Shipboard measurements of atmospheric and surface seawater pCO2
in the North Pacific carried out from January 1999 to October 2000
on the voluntary observation ship MS Alligator Liberty

by

Kan Ogawa1, Toshihiro Usui2*, Sukeyoshi Takatani1, Takashi Kitao3,
Takashi Harimoto3, Shinji Katoh4, Shiro Dobashi4,
Takashi Midorikawa***, Hisayuki Yoshikawa Inoue5* and Yukiko Dokiya***

1. Japan Meteorological Agency
2. Ocean Research Institute, University of Tokyo
3. The General Environmental TECHNOS Co., Ltd.
4. Foundation for Promoting Personal Mobility and Ecological Transportation
5. Geochemical Research Department, Meteorological Research Institute
6. Tokyo University of Agriculture and Technology

(Received May 1, 2006; Accepted October 19, 2006; Published December 28, 2006)

Abstract

Partial pressures of CO2 in surface seawater (pCO2sea) and the overlying air (pCO2air) were measured in the North Pacific (mainly 30–40°N) from January 1999 to October 2000 (9 cruises) onboard the voluntary observation ship MS Alligator Liberty. Distributions of pCO2air and pCO2sea showed that the western North Pacific (west of 180°) acted as a sink for atmospheric CO2 throughout the year except for August, whereas the eastern North Pacific (east of 160°W) acted as a sink for only half the year (November to May). Total dissolved inorganic carbon (TCO2) estimated from pCO2sea and total alkalinity showed a larger seasonal decrease (April to June) in the western North Pacific than in the eastern North Pacific, in accordance with the seasonal decrease in nitrate + nitrite (NOx = NO3− + NO2−). The 9.5 C/N ratio calculated from the relationship between decreased TCO2 and [NOx] implied a larger influence of biological activity in the western North Pacific. Using pCO2sea estimated from the relationship between pCO2sea and sea surface temperature, we assessed the monthly CO2 fluxes in the western North Pacific for the year 2000. The fluxes ranged from ca. 0 Gt-C yr−1 in the summer to ca. –0.4 Gt-C yr−1 in the winter, with an annual average of –0.2 Gt-C yr−1, which corresponds to about 10% of the annual oceanic CO2 uptake over the 1990s.

1. Introduction

The ocean plays an important role in determining the level of atmospheric CO2, which has been increasing due to human activities. The current estimation of the distribution of CO2 among carbon reservoirs, however, remains uncertain (IPCC, 1995, 2001). Measurements of the partial pressures of CO2 in the ocean surface (pCO2sea) and the
overlying air (pCO$_2$$_{air}$) are important to estimate the oceanic CO$_2$ uptake, because the fluxes of CO$_2$ across the air–sea interface are driven by differences of pCO$_2$ between the two phases.

According to Takahashi et al. (2002), approximately 940,000 measurements of pCO$_2$$_{sea}$ of the global ocean have been made since the International Geophysical Year of 1957–1958. Because of the paucity of pCO$_2$$_{sea}$ data collected during this period, they estimated CO$_2$ fluxes between the sea and air for the single virtual calendar year of 1995 by compiling data collected over 40 years. Their results indicated that there were insufficient pCO$_2$$_{sea}$ data to elucidate interannual to decadal variations in CO$_2$ fluxes between the sea and air, which are the characteristic timescales necessary to understand the current global carbon cycle (IPCC, 1995).

Due to technical issues that remain to be solved, platforms for measurement of pCO$_2$$_{sea}$ have long been limited to research vessels. However, measurement of pCO$_2$$_{sea}$ by automated systems onboard voluntary observation ships is now recognized to be a useful way to investigate variations of the oceanic carbonate system. Recently, extensive development of a CO$_2$ measuring system has made it possible to utilize commercial “vessels of opportunity” for pCO$_2$ measurements along their regular trade routes. Cooper et al. (1998) reported an annual variation of pCO$_2$$_{sea}$ in the North Atlantic, using an onboard unattended measurement system. Lefèvre et al. (1999) assessed the seasonality of the oceanic sink for CO$_2$ in the Northern Hemisphere, using data collected on the M/V Prince of Seas between the UK and Costa Rica, and the RMS St. Helena between the UK and South Africa. Lüger et al. (2004) reported results of 1 year of automated pCO$_2$$_{sea}$ measurements made onboard the car carrier M/V Falstaff during 2002–2003 and analyzed factors controlling pCO$_2$$_{sea}$ in the midlatitude North Atlantic Ocean.

In a study of the CO$_2$ flux in the Pacific, Inoue and Sugimura (1992) combined pCO$_2$$_{sea}$ data collected over the period from 1987 to 1989 aboard research and commercial vessels (MS Wellington-maru and MS Yashirogawa-maru) and reported variations in CO$_2$ outflux in the equatorial Pacific. Wong et al. (1993) also reported the CO$_2$ fluxes in the equatorial Pacific during 1986–1987 El Niño, utilizing data collected onboard the MS Lillooet between Canada and Australia. They also investigated geographical, seasonal, and interannual variations of air–sea CO$_2$ exchange in subtropical Pacific surface water during 1983–1988 (Wong et al., 1995a, 1995b). Zeng et al. (2002) constructed monthly distributions of ΔpCO$_2$ in the northern North Pacific based on measurements made onboard the commercial vessel M/S Skaugran in 1995–1999 and reported a small sink (−0.26 Gt-C yr$^{-1}$) for atmospheric CO$_2$.

Despite these extensive efforts, vast areas still lack pCO$_2$$_{sea}$ data. In particular, the transitional area between the subtropical and subarctic gyres in the North Pacific needs to be surveyed intensively, because the area is one of the largest sinks in the global oceans (Takahashi et al., 2002).

The objective of the present study was to examine temporal and spatial distributions of pCO$_2$$_{sea}$ in the North Pacific, especially in the transitional area between the subtropical and subarctic gyres. For this purpose, we installed an underway pCO$_2$ measuring system onboard the container ship MS Alligator Liberty (Mitsui O.S.K. Lines, Ltd.).

The outline of our paper is as follows. In Section 2, we describe the shipboard measurements of pCO$_2$$_{air}$ and pCO$_2$$_{sea}$ carried out on the voluntary observation ship. In Section 3, we discuss the distributions of pCO$_2$$_{air}$ and pCO$_2$$_{sea}$ along the cruise routes, with special reference to oceanic sinks and sources for atmospheric CO$_2$. In Section 4, we estimate the air–sea fluxes of CO$_2$ and evaluate the CO$_2$ sink capacity in the area. We conclude with a short summary and some closing remarks.

---

Fig. 1 Cruise tracks of the MS Alligator Liberty between Tokyo, Japan, and Manzanilo, Republic of Panama, from January 1999 to October 2000: thin dotted lines, winter cruise (from December to February); thick dotted line, spring cruise (from March to May); solid line, summer cruise (from June to August); dash–dotted line, fall cruise (from September to November). The cruise track for June 2000 (not shown) was almost same as that for April 2000.
Table 1 Cruise information

<table>
<thead>
<tr>
<th>Cruise date</th>
<th>Cruise name</th>
<th>Northernmost position</th>
</tr>
</thead>
<tbody>
<tr>
<td>January 23–February 10, 1999</td>
<td>080E</td>
<td>36°N, 158°E</td>
</tr>
<tr>
<td>May 29–June 15, 1999</td>
<td>082E</td>
<td>44°N, 170°W</td>
</tr>
<tr>
<td>August 1–17, 1999</td>
<td>083E</td>
<td>44°N, 174°W</td>
</tr>
<tr>
<td>December 4–21, 1999</td>
<td>085E</td>
<td>36°N, 172°E</td>
</tr>
<tr>
<td>February 6–23, 2000</td>
<td>086E</td>
<td>34°N, 141°E</td>
</tr>
<tr>
<td>April 8–26, 2000</td>
<td>087E</td>
<td>40°N, 175°E</td>
</tr>
<tr>
<td>June 10–27, 2000</td>
<td>088E</td>
<td>40°N, 178°E</td>
</tr>
<tr>
<td>August 13–29, 2000</td>
<td>089E</td>
<td>45°N, 176°W</td>
</tr>
<tr>
<td>October 14–31, 2000</td>
<td>090E</td>
<td>39°N, 170°E</td>
</tr>
</tbody>
</table>

2. Shipboard measurements

Measurements of pCO$_2$$_{\text{sea}}$ and pCO$_2$$_{\text{air}}$ were made in the North Pacific (Tokyo, Japan to Manzanilo, Republic of Panama) onboard the voluntary observation ship MS Alligator Liberty (Mitsui O.S.K. Lines, Ltd.) during 9 cruises from January 1999 to October 2000 (Table 1, Fig. 1). We operated our underway pCO$_2$ measuring system on the eastbound cruises.

All the data for pCO$_2$$_{\text{sea}}$, pCO$_2$$_{\text{air}}$, temperature, and salinity reported here are available from the World Meteorological Organization/World Data Centre for Greenhouse Gases (WMO/WDCGG), Japan Meteorological Agency (JMA), Tokyo Japan.

2.1. Onboard pCO$_2$ measuring system

We installed our system for measuring pCO$_2$$_{\text{sea}}$ and pCO$_2$$_{\text{air}}$ in the air-conditioned control room of the MS Alligator Liberty. The system also monitored sea surface temperature (SST), sea surface salinity (SSS), flow rate of seawater, and seawater level in an equilibrator. The details of the system are reported elsewhere (Foundation for Promoting Personal Mobility and Ecological Transportation, 2001).

The system is basically the same as that reported previously (Hirota et al., 1991; Inoue et al., 1999; Körtzinger et al., 2000). It consists of a nondispersive infrared gas analyzer (BINOS, MLT 3.1, Fisher-Rosemount GmbH & Co.), two electric dehumidifiers, a Nafion tube (Perma Pure Inc.), a chemical desiccant column (Mg(ClO$_4$)$_2$), a shower-head-type water–gas equilibrator, diaphragm pumps, a series of solenoid valves, and a data acquisition unit connected to a personal computer. Water temperature in the equilibrator was measured with a Pt 100-ohm thermometer. The CO$_2$ measuring system was calibrated onboard with 4 reference gases (nominally 272, 330, 360, 405 ppm), which were calibrated before and after the cruise against standard JMA gases, traceable to the WMO mole fraction scale (Watanabe et al., 2000).

2.2. Sea surface temperature (SST) and salinity (SSS)

To measure the SST, we placed a flat-head-type thermocouple probe on the sea chest (very close to the water inlet, ~11 m below the sea surface). The SST was monitored every 5 min. SSS was measured by introducing seawater into a container (20 L) and immersing CTD sensors (SBE21, Sea Bird Co. Ltd.) into it.

Surface seawater was sampled twice a day from the upper deck using a Kamiya-type sampler for measurements of temperature and salinity. We confirmed that the water temperature at the sea chest coincided with that in the sampler within ±0.1 °C and that the salinity measured by the CTD sensor usually coincided within ±0.005 with laboratory measurements on land.

Water temperature typically increased by 0.3 °C from the seawater inlet to the equilibrator. To correct pCO$_2$$_{\text{sea}}$ for increasing water temperature, we used the equation given by Gordon and Jones (1973).

2.3. Sea surface nutrients

During the cruise in August 1999, surface seawater samples for nutrient determination were collected in 10-mL screw-capped test tubes 2 or 4 times a day from a tap attached to the seawater line of the CO$_2$ measuring system. The samples were frozen and stored until laboratory analysis on land. The concentrations of nitrate + nitrite (hereafter denoted NO$_x$) and phosphate (PO$_4$) in seawater were determined by the method of Strickland and Parsons (1972) using an autoanalyzer (AACS III, Bran+Luebbe, Germany).

3. Results and discussion

Figure 1 shows the tracks of the 9 cruises from January 1999 to October 2000 (Table 1), when the pCO$_2$ measurements were made. Since the season and route varied from cruise to cruise, characterizing the temporal and spatial variations of pCO$_2$$_{\text{air}}$ and pCO$_2$$_{\text{sea}}$, we first analyze our data by summarizing a few months (seasonal) of data at a time, neglecting year-to-year differences (Section 3.1). Then, using selected data, we examine seasonal variations of pCO$_2$$_{\text{sea}}$ (Section 3.2).

3.1. General views of the pCO$_2$$_{\text{air}}$ and pCO$_2$$_{\text{sea}}$ distributions

3.1.1. January–February (080E and 086E cruises)

pCO$_2$$_{\text{air}}$ was almost constant along the cruise track, and was generally higher than pCO$_2$$_{\text{sea}}$ (Fig. 2a). West of 150°W, pCO$_2$$_{\text{sea}}$ was almost constant (310 ± 10 µatm), whereas east of 150°W, pCO$_2$$_{\text{sea}}$ increased gradually to the east. As a whole, distributions of pCO$_2$$_{\text{sea}}$ as a function of longitude showed gradual variations. This is probably because, on these cruises, the ship sailed mostly in the subtropical gyre.
south of 36°N, where nutrients are almost depleted (Fig. 2b) and variation of pCO$_2$$_{sea}$ is mostly controlled by variations of SST and SSS (Inoue et al., 1995, 2003). In this season, the area overall acted as a sink for atmospheric CO$_2$.

### 3.1.2. April–June (082E, 087E, and 088E cruises)

The pCO$_2$$_{air}$ in this season was highest (~370 µatm; Fig. 3a) among all data collected during the 9 cruises. The high pCO$_2$$_{air}$ was mainly caused by the seasonal increase in atmospheric CO$_2$ concentration from winter to spring in the Northern Hemisphere (Conway et al., 1994).

Spatial variations of pCO$_2$$_{sea}$ in this season were larger than those in Fig. 2, and this difference is attributable to northward shifts of the cruise tracks (up to 40–44°N; Table 1, Fig. 1). That is, the ship entered the transitional area between the subtropical and subarctic gyres, where pCO$_2$$_{sea}$ is usually affected not only by SST and SSS but also by biological activity (Takahashi et al., 2002). Consequently, the pCO$_2$$_{sea}$–SST relationship became complicated, and pCO$_2$$_{sea}$ showed variations associated with those of NO$_3$ and PO$_4$ (Fig. 3b). For example, from 140 to 160°E, pCO$_2$$_{sea}$ increased as SST decreased on the 087E cruise (April 2000), whereas pCO$_2$$_{sea}$ decreased as SST decreased on the 082E cruise (late May–June 1999) and the 088E cruise (June 2000); in April 2000, pCO$_2$$_{sea}$ decreased as SST increased from 160°E to 150°W, whereas pCO$_2$$_{sea}$ increased as SST increased east of 150°W. A positive correlation between pCO$_2$$_{sea}$ and SST (subtropical characteristics; 140 to 160°E in late May–June 1999 and June 2000, east of 150°W in June 2000) was observed in the area with depleted nutrients, indicating relatively large effects of thermodynamics. On the other hand, a negative pCO$_2$$_{sea}$–SST relationship (subarctic characteristics; 140 to 160°E in April 2000, 160°E to 150°W in June 2000) was found in the area with relatively rich nutrients, indicating relatively large effects of the entrainment of total inorganic carbon (TCO$_2$) from the lower layer. In late May–June 1999, pCO$_2$$_{sea}$ varied steeply around 160°W, but both SST and SSS varied monotonously.

---

Fig. 2 Longitudinal distributions of surface properties observed in January–February 1999 (080E) and February 2000 (086E). (a) pCO$_2$$_{air}$ (open circle, January–February 1999; plus, February 2000) and pCO$_2$$_{sea}$ (dashed line, January–February 1999; solid line, February 2000). (b) NO$_3$ (open circle) and PO$_4$ (open triangle) in February 2000. (c, d) SSS and SST (dashed line, January–February 1999; solid line, February 2000).

Fig. 3 Longitudinal distributions of surface properties observed in May–June 1999 (082E), April 2000 (087E), and June 2000 (088E). (a) pCO$_2$$_{air}$ (open circle, May–June 1999; plus, April 2000; open triangle, June 2000) and pCO$_2$$_{sea}$ (thin solid line, May–June 1999; thick dashed line, April 2000; thick solid line, June 2000). (b) NO$_3$ (open circle, April 2000; solid circle, June 2000) and PO$_4$ (open triangle, April 2000; solid triangle, June 2000). (c, d) SSS and SST (thin solid line, May–June 1999; thick dashed line, April 2000; thick solid line, June 2000).
(nutrients were not measured on this cruise). In the same area, no clear steep variations of pCO$_{2\text{sea}}$ occurred in June 2000.

In this season, pCO$_{2\text{sea}}$ showed an overall increase from west to east. Consequently, the area west of 150°W acted as a sink for atmospheric CO$_2$, whereas the area east of 150°W generally acted as a source of atmospheric CO$_2$.

### 3.1.3. August (083E and 089E cruises)

During these cruises, the ship took a northern route up to 44–45°N (180°–170°W) and then headed southward down to 29°N, 120°W (Fig. 1). pCO$_{2\text{sea}}$ exhibited a greater variation in this season (Fig. 4a) than in other seasons, probably due to differences in air masses.

Spatial variations of pCO$_{2\text{sea}}$ in August (Fig. 4a) were as large as those in the April–June season (Fig. 3a); in August 1999, pCO$_{2\text{sea}}$ varied steeply from 400 to 320 µatm around 160°W, but with monotonous variations of SST and SSS (Figs. 4c and 4d). At 158°E, 161°E, and 170°E, pCO$_{2\text{sea}}$ showed large variations, but SST and SSS exhibited no such variations. Between 150 and 170°W and east of 130°W, pCO$_{2\text{sea}}$ in August 2000 showed distributions greatly different from those in August 1999. In particular, no steep variation of pCO$_{2\text{sea}}$ occurred around 160°W in August 2000.

The concentrations of nitrate and phosphate were low in both the western and eastern subtropical North Pacific (Fig. 4b). On the other hand, significant increases in both concentrations were observed in the transitional area around 160°E–160°W (highest concentrations: 11.8 µmol/kg for nitrate and 1.15 µmol/kg for phosphate). Corresponding to the above-mentioned steep decrease in pCO$_{2\text{sea}}$ of ~50 µatm around 160°W (43°E) in August 1999, nutrient concentrations decreased significantly from 163°W to 155°W. From the combination of the decrease in nitrate of 6 µmol/kg and a C/N ratio of 9.5 for biological consumption (cf. Section 3.2), we expected a TCO$_2$ change of ~57 µmol/kg and subsequent pCO$_{2\text{sea}}$ change of ~90 µatm.

![Fig. 4 Longitudinal distributions of surface properties observed in August 1999 (083E) and August 2000 (089E). (a) pCO$_{2\text{sea}}$ (open circle, August 1999; plus, August 2000) and pCO$_{2\text{sea}}$ (dashed line, August 1999; solid line, August 2000). (b) NO$_x$ (open circle, August 1999; solid circle, August 2000). (c) SSS and SST (dashed line, August 1999; solid line, August 2000).](image)

![Fig. 5 Longitudinal distributions of surface properties observed in December 1999 (085E) and October 2000 (090E). (a) pCO$_{2\text{sea}}$ (open circle, December 1999; plus, October 2000) and pCO$_{2\text{sea}}$ (dashed line, December 1999; solid line, October 2000). (b) NO$_x$ (open circle, December 1999; solid circle, October 2000) and PO$_4$ (open triangle, December 1999; solid triangle, October 2000). (c) SSS and SST (dashed line, December 1999; solid line, October 2000).](image)
Considering that an SST increase of 1.5 °C leads to a pCO$_2$sea change of +20 µatm, we calculated a total pCO$_2$sea drawdown of ~70 µatm. Taking into account the scattering of the C/N ratio for biological consumption (shown in Fig. 6), a major portion of the pCO$_2$sea drawdown — ~50 µatm around 160°W — could be explained by biological consumption.

pCO$_2$sea was generally higher than pCO$_2$air, meaning that in this season, the area generally acted as a source for atmospheric CO$_2$.

3.1.4. October and December (085E and 090E cruises)

The distributions of pCO$_2$sea (Fig. 5a) in October and December, like those in the January–February season, showed a small variation (Fig. 2a). This is probably because the ship took a southern route, entering the subtropical gyre at around 160°W in October 2000 and of 60 µatm from 160 to 120°W in December 1999 were larger than those due to the thermodynamic effects of SST increases of 3 and 2 °C, respectively. We believe that these variations of pCO$_2$sea are influenced by the supply of TCO$_2$ from the lower layer due to enhanced vertical mixing in these seasons.

In this season, the area overall acted as a sink for atmospheric CO$_2$.

3.1.5. CO$_2$ sinks and sources

From the distributions of pCO$_2$air and pCO$_2$sea (Figs. 2a–5a), we summarize as follows: west of 180°, the area acted as a sink for atmospheric CO$_2$ throughout the year except for August, whereas east of 160°W, it acted as a sink for only half the year (December to May).

3.2. Seasonal variability of pCO$_2$sea

Among the 9 cruises, the MS Alligator Liberty steamed from Tokyo to Manzanillo along the same cruise track in April 2000 and June 2000, which allows us to evaluate seasonal variations of pCO$_2$sea from April to June. We examined variations of pCO$_2$sea against those of SST, SSS, and NO$_x$ during these two cruises.

In the eastern subtropical North Pacific, NO$_x$ was depleted throughout the year. West of 180°, the NO$_x$ concentrations decreased significantly from April to June, which means that biological activity has a larger effect on the surface carbonate system in the western North Pacific than in the eastern North Pacific (Takahashi et al., 1993). In fact, we found that pCO$_2$sea varied according to NO$_x$ concentration (>1 µmol/kg). Assuming a thermodynamic temperature effect on pCO$_2$sea, we calculated pCO$_2$sea normalized (n-pCO$_2$sea) to the average SST temperature (13.8 °C) for the two cruises. Using the equation given by Millero et al. (1998), we estimated the total alkalinity in surface waters. From n-pCO$_2$sea and total alkalinity, we calculated the TCO$_2$ concentrations, using the chemical equilibrium constants recommended by DOE (1994).

Figure 6 illustrates the relationship between TCO$_2$ and NO$_x$ concentration (>1 µmol/kg). Linear least-squares regression analysis gave 9.5 as the TCO$_2$ increase per unit increase of NO$_x$ concentration, which is slightly larger than the Redfield C/N ratio (6.6). Figure 6 clearly indicates that seasonal variations of pCO$_2$sea can be well accounted for by the effects of thermodynamics and biological activity.

4. Air–sea exchanges of CO$_2$

4.1. Calculation of air–sea fluxes of CO$_2$

Air–sea fluxes of CO$_2$ (F$_{CO2}$) were calculated as the product of the gas-transfer velocity $K_{CO2}$ as a function of wind speed (Wanninkhof, 1992; Wanninkhof and McGillis, 1999), the solubility of CO$_2$ ($ß$; Weiss, 1974), and the partial pressure difference in pCO$_2$ between the sea surface and the air ($affles pCO2$) as follows:

$$F_{CO2} = K_{CO2} \times ß \times (pCO2_sea - pCO2_air) = K_{CO2} \times ß \times Æaffles pCO2$$

(1).

We used Eq. (2) to compute the gas-transfer velocity from wind speed data (Wanninkhof, 1992):

$$K_{CO2} = 0.39 w_{10}^2 (660/Sc)^{0.5}$$

(2),

where Sc is the Schmidt number of CO$_2$ at the observed SST and SSS (660 is the Schmidt number of CO$_2$ in seawater at 20 °C) and $w_{10}$ is the wind speed in m s$^{-1}$ at a height of 10 m. For the wind speed, we used the NCEP/NCAR reanalysis data (Kalnay et al., 1996). Since the NCEP/NCAR reanalysis data are prepared for a 2.5° × 2.5° grid, the wind speed was linearly interpolated into 1° × 1° pixels.

4.2. Interpolation/extrapolation of pCO$_2$sea

Relationships between pCO$_2$sea and SST have been used extensively to estimate pCO$_2$sea distributions on a basin scale (e.g., Tans et al., 1990; Ishii et al., 2004). In the present study, we also attempted to use a pCO$_2$sea–SST relationship.

Using pCO$_2$sea data taken during the 9 cruises of the MS Alligator Liberty, we examined distributions of pCO$_2$sea...
as a function of SST (Fig. 7). From Fig. 7a, we found that a simple $pCO_2$-SST relationship (quadratic function) existed in the western North Pacific (30–40°N, 140°E–180°) throughout the year. However, $pCO_2$ in the latitudinal zone between 30 and 40°N of the eastern North Pacific (180° to 122°W) did not reveal a simple pattern (Fig. 7b), implying that estimation of $pCO_2$ distributions from the SST field is difficult in the eastern North Pacific. Therefore we decided to interpolate/extrapolate $pCO_2$ and to calculate $\Delta pCO_2$ and CO$_2$ fluxes only in the western North Pacific covering the area from 30 to 40°N and 140°E to 180° (Fig. 1). The monthly mean SST data were taken from Reynolds and Smith (1994)(ftp://ftp.ncep.noaa.gov/pub/cmb/sst/oimonth).

In the western North Pacific, $\Delta pCO_2$ is largest around the area with an SST of 16–19 °C because, under this condition, $pCO_2$ is lowest (Fig. 7a). In other words, for the same gas-transfer coefficient, the ocean absorbs CO$_2$ most efficiently in the area of this SST. The North Pacific Subtropical Mode Water (NPSTMW), characterized by an average temperature of 16.5–18.5 °C, forms and subducts through seasonal cooling at the ocean surface in the transitional area between the subtropical and subarctic gyres (Masuzawa, 1969; Taneda et al., 2000). This downward movement of NPSTMW is believed to be accompanied by absorption of CO$_2$. Therefore, the transitional area is a typical example of this situation, and absorption of CO$_2$ was largest in this area.
4.3. \( \Delta p \text{CO}_2 \) and air–sea fluxes of \( \text{CO}_2 \) in the western North Pacific

The calculated annual mean \( \Delta p \text{CO}_2 \) field for the year 2000 is shown in Fig. 8. This figure indicates that the western North Pacific acted as a strong sink for atmospheric \( \text{CO}_2 \). Large negative values of \( \Delta p \text{CO}_2 \) predominate in the northeastern area, which was caused by the decreases in \( p \text{CO}_2 \)\(_{\text{sea}} \) associated with a low SST. Small negative values of \( \Delta p \text{CO}_2 \) occurred in the subtropics gyre, which was caused by the increases in \( p \text{CO}_2 \)\(_{\text{sea}} \) in response to the warmer SST of the Kuroshio.

The annual mean of the \( \text{CO}_2 \) fluxes in 2000 is illustrated in Fig. 9. Distributions of the \( \text{CO}_2 \) fluxes revealed an east–west contrast; in the western area, the \( \text{CO}_2 \) fluxes were constant against latitude (west of 145\(^\circ\)E), whereas in the eastern area, the \( \text{CO}_2 \) fluxes became more negative from south to north.

The \( \text{CO}_2 \) fluxes in 2000 showed a seasonal variation (Table 2). The variation was close to ca. 0 Gt-C yr\(^{-1} \) during the summer season and ca. –0.4 Gt-C yr\(^{-1} \) during the winter season, resulting in an annual mean value of –0.2 Gt-C yr\(^{-1} \). In the western part of the North Pacific, large negative values of \( \Delta p \text{CO}_2 \) and high wind speed occurred during the winter season, and the opposite conditions occurred during the summer season. These differences in conditions led to large seasonal variations in the \( \text{CO}_2 \) fluxes, ranging from 0 to –0.4 Gt-C yr\(^{-1} \) (Table 2). The peak-to-trough amplitude of \( p \text{CO}_2 \) in the area could affect the seasonal variation in atmospheric \( \text{CO}_2 \) up to ~0.2 ppm.

According to an IPCC report (2001), the oceanic \( \text{CO}_2 \) uptake over the 1990s was about 1.7 Gt-C yr\(^{-1} \) based on measurements of atmospheric \( \text{O}_2/\text{N}_2 \). The surface area examined in this work is about 1.6% of the global ocean, but the \( \text{CO}_2 \) flux between the sea and the air corresponds to about 10% of the annual oceanic \( \text{CO}_2 \) uptake in the global ocean over the 1990s. In other words, the study area could decrease atmospheric \( \text{CO}_2 \) by ~0.1 ppm every year.

5. Concluding remarks

We have found that the transitional area between the subtropical and subarctic gyres in the western North Pacific (30–40\(^\circ\)N, 140\(^\circ\)E–180\(^\circ\)) significantly contributes to the absorption of atmospheric \( \text{CO}_2 \) in spite of its relatively small area. This is probably because the area includes the Kuroshio Extension, which is one of the strongest sinks in the global ocean (Takahashi et al., 2002). These results suggest the efficient uptake of \( \text{CO}_2 \) associated with the formation of North Pacific Subtropical Mode Water in this area. On this account, monitoring of \( p \text{CO}_2 \)\(_{\text{sea}} \) and related properties in this area should be intensified.

We have already confirmed that the data we obtained using the voluntary observation ship are of good quality. These data could be combined with data obtained by the RV Ryofu-maru, which provided data for secular changes in \( p \text{CO}_2 \)\(_{\text{sea}} \) (Inoue et al., 1995). Thus, using voluntary observation ships, it may be possible to quantify temporal changes in the basin-scale oceanic uptake of \( \text{CO}_2 \).

\( p \text{CO}_2 \)\(_{\text{sea}} \) was controlled primarily by the thermodynamic effects of the SST in the subtropical gyre, where nutrients were almost depleted, whereas we observed differences in \( p \text{CO}_2 \)\(_{\text{sea}} \) variation between the western and eastern subtropical regions. In the transitional area, the temporal and spatial variations of \( p \text{CO}_2 \)\(_{\text{sea}} \) were affected not only by thermodynamic effects but also by biological activity or entrainment. We interpreted these variations in terms of their relationship to variations of nutrient concentrations. Thus an elaborate system needs to be developed that can simultaneously measure both \( p \text{CO}_2 \) and \( \text{CO}_2 \)-related properties. More investigations using such a system are needed to elucidate the processes controlling the variations in the surface carbonate system over the North Pacific.

Acknowledgements

The authors are deeply indebted to M.O. Ship Management Co. Ltd. and Mitsui O.S.K. Lines for extensive cooperation, particularly in allowing the use of the M/V Alligator Liberty and construction of the \( \text{CO}_2 \) measurement system on board. The authors appreciate the support and cooperation of the captains, officers, and crews of the ship during the measurements, without which this work would not have been possible. Thanks are also due to the Japan Association of Marine Safety for help in selecting the ship. This project was financially supported by the Nippon Foundation and directed by the Foundation for Promoting Personal Mobility and Ecological Transportation.

<table>
<thead>
<tr>
<th>Month</th>
<th>( \Delta p \text{CO}_2 ) (\text{atm})</th>
<th>Wind speed (m s(^{-1} ))</th>
<th>( \text{CO}_2 ) flux (Gt-C yr(^{-1} ))(^{*} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>–54.3</td>
<td>9.3</td>
<td>–0.32 ± 0.05</td>
</tr>
<tr>
<td>February</td>
<td>–50.2</td>
<td>11.2</td>
<td>–0.44 ± 0.06</td>
</tr>
<tr>
<td>March</td>
<td>–51.5</td>
<td>10.7</td>
<td>–0.40 ± 0.06</td>
</tr>
<tr>
<td>April</td>
<td>–57.8</td>
<td>7.9</td>
<td>–0.24 ± 0.05</td>
</tr>
<tr>
<td>May</td>
<td>–56.3</td>
<td>7.1</td>
<td>–0.20 ± 0.05</td>
</tr>
<tr>
<td>June</td>
<td>–44.5</td>
<td>6.6</td>
<td>–0.14 ± 0.05</td>
</tr>
<tr>
<td>July</td>
<td>–20.3</td>
<td>6.2</td>
<td>–0.06 ± 0.04</td>
</tr>
<tr>
<td>August</td>
<td>1.8</td>
<td>5.2</td>
<td>0.00 ± 0.04</td>
</tr>
<tr>
<td>September</td>
<td>–2.3</td>
<td>6.4</td>
<td>–0.01 ± 0.04</td>
</tr>
<tr>
<td>October</td>
<td>–22.5</td>
<td>7.0</td>
<td>–0.08 ± 0.05</td>
</tr>
<tr>
<td>November</td>
<td>–40.0</td>
<td>8.2</td>
<td>–0.19 ± 0.05</td>
</tr>
<tr>
<td>December</td>
<td>–50.3</td>
<td>9.8</td>
<td>–0.34 ± 0.05</td>
</tr>
<tr>
<td>Annual</td>
<td>–37.4</td>
<td>8.0</td>
<td>–0.20 ± 0.05</td>
</tr>
</tbody>
</table>

\(^{*}\) The uncertainty was estimated based on the \( p \text{CO}_2 \)\(_{\text{sea}} \)-SST relationship and wind speed (Kalnay et al., 1996).
References


Watanabe, F., Uchino, O., Joo, Y., Aono, M., Higashijima, K., Hirano, Y., Tsuibo, K., and Suda, K. 2000. Interannual variation of growth rate of atmospheric carbon dioxide concentration at the JMA's three monitoring stations: large