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Citation	Geophysical Research Letters, 32, L05612 <a href="https://doi.org/10.1029/2004GL021952">https://doi.org/10.1029/2004GL021952</a>
Issue Date	2005-03-11
Doc URL	<a href="http://hdl.handle.net/2115/906">http://hdl.handle.net/2115/906</a>
Type	article (author version)
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File Information	GRL32.pdf



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## **Persistently strong oceanic CO<sub>2</sub> sink in the western subtropical North Pacific**

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## Abstract

The long-term trend of the partial pressure of CO<sub>2</sub> in surface seawater ( $p\text{CO}_2^{\text{sea}}$ ) in late-January to early-February during the past two decades was examined in the western North Pacific along the repeat line at 137°E from 3°N to 34°N. The growth rate of  $p\text{CO}_2^{\text{sea}}$  at each 1° in latitude ranged from  $+1.3 \pm 0.2$  to  $+2.1 \pm 0.3$   $\mu\text{atm yr}^{-1}$ , and the average was  $+1.7 \pm 0.2$   $\mu\text{atm yr}^{-1}$ . The growth of  $p\text{CO}_2^{\text{sea}}$  is attributable mainly to the uptake of anthropogenic CO<sub>2</sub> in surface water and, to a small extent, to the regional changes in sea surface temperature (SST). The net air-to-sea CO<sub>2</sub> flux in January–February that accounts for 40 to 60% of the annual flux remained at a similar level in the subtropical regions (7°N to 34°N). In the equatorial region (3°N to 6°N), however, a slight increase in the CO<sub>2</sub> efflux was seen.

## 1. Introduction

The ocean is believed to be a major sink for the increasing atmospheric CO<sub>2</sub> resulting from anthropogenic CO<sub>2</sub> emissions, and a large number of observational and modeling studies have been carried out to quantify its strength. The recent estimate for the net annual CO<sub>2</sub> uptake by the ocean in the past two decades ranges between 1.5 and 2.8 PgC yr<sup>-1</sup> (IPCC, 2001). However, many uncertainties are associated with these estimates, and little has been determined about the long-term trend because only a small amount of time-series data for CO<sub>2</sub> has been acquired in the oceans.

Time-series measurements for CO<sub>2</sub> in the ocean provide direct and critical information on the uptake of atmospheric CO<sub>2</sub>. The growth rate of  $p\text{CO}_2^{\text{sea}}$  ( $1.5 \pm 0.1$   $\mu\text{atm yr}^{-1}$ ) has been reported to be similar to that of the atmospheric one ( $p\text{CO}_2^{\text{air}}$ ) for the subtropical North Atlantic (Gruber *et al.*, 2002). At the Hawaii Ocean Time-series (HOT) site in the eastern subtropical North Pacific,  $p\text{CO}_2^{\text{sea}}$  is rapidly increasing due to the increase in salinity, and, consequently, the strength of the oceanic CO<sub>2</sub> sink is declining (Dore *et al.*, 2003). In the western and central equatorial Pacific, a significant acceleration in the  $p\text{CO}_2^{\text{sea}}$  growth after the phase shift of the Pacific Decadal Oscillation (PDO) has been documented (Takahashi *et al.*, 2003). However, Ishii *et al.* (2004) reported that the growth rate of  $p\text{CO}_2^{\text{sea}}$  within the western equatorial Pacific

warm pool does not differ significantly from that of  $p\text{CO}_2^{\text{air}}$ .

The repeat line at 137°E in the western North Pacific is also one of the few areas where oceanic  $\text{CO}_2$  measurements have been routinely made since the early 1980s. We have previously described the latitudinal and seasonal variations of  $p\text{CO}_2^{\text{sea}}$  along 137°E and its trend of increase in winter for the period from 1984 through 1993 (Inoue *et al.*, 1987; 1995). In this study, we analyze further trends of  $p\text{CO}_2^{\text{sea}}$  over two decades from 1984 through 2003 and discuss factors controlling the long-term growth as well as the change in the net air-sea  $\text{CO}_2$  flux along this line.

## **2. Data and Methods**

A comprehensive set of data for hourly  $p\text{CO}_2^{\text{sea}}$ ,  $p\text{CO}_2^{\text{air}}$ , and related hydrographic parameters, such as SST and sea surface salinity (SSS), has been acquired aboard the R/V *Ryofu Maru* of the Japan Meteorological Agency (JMA). Measurements have been made from 3°N to 34°N along the 137°E line in the western North Pacific (Fig. 1) from late January to early February since 1981, and details of the methods have been described in Inoue *et al.* (1995).

The net flux of  $\text{CO}_2$  across the air-sea interface was calculated as the product of the gas transfer piston velocity of  $\text{CO}_2$ , the solubility of  $\text{CO}_2$  in seawater, and the

difference between  $p\text{CO}_2^{\text{sea}}$  and  $p\text{CO}_2^{\text{air}}$  ( $\Delta p\text{CO}_2$ ). The gas transfer piston velocity was calculated using the equation given by Wanninkhof (1992) for the long-term averaged wind speed. The wind speed data at 10 m above the sea surface at every 6 hours were taken from the reanalysis by the National Center for Environmental Prediction (NCEP)/National Center for Atmospheric Research (<http://www.cdc.noaa.gov/cdc/reanalysis>) and averaged over January and February.

In this study, we have used the  $p\text{CO}_2^{\text{sea}}$  data taken in January/February from 1983 to 2003 for analysis rather than those from 1981 and 1982 because of a technical problem in the measurements (Inoue *et al.*, 1995). The data used in this study are available from the World Meteorological Organization's World Data Center for Greenhouse Gases (WDCGG; <http://gaw.kishou.go.jp/wdcgg.html>) operated by JMA.

### 3. Results and Discussion

The latitudinal distributions of  $p\text{CO}_2^{\text{air}}$ ,  $p\text{CO}_2^{\text{sea}}$ , and related surface properties along 137°E in winter have been described previously (Inoue *et al.*, 1987, 1995; Ishii *et al.*, 2001). In general, the  $p\text{CO}_2^{\text{air}}$  shows a gentle decrease toward the south (data not shown), while  $p\text{CO}_2^{\text{sea}}$  shows much larger latitudinal variation;  $p\text{CO}_2^{\text{sea}}$  is low off of Japan and increases toward the south with the increase in SST (Figs. 2a, d). The  $\Delta p\text{CO}_2$

ranges between  $-60 \mu\text{atm}$  or less in the northern part of the subtropical gyre to the north of  $25^\circ\text{N}$  and  $0$  to  $+10 \mu\text{atm}$  in the equatorial region between  $3^\circ\text{N}$  and  $6^\circ\text{N}$  (Fig. 2e). The region to the north of  $7^\circ\text{N}$  is typically a sink for the atmospheric  $\text{CO}_2$  due to winter cooling, whereas the equatorial region acts as a weak source.

In the western equatorial Pacific at  $137^\circ\text{E}$ , Inoue *et al.* (1987) and Nemoto *et al.* (2001) reported large positive anomalies of dissolved inorganic carbon (DIC) during the strong El Niño events of 1983 and 1998 as a result of vertical mixing enhanced by the leaving of warm water with low DIC and consequent shoal of thermocline. The elevated DIC concentration increased  $p\text{CO}_2^{\text{sea}}$  in 1983 but not in 1998 because of its cancellation by the effect of the low SST. In January 1987, during another El Niño event, no distinct anomaly of  $p\text{CO}_2^{\text{sea}}$  or DIC was observed at  $137^\circ\text{E}$ . In order to remove any effects of strong El Niño events on the long-term trend, we excluded  $p\text{CO}_2^{\text{sea}}$  data taken in 1983 and 1998 when SST anomalies recorded negative values as large as  $-1.0^\circ\text{C}$  (Fig. 2a).

The increase rate of  $p\text{CO}_2^{\text{sea}}$  averaged in each  $1^\circ$  in latitude along  $137^\circ\text{E}$  was calculated using the linear least-squares method. The values ranged from  $+1.3 \pm 0.2$  to  $+2.1 \pm 0.3 \mu\text{atm yr}^{-1}$  (Fig. 3a) for the past two decades and averaged  $+1.7 \pm 0.2 \mu\text{atm yr}^{-1}$  ( $r^2 = 0.88$ ) over the whole study region. High increase rates that exceeded  $+2.0 \mu\text{atm yr}^{-1}$  were observed in the equatorial region ( $3^\circ\text{N}$  to  $6^\circ\text{N}$ ) and at the northernmost

latitude of 34°N. In the subtropical regions north of the North Equatorial Counter-Current (Fig. 1), the growth rate of  $p\text{CO}_2^{\text{sea}}$  did not significantly differ from that of  $p\text{CO}_2^{\text{air}}$  ( $+1.60 \pm 0.03 \mu\text{atm yr}^{-1}$ ;  $r^2 = 0.99$ ), and  $\Delta p\text{CO}_2$  remained virtually unchanged ( $-0.1 \pm 0.1$  to  $+0.3 \pm 0.3 \mu\text{atm yr}^{-1}$ ;  $r^2 < 0.05$ ; Fig. 3b) except at latitudes 20°N and 21°N. At 20°N and 21°N, the  $p\text{CO}_2^{\text{sea}}$  increase rate ( $+1.3 \pm 0.2 \mu\text{atm yr}^{-1}$ ) was smaller than that of  $p\text{CO}_2^{\text{air}}$ , and  $\Delta p\text{CO}_2$  showed a trend of  $-0.3 \pm 0.3 \mu\text{atm yr}^{-1}$  ( $r^2 = 0.09$ ), indicating the increase in the magnitude of negative  $\Delta p\text{CO}_2$  at these latitudes.

The concurrent increases in  $p\text{CO}_2^{\text{sea}}$  and  $p\text{CO}_2^{\text{air}}$  in the extensive region along 137°E suggest that the surface layer over this region is responding rapidly to the rising atmospheric  $\text{CO}_2$  level caused by anthropogenic emissions, i.e., elevated influx enables the rapid response of  $p\text{CO}_2^{\text{sea}}$  even in a region where strong vertical mixing (e.g., the mixed layer depth of 150-200m in 29°N-32°N) occurs in winter. However, we cannot rule out the effects of long-term changes in other factors that control  $p\text{CO}_2^{\text{sea}}$ , such as those of SST/SSS and DIC due to changes in heat/freshwater flux, vertical/horizontal mixing, and biological activities (Ishii *et al.*, 2001).

In order to evaluate the contributions from processes other than the anthropogenic effect to the growth of  $p\text{CO}_2^{\text{sea}}$ , we examined the thermodynamic effects of SST/SSS changes by applying the equations given by Weiss *et al.* (1982). In the western North



Pacific along 137°E, we observed an SST rise of  $+0.02 \pm 0.02$  °C yr<sup>-1</sup> from 1984 to 2003, which is consistent with the SST rise of  $+0.018 \pm 0.005$  °C yr<sup>-1</sup> from 1976 to 2000 in the Northern Hemisphere reported in the IPCC (2001). On the other hand, SSS showed very little change,  $0.000 \pm 0.004$  yr<sup>-1</sup> on the average. These changes in both SST and SSS contribute totally to the  $p\text{CO}_2^{\text{sea}}$  increase of only  $+0.2 \pm 0.3$  µatm yr<sup>-1</sup>. The apparent  $p\text{CO}_2^{\text{sea}}$  change could be somewhat different from that expected from the thermodynamic effects of SST and SSS changes because the changes in SST and/or SSS would be connected to the changes in mixing dynamics and the biogeochemical processes in the upper layer in the respective latitudes. However, the small effects of the SST and SSS changes strongly suggest that the long-term increase in  $p\text{CO}_2^{\text{sea}}$  has been caused primarily by the increase in DIC due to the anthropogenic effect on the CO<sub>2</sub> uptake.

Dore *et al.* (2003) demonstrated the higher growth rate of  $p\text{CO}_2^{\text{sea}}$  ( $+2.46 \pm 0.28$  µatm yr<sup>-1</sup>) accompanied by the recent increase in SSS at the HOT site in the eastern subtropical North Pacific. Keeling *et al.* (2004) proposed that the recent increase in  $p\text{CO}_2^{\text{sea}}$  resulted mainly from the increased flow from northwestern waters with greater  $p\text{CO}_2^{\text{sea}}$  and salinity related to a large-scale reorganization of the climate system over the North Pacific. In the western subtropical North Pacific, however, the effects of

changes in salinity and water masses were markedly less than those around the HOT site in the long term.

The growth rate of  $p\text{CO}_2^{\text{sea}}$  was relatively low at latitudes 20°N and 21°N (Fig. 3a) at the zones of the eastward Subtropical Counter-Current (SCC). It has been reported that the SCC is strongly affected by the wind field and wind-shielding effects of high mountains in Hawaii as well as the surrounding bottom topography (Xie *et al.*, 2001). Thus, long-term changes in the wind field may affect the growth of  $p\text{CO}_2^{\text{sea}}$  via the change in the SCC system. The decrease in SST ( $-0.03 \pm 0.02 \text{ } ^\circ\text{C yr}^{-1}$ ) at 20-21°N suggests its relation to the southward movement of the northern edge of the SCC. In contrast, higher growth rates of  $p\text{CO}_2^{\text{sea}}$  were observed at 34°N and in the equatorial region south of 7°N (Fig. 3a). The former was probably due to the migration of the Kuroshio pathway and related intrusion of northern coastal water with higher  $p\text{CO}_2^{\text{sea}}$  (Inoue *et al.*, 1995).

The higher growth rates of  $p\text{CO}_2^{\text{sea}}$  ( $+2.1 \pm 0.2 \text{ } \mu\text{atm yr}^{-1}$ ;  $r^2 = 0.84$ ) between 3°N and 6°N (Fig. 3a) were accompanied by a rising trend of SST ( $+0.04 \pm 0.02 \text{ } ^\circ\text{C yr}^{-1}$ ,  $r^2 = 0.17$ ) due to the frequent prevalence of warm water at 137°E under La Niña conditions in the late 1990s. After removing the thermodynamic effects of SST/SSS changes, the growth rate of  $p\text{CO}_2^{\text{sea}}$  was calculated to be  $+1.6 \text{ } \mu\text{atm yr}^{-1}$ , which was equal to the

growth of  $p\text{CO}_2^{\text{air}}$  ( $+1.60 \pm 0.03 \mu\text{atm yr}^{-1}$ ). This result suggests that the  $p\text{CO}_2^{\text{sea}}$  in the western equatorial Pacific at  $137^\circ\text{E}$  has also changed rapidly in response to rising  $p\text{CO}_2^{\text{air}}$ . In the western and central equatorial Pacific between  $135^\circ\text{E}$  and  $175^\circ\text{E}$ , Takahashi *et al.* (2003) reported that the mean growth rate of  $p\text{CO}_2^{\text{sea}}$  has changed from  $+0.5 \pm 0.3 \mu\text{atm yr}^{-1}$  to  $+3.4 \pm 0.4 \mu\text{atm yr}^{-1}$  before and after the PDO shift that occurred between 1988 and 1992. However, our  $p\text{CO}_2^{\text{sea}}$  record in the equatorial region along  $137^\circ\text{E}$  showed only the difference in the growth rate between before ( $+1.0 \pm 1.2 \mu\text{atm yr}^{-1}$ ) and after the PDO shift ( $+2.0 \pm 0.5 \mu\text{atm yr}^{-1}$ ) with a confidence level of less than 86%. In order to ascertain the changes in the growth rate on the time scale of a few decades, more data, including repeated measurements, would be necessary.

The latitudinal distribution of the wind speed averaged for January and February (Fig. 2c) generally showed its maxima in two zones, the strong trade winds ( $16^\circ\text{N}$  to  $17^\circ\text{N}$ ;  $8.4 \pm 0.5 \text{ m s}^{-1}$ ) and the northwesterly winter monsoon ( $31^\circ\text{N}$  to  $32^\circ\text{N}$ ;  $8.5 \pm 0.4 \text{ m s}^{-1}$ ). The net air-sea  $\text{CO}_2$  flux for January and February in the subtropical regions between  $7^\circ\text{N}$  and  $34^\circ\text{N}$  was negative and became more negative toward the north; the influxes for two months increased on average from  $-0.02 \pm 0.04 \text{ mol m}^{-2}$  at  $7^\circ\text{N}$  to  $-0.85 \pm 0.11 \text{ mol m}^{-2}$  at  $31^\circ\text{N}$  (Fig. 2f). It should be noted that they remained at fairly similar levels for the past two decades over the zones north of  $7^\circ\text{N}$  because of the insignificant

long-term changes in both  $\Delta p\text{CO}_2$  and wind speed (Figs. 3b-d). Because the influx in January and February accounted for 40 to 60% of the annual flux (JMA, 2004), the long-term trend of the  $\text{CO}_2$  flux detected in this study might roughly be extrapolated to that of the annual oceanic  $\text{CO}_2$  uptake in the western subtropical North Pacific.

By contrast,  $\Delta p\text{CO}_2$  was mostly positive, but the  $\text{CO}_2$  efflux to the atmosphere was small in the equatorial region between  $3^\circ\text{N}$ - $6^\circ\text{N}$ . The sum of effluxes in January and February during the study period was no more than  $+0.04 \pm 0.03 \text{ mol m}^{-2}$  (Fig. 2f). In the long term, however, the efflux had a tendency to increase at a rate of  $+2.4 \pm 0.8 \text{ mmol m}^{-2} \text{ yr}^{-1}$  ( $r^2 = 0.32$ ,  $p < 0.05$ ) on the average in  $3^\circ\text{N}$ - $6^\circ\text{N}$  due to the increase in  $\Delta p\text{CO}_2$  at  $+0.57 \pm 0.22 \text{ } \mu\text{atm yr}^{-1}$  ( $r^2 = 0.28$ ) (Figs. 3b, d). These increases could be attributed principally to the above-mentioned SST rise in this region.

It has been suggested that the marine carbon cycle could change mostly to reduce the overall ability of surface waters to take up atmospheric  $\text{CO}_2$  through changes in the oceanic processes due to a further atmospheric  $\text{CO}_2$  increase, global warming, and its related feedback on a decade-to-century time scale (IPCC, 2001). In our present results for the western Pacific, however, no appreciable long-term changes were found in the carbonate system in surface water other than that corresponding to the anthropogenic  $\text{CO}_2$  uptake, i.e.,  $\Delta p\text{CO}_2$  did not change dramatically, and the wind speed showed no

remarkable trend over the last two decades. If we are to predict changes in the future, these results suggest that the large winter-time oceanic CO<sub>2</sub> uptake in the western subtropical North Pacific will continue persistently in the near future as well. However, it is necessary to keep examining how the contributions of respective properties to the air-sea CO<sub>2</sub> flux could change in response to the future progress of climate change by monitoring the temporal variation of the oceanic carbonate system precisely and systematically in a variety of regions.

**Acknowledgments.** The authors are grateful to the past and present staff of the Marine Division, Climate and Marine Department, JMA, for their efforts to maintain the monitoring program and to the captains and crew of the of R/V *Ryofu Maru* for their kind cooperation in the measurement and collection of seawater samples. We also thank Y. Kitamura, S. Sugimoto, Y. Takatsuki, and T. Soga of JMA for their support in the physical structure analysis, H. Morooka of JMA for the use of wind data and two anonymous reviewers for their helpful and supportive comments. Finally, we acknowledge the staff of the Geochemical Research Department of the Meteorological Research Institute for their support of this work.

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## Figure captions

**Figure 1.** Locations of the observation line and major currents along 137°E in the western North Pacific. Abbreviations: KCC, Kuroshio Counter-Current; SCC, Subtropical Counter-Current; NEC, North Equatorial Current; NECC, North Equatorial Counter-Current.

**Figure 2.** Time series of surface properties observed along 137°E in the western North Pacific in the winters of 1983 to 2003. (a) SST (°C), (b) salinity, (c) wind speed ( $\text{m s}^{-1}$ ) averaged in January and February from the reanalysis by NCEP, (d)  $p\text{CO}_2^{\text{sea}}$  ( $\mu\text{atm}$ ), (e)  $\Delta p\text{CO}_2$  ( $p\text{CO}_2^{\text{sea}} - p\text{CO}_2^{\text{air}}$ ;  $\mu\text{atm}$ ), and (f) air-sea  $\text{CO}_2$  flux ( $\text{mol m}^{-2}$ ) estimated by using the equation for the gas transfer velocity of Wanninkhof (1992) for January and February. A positive  $\text{CO}_2$  flux means efflux to the atmosphere, and a negative one means influx from the atmosphere.

**Figure 3.** Latitudinal distributions of the increase rates of (a)  $p\text{CO}_2^{\text{sea}}$  (closed circle) and  $p\text{CO}_2^{\text{air}}$  (open square), (b)  $\Delta p\text{CO}_2$ , (c) wind speed, and (d) net air-sea  $\text{CO}_2$  flux. The respective rates were calculated by using the data illustrated in Figure 2 except for 1983

and 1998 (see text). Wind speed and CO<sub>2</sub> flux are values for January and February.

Error bars represent 1 $\sigma$  values for the increase rate in each latitude.

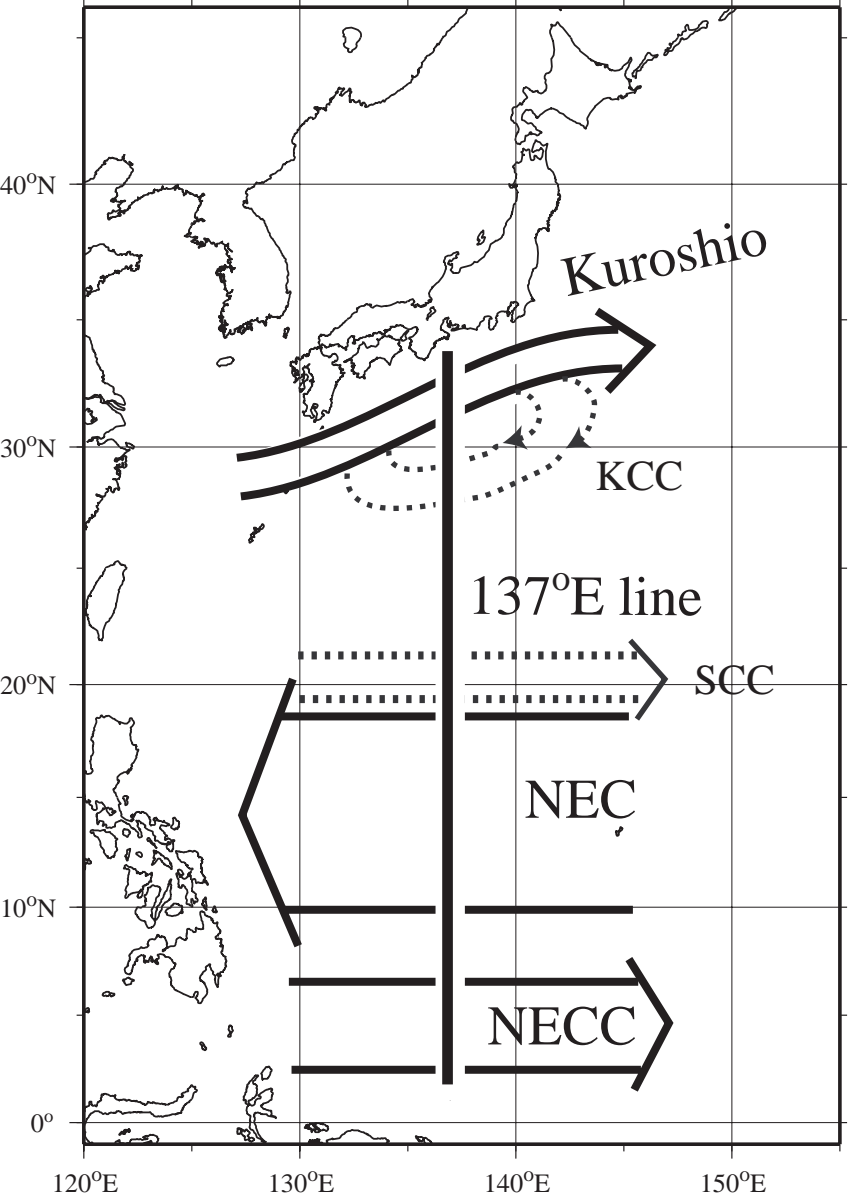


Figure 1. Locations of the observation line and major currents along  $137^{\circ}\text{E}$  in the western North Pacific. Abbreviations: KCC, Kuroshio Counter-Current; SCC, Subtropical Counter-Current; NEC, North Equatorial Current; NECC, North Equatorial Counter-Current.

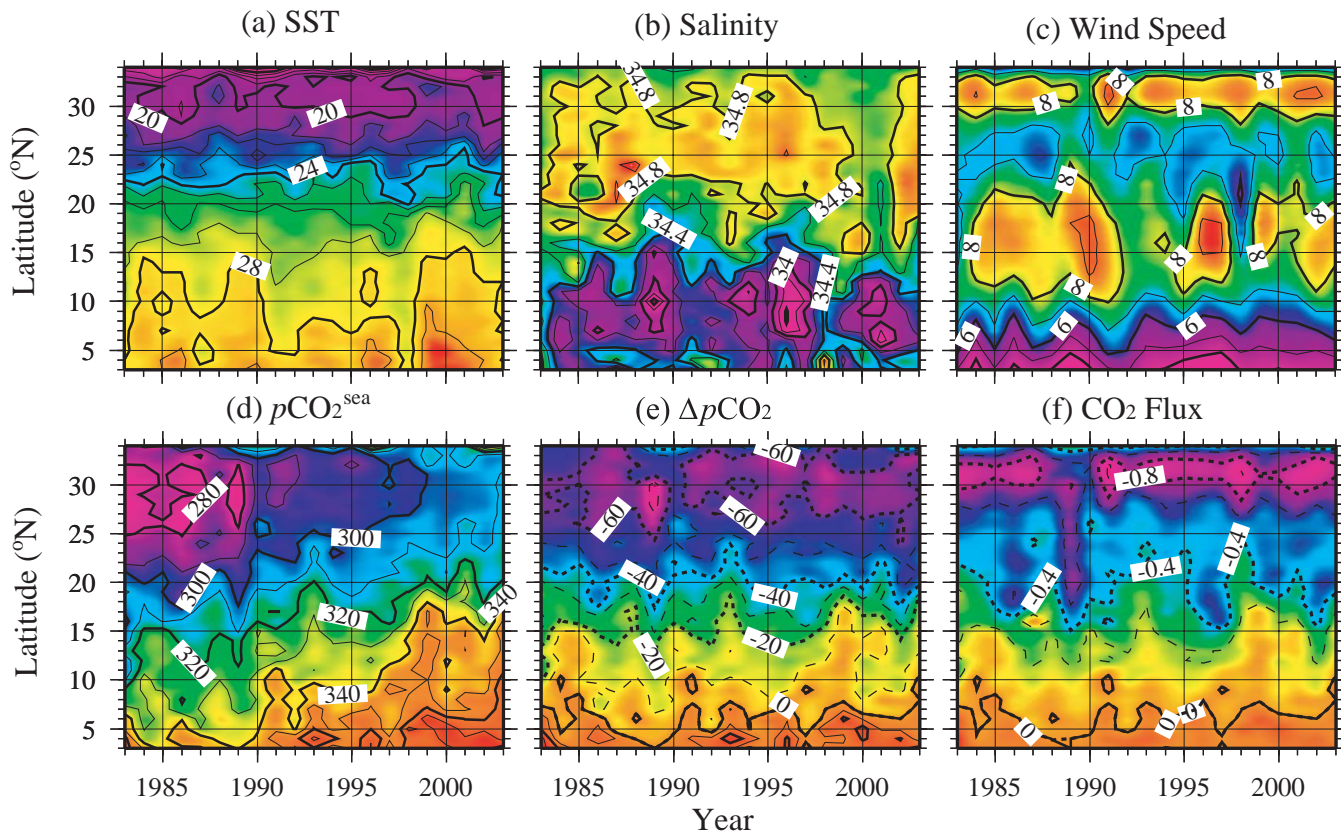


Figure 2. Time series of surface properties observed along  $137^{\circ}\text{E}$  in the western North Pacific in the winters of 1983 to 2003. (a) SST ( $^{\circ}\text{C}$ ), (b) salinity, (c) wind speed ( $\text{m s}^{-1}$ ) averaged in January and February from the reanalysis by NCEP, (d)  $p\text{CO}_2^{\text{sea}}$  ( $\mu\text{atm}$ ), (e)  $\Delta p\text{CO}_2$  ( $p\text{CO}_2^{\text{sea}} - p\text{CO}_2^{\text{air}}$ ;  $\mu\text{atm}$ ) and (f) air-sea  $\text{CO}_2$  flux ( $\text{mol m}^{-2}$ ) estimated by using the equation for the gas transfer velocity of Wanninkhof (1992) for January and February. A positive  $\text{CO}_2$  flux means efflux to the atmosphere and a negative one means influx from the atmosphere.

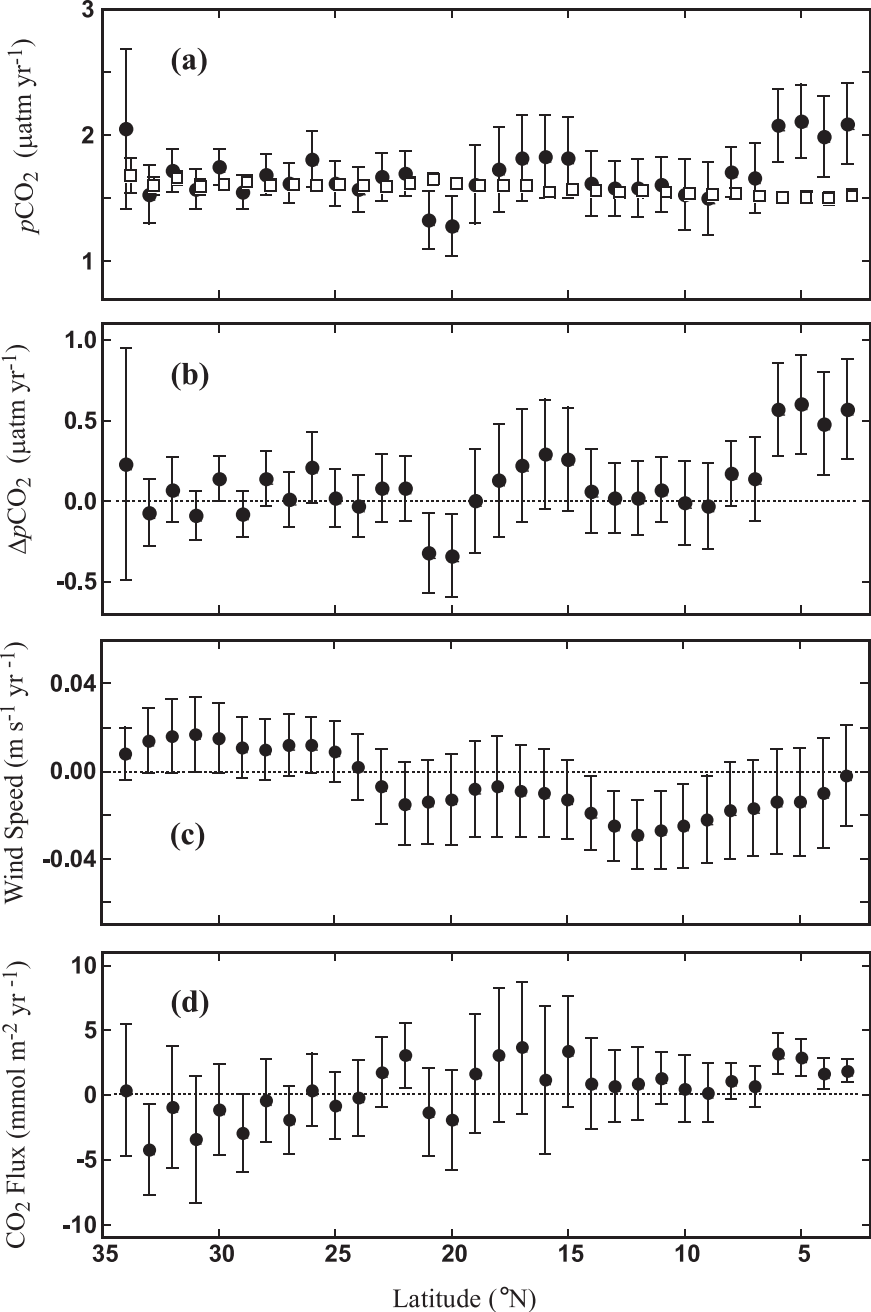


Figure 3. Latitudinal distributions of the increase rates of (a)  $p\text{CO}_2^{\text{sea}}$  (closed circle) and  $p\text{CO}_2^{\text{air}}$  (open square), (b)  $\Delta p\text{CO}_2$ , (c) wind speed and (d) net air-sea  $\text{CO}_2$  flux. The respective rates were calculated by using the data illustrated in Figure 2 except for 1983 and 1998 (see text). Wind speed and  $\text{CO}_2$  flux are values for January and February. Error bars represent  $1\sigma$  values for the increase rate in each latitude.