperature change, (2) the rate of CO_2 gas exchange across the air–sea interface, (3) the rate of biological CO_2 removal from sea water, (4) the rate of upwelling of subsurface water rich in CO_2 and nutrients, and (5) the thickness of the mixed layer of the ocean. Rates of pCO_2 variation against temperature and salinity observed here reflect results of superposition of these processes.

3.4.5. Effect of an upwelling on the variation of pCO_2 in the area near the Equator. Fig. 13 shows a vertical section of potential pCO_2 along the

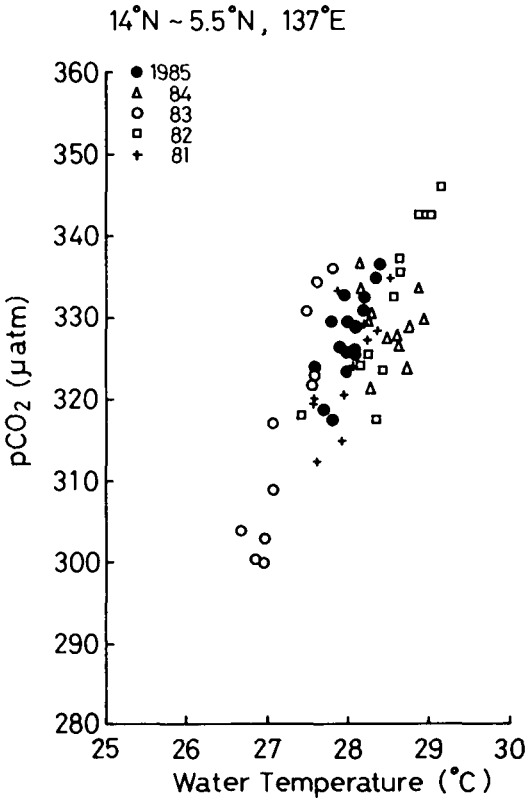

Fig. 11. Correlation between pCO_2 and SST in the area from 14°N to 5.5°N along 137°E line.

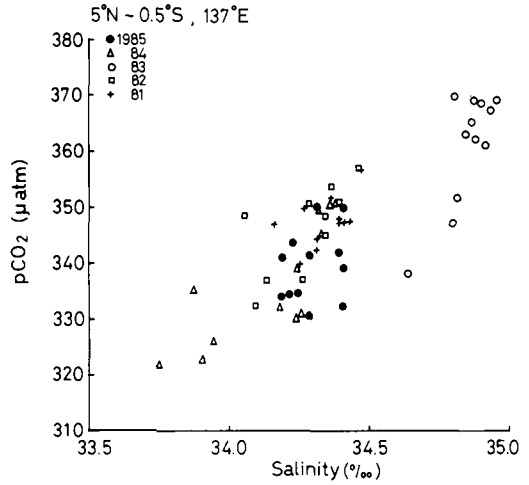

Fig. 12. Correlation between pCO_2 and salinity in the surface water in the area from 5°N to 0.5°S along the 137°E line.

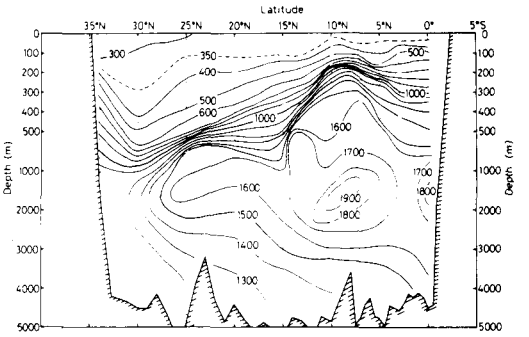

Fig. 13. Vertical section of potential pCO_2 calculated from total carbon dioxide and pH along the 137°E line (January 1984) (μatm).

137°E line in 1984 which was calculated on the basis of data of total inorganic carbon, pH, temperature and salinity of water. As seen in this section, high pCO_2 water lies just under the surface water in the area south of 10°N, where surface water will be easily affected by an upwelling of deeper water and its strong vertical mixing with the surface water.

As shown in Fig. 14, a high phosphate concentration in surface water in the area south of 5°N in 1983 reveals evidence that an appreciable upwelling and vertical mixing of water occurred there. Nutrient rich water promotes the proliferation of phytoplanktons which contributes to the reduction of pCO_2 in the surface sea water. However, it could be said that the supply of nutrients from deeper water dominated the assimilation rate when the observation was made. As an index of a vertical mixing, a ratio of salinity in the surface water to that in 100 m deep water was taken and plotted against pCO_2. A positive correlation was obtained as shown in Fig. 15.

From these results, it could be concluded that in this equatorial area along the 137°E line, a high pCO_2 value observed in 1983 was brought about by a strong upwelling of CO_2-rich subsurface water and its vertical mixing with surface water.

3.4.6. Secular trend of pCO_2 variation in the western North Pacific. Parallel to the atmospheric increase of CO_2, the increase of pCO_2 in the surface seawater is also expected through the uptake of the atmospheric CO_2 by the ocean.

As seen from Figs. 5 and 11, no distinct secular

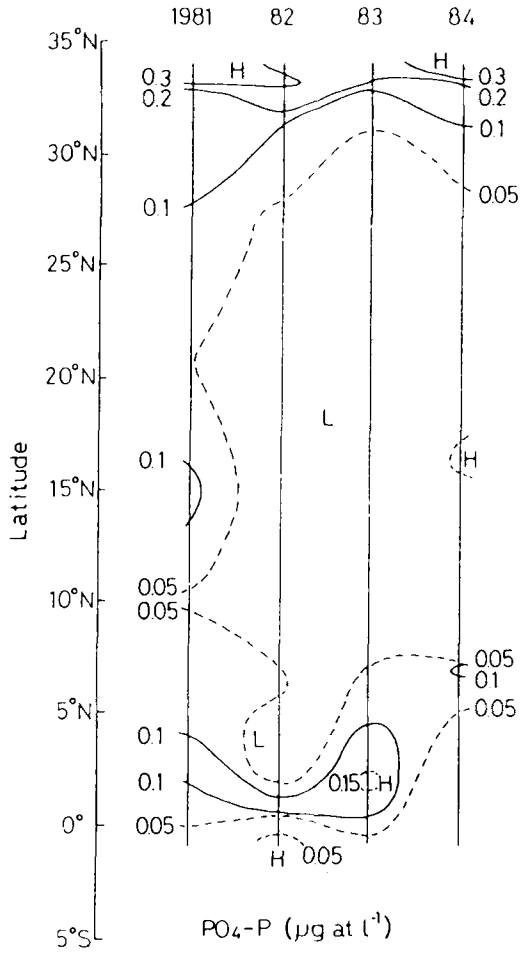

Fig. 14. Year-to-year change of meridional distributions of PO_4-P along the 137°E line.

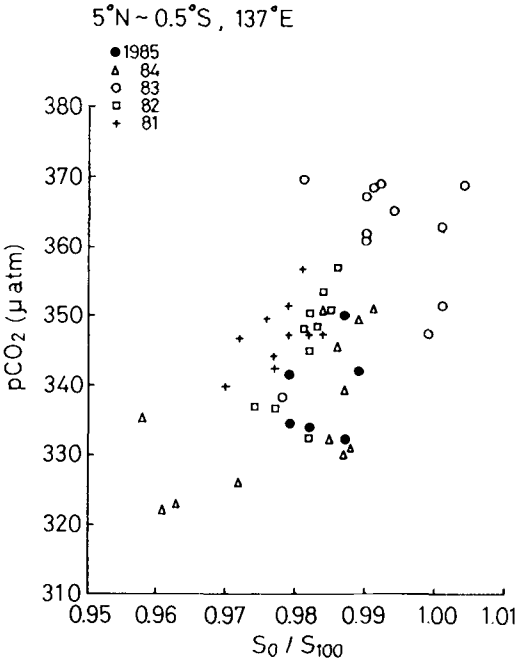

Fig. 15. Correlation between pCO_2 and the ratio of salinity (surface to 100 m depth) in the area from 5°N to 0.5°S along the 137°E line.

trend of pCO_2 variation in the surface sea water was observed in the area of the western North Pacific during the last 5 years. However, by taking into account the earlier observations (Akiyama, 1968; Miyake et al., 1974), an increase of pCO_2 in the surface sea water in the subtropical gyre north of 15°N along 137°E was estimated to be 10–20 μatm in these 16 years by Inoue el al. (1987), as reported in the North Atlantic (Roos and Gravenhorst, 1984; Takahashi et al., 1983).

4. Conclusions

Observations of pCO_2 in the surface sea water of the western North Pacific were made during the years from 1981 to 1985, including the El Niño event. The characteristic feature of oceanic conditions along 137°E during the El Niño event was the relatively low temperatures and high salinities in the surface water of the tropical region. During the El Niño event, a drastic increase of pCO_2 in the surface sea water, more than 20 μatm, was observed, especially in the area near the equator and along the western section of the western North Pacific.

A remarkable increase of pCO_2 near the equator along the meridian of 137°E was strongly correlated with the variation of salinity in the surface sea water. High pCO_2 and high salinity in the surface sea water observed near the equator in January 1983 were estimated to be caused by a prominent upwelling of subsurface water and vertical mixing with surface water during the El Niño event.

In the area south of 17°N along the meridian of 137°E, the pCO_2 observed in the surface sea water in January 1983 was lower by up to 20 μatm and 1°C, than usual values. In the area from 14°N to 5.5°N, it was found that the variation of pCO_2 was strongly correlated with that of SST with a rate of about 4% pCO_2/°C.

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