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Recent deceleration of oceanic pCO$_2$ increase in the western North Pacific in winter

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[1] Recent changes in oceanic CO$_2$ partial pressure (pCO$_2^{\text{sea}}$) have attracted increasing interest as they relate to the increase in atmospheric CO$_2$ and climate change. We report decadal changes in the growth rates of pCO$_2^{\text{sea}}$ in latitudinal zones from 3°N to 33°N along the repeat hydrographic line at 137°E in the western North Pacific in winter. The growth rates of pCO$_2^{\text{sea}}$ for 1999–2009 (-0.3 ± 0.9 [mean $\pm 1\sigma$] to 1.7 ± 0.5 μatm yr^{-1}) were lower than those for 1984–1997 (0.7 ± 0.3 to 2.2 ± 0.6 μatm yr^{-1}) at most latitudes, indicative of the recent notable deceleration of pCO$_2^{\text{sea}}$ increase. For latitudes around 10–20°N, we attribute the reduction in the growth rate of pCO$_2^{\text{sea}}$ for 1999–2009 primarily to the reduction in the contribution from dissolved inorganic carbon (DIC) originating from a reduction in carbon accumulation associated with the expansion of the western Subtropical Gyre towards the south. **Citation:** Midorikawa, T., M. Ishii, N. Kosugi, D. Sasano, T. Nakano, S. Saito, N. Sakamoto, H. Nakano, and H. Y. Inoue (2012), Recent deceleration of oceanic pCO$_2$ increase in the western North Pacific in winter, *Geophys. Res. Lett.*, *39*, L12601, doi:10.1029/2012GL051665.

1. Introduction

[2] The growth rate of atmospheric CO$_2$ concentration is controlled by the emission of anthropogenic CO$_2$ due to fossil fuel combustion and land-use changes, and by the strengths of various carbon sinks in the land biosphere and the oceans. The strengths of these carbon sinks are known to fluctuate on various time scales in response to the continually rising atmospheric CO$_2$ and to climate variability and change [e.g., *Canadell et al.*, 2007; *Gruber et al.*, 2009; *Le Quéré et al.*, 2009]. Although the ocean carbon sink will likely continue to grow with time as atmospheric CO$_2$ concentration continues to rise, recent studies have suggested that the ocean sink is variable, dependent on the region and period [e.g., *Gruber et al.*, 2009; *Watson et al.*, 2009; *McKinley*

et al., 2011]. The CO$_2$ partial pressure in surface waters (pCO$_2^{\text{sea}}$) has not always been increasing at the same rate as that of overlying air (pCO$_2^{\text{air}}$) and, consequently, the rate of carbon uptake by the oceans has been changing. Accurate quantification of the growth rate of pCO$_2^{\text{sea}}$ and the interpretation of the mechanisms responsible for its variability are of importance in understanding the evolution of the ocean carbon sink.

[3] The synthesis of international global ocean surface CO$_2$ observations has provided a climatological monthly mean field of the ocean carbon sink [*Takahashi et al.*, 2009]. However, the time scales over which pCO$_2^{\text{sea}}$ and the ocean carbon sink vary remain undetermined. For decadal and longer time-scales, the growth rate of pCO$_2^{\text{sea}}$ is reportedly following pCO$_2^{\text{air}}$ in some regions, based on in-situ time-series observations [e.g., *Takahashi et al.*, 2009]. The growth rate of pCO$_2^{\text{sea}}$ was found to be higher than that of pCO$_2^{\text{air}}$ in the subarctic North Atlantic [*Schuster et al.*, 2009; *Metzl et al.*, 2010] and the Southern Ocean [*Metzl*, 2009; *Takahashi et al.*, 2009], suggesting a weakening of the CO$_2$ sink in these regions; the opposite was found in part of the North Pacific [*Takahashi et al.*, 2006; *Midorikawa et al.*, 2011], suggesting an intensification of the sink. In addition, decadal changes in the pCO$_2^{\text{sea}}$ growth rate related to changes in the ocean circulation state, vertical convection and warming, have also been reported in the subtropical North Pacific [*Keeling et al.*, 2004], the subarctic North Atlantic [*Metzl et al.*, 2010] and the equatorial Pacific [*Ishii et al.*, 2009]. On the other hand, for accurate quantification of the growth rate of pCO$_2^{\text{sea}}$, sampling bias also needs to be examined with great caution in use of sparse observation data because the heterogeneity in space and time for sample collection might give rise to artificial variations [e.g., *McKinley et al.*, 2011].

[4] In the western North Pacific, the repeat hydrographic line at 137°E is one of the few areas where oceanic CO$_2$ has been routinely measured since the early 1980s. In the present study, we describe the evolution of the pCO$_2^{\text{sea}}$ in the extensive area over the latitudinal band of 30° during the period of 1984–2009. The changes in the growth rates of pCO$_2^{\text{sea}}$ and related surface seawater properties are investigated through the comparison of the growth rates for a recent decade with those for 1980s–1990s. The causes of the observed changes in the pCO$_2^{\text{sea}}$ growth rate are discussed in terms of the changes in the contributions from oceanic carbon properties and associated changes in the oceanographic conditions in the upper water column.

2. Data and Methods

[5] Winter time-series data for pCO$_2^{\text{air}}$, pCO$_2^{\text{sea}}$ and related properties such as sea surface temperature (SST) and sea

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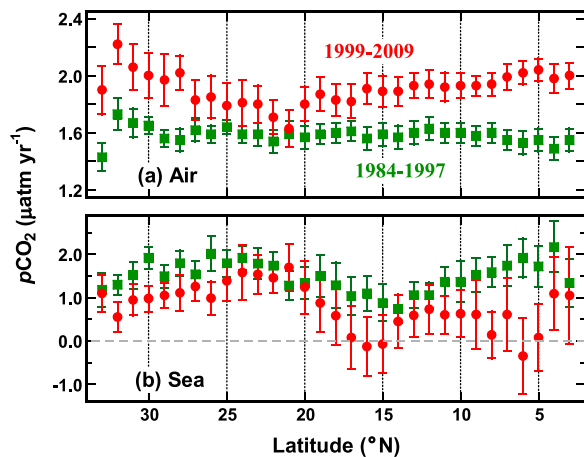
Figure 1. Latitudinal distribution of the growth rates of (a) $p\mathrm{CO}_2^{\mathrm{air}}$ and (b) $p\mathrm{CO}_2^{\mathrm{sea}}$ for the periods 1984–1997 (green squares) and 1999–2009 (red circles). Error bars represent 1σ values for the rates of change at each latitude. See also Text S2 in the auxiliary material and Figure S4, which was rearranged from this figure, for a comparison of growth rates of $p\mathrm{CO}_2^{\mathrm{sea}}$ to $p\mathrm{CO}_2^{\mathrm{air}}$.

surface salinity (SSS) have been collected from south of Japan to the equatorial region along 137°E (see Figure S1 in the auxiliary material) during the periodic observations onboard the R/V *Ryofu Maru* and R/V *Keifu Maru* of the Japan Meteorological Agency (JMA).[1] These observations have been conducted during nearly the same periods each year—from late January to early February—since the early 1980s [*Midorikawa et al.*, 2006]. Details of the data collection methods have been described by *Midorikawa et al.* [2006]. The data for 1984–2009 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/) operated by JMA.

[6] Dissolved inorganic carbon (DIC) was measured at irregular intervals after the WOCE P9 one-time observations in June 1994 [*Ishii et al.*, 2001] by using a coulometric technique and Certified Reference Material provided by Dr. A. G. Dickson of Scripps Institution of Oceanography (La Jolla, California, USA). Total alkalinity (TA) was not measured until recently, but instead was calculated by the methods of *Dickson et al.* [2007] from SST, SSS, $p\mathrm{CO}_2^{\mathrm{sea}}$ and DIC for cruises where these four surface parameters were measured. The calculated TA normalized to a salinity of 35 (nTA) at the respective latitudes for 1994–2008 ranged from 2294 ± 4 to $2298 \pm 3 \ \mu\mathrm{mol\ kg}^{-1}$ (mean $\pm$ 1 standard deviation [1σ]), suggesting that nTA was almost constant (average of $2295 \pm 5 \ \mu\mathrm{mol\ kg}^{-1}$) over 3–33°N along 137°E [*Midorikawa et al.*, 2010]. These results are in good agreement with the nTA values of $2297 \pm 3 \ \mu\mathrm{mol\ kg}^{-1}$ measured at five latitudes from 9°N to 30°N around 158°E in February 1970 [*Inoue et al.*, 1999], suggesting that nTA has remained unchanged in this region for the last 40 years.

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[7] Measurements of DIC were not available for the period from 1984 to 1993 and were limited in the frequency of observations even for 1994–2009. The DIC values calculated for 1994–2009 by the methods of *Dickson et al.* [2007], using the data for $p\mathrm{CO}_2^{\mathrm{sea}}$, SST and SSS, and assuming TA = $[(2295/35) \times \mathrm{SSS}] \ \mu\mathrm{mol\ kg}^{-1}$ [*Midorikawa et al.*, 2010], were in good agreement with measured values; the differences averaged at $-3 \pm 4 \ \mu\mathrm{mol\ kg}^{-1}$ (mean $\pm 1\sigma$), with calculated values slightly lower than measured. For this study, DIC values were calculated for the entire period from 1984 to 2009 from the data for $p\mathrm{CO}_2^{\mathrm{sea}}$, SST and SSS, and calculated TA, and were used to obtain a time series of DIC and to evaluate its contribution to the variability of $p\mathrm{CO}_2^{\mathrm{sea}}$ over the entire study period.

[8] To investigate the recent variability of $p\mathrm{CO}_2^{\mathrm{sea}}$ on decadal scales and its cause, the data for 1984–2009 were divided into the periods before and after 1998 (see Text S1 in the auxiliary material), when a strong El Niño occurred and affected the surface carbonate system over an extensive region including the study area [*Midorikawa et al.*, 2005, 2006], and these two data sets were compared. The decadal rates of changes in surface properties at the respective latitudes were characterized using averaged values within $\pm0.5°$ of latitude for each, assuming a linear trend for the respective periods [*Midorikawa et al.*, 2005, 2010].

3. Results and Discussion

[9] The $p\mathrm{CO}_2^{\mathrm{air}}$ data revealed significant growth rates for both periods at all latitudes (Student's t-test, $P < 2 \times 10^{-6}$), and the growth rates of $p\mathrm{CO}_2^{\mathrm{air}}$ ranged from 1.43 ± 0.10 (mean $\pm 1\sigma$) to $1.73 \pm 0.11 \ \mu\mathrm{atm\ yr}^{-1}$ (average, $1.58 \pm 0.05 \ \mu\mathrm{atm\ yr}^{-1}$) for 1984–1997 and from 1.63 ± 0.13 to $2.22 \pm 0.14 \ \mu\mathrm{atm\ yr}^{-1}$ (average, $1.91 \pm 0.11 \ \mu\mathrm{atm\ yr}^{-1}$) for 1999–2009 (Figure 1a). The rates for 1999–2009 were higher than those for 1984–1997 at all latitudes and the differences between the rates for the two periods were significant ($P < 0.05$) at all latitudes except for 17°N and 20–27°N ($P = 0.09 - 0.75$).

[10] In contrast to the acceleration of the $p\mathrm{CO}_2^{\mathrm{air}}$ growth, the growth rates of $p\mathrm{CO}_2^{\mathrm{sea}}$ for 1999–2009 were below those for 1984–1997 at most latitudes. The growth rates of $p\mathrm{CO}_2^{\mathrm{sea}}$ ranged from 0.7 ± 0.3 to $2.2 \pm 0.6 \ \mu\mathrm{atm\ yr}^{-1}$ (average, $1.5 \pm 0.4 \ \mu\mathrm{atm\ yr}^{-1}$) for 1984–1997 and from -0.3 ± 0.9 to $1.7 \pm 0.5 \ \mu\mathrm{atm\ yr}^{-1}$ (average, $0.8 \pm 0.5 \ \mu\mathrm{atm\ yr}^{-1}$) for 1999–2009 (Figure 1b). The growth rates of $p\mathrm{CO}_2^{\mathrm{sea}}$ were comparable to those of $p\mathrm{CO}_2^{\mathrm{air}}$ for 1984–1997, but were lower than those of $p\mathrm{CO}_2^{\mathrm{air}}$ for 1999–2009 (see also Figure S4 in the auxiliary material); notably, the growth rates of $p\mathrm{CO}_2^{\mathrm{sea}}$ were insignificant ($P > 0.2$) at latitudes south of 20°N for 1999–2009. It appears, that since 1999 $p\mathrm{CO}_2^{\mathrm{sea}}$ does not increase in a manner similar to $p\mathrm{CO}_2^{\mathrm{air}}$ in this region. The differences in the growth rates of $p\mathrm{CO}_2^{\mathrm{sea}}$ between the two periods were insignificant at most latitudes but were significant at 5, 6, 8, 26, 30 and 32°N ($P < 0.05$). At these latitudes, the growth rates of $p\mathrm{CO}_2^{\mathrm{sea}}$ for 1999–2009 were significantly lower than those for 1984–1997, representative of a recent notable reduction in $p\mathrm{CO}_2^{\mathrm{sea}}$ growth rate.

[11] To examine the cause of the changes in the growth rates of $p\mathrm{CO}_2^{\mathrm{sea}}$, we evaluated the contributions from changes in parameters related to $p\mathrm{CO}_2^{\mathrm{sea}}$ for the respective periods. The growth rate of $p\mathrm{CO}_2^{\mathrm{sea}}$ reflects the rates of
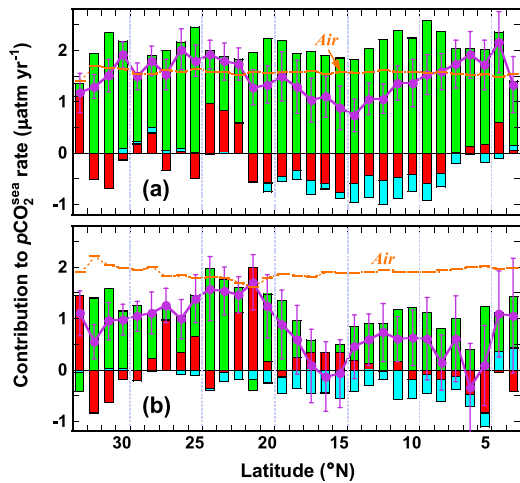
Figure 2. Latitudinal distribution of contributions of SST (red bars), SSS (light blue bars), and DIC concentration (green bars) to the pCO$_2^{\mathrm{sea}}$ growth rate for (a) 1984–1997 and (b) 1999–2009. Rates of changes in the three parameters were converted to pCO$_2^{\mathrm{sea}}$ values. The violet circles and lines represent the pCO$_2^{\mathrm{sea}}$ growth rate and are equivalent to the sum of contributions from SST, SSS, and DIC changes. Growth rates of pCO$_2^{\mathrm{air}}$ are shown as orange bars. The uncertainties of the respective contributions to the pCO$_2^{\mathrm{sea}}$ and their original values for the changes in respective surface properties are shown in Figure S5.

changes in SST, SSS, DIC and TA, as shown in the following equation:

$$\Delta p\mathrm{CO_2}^{\mathrm{sea}} = \frac{\partial p\mathrm{CO_2^{sea}}}{\partial \mathrm{SST}} \cdot \Delta \mathrm{SST} + \frac{\partial p\mathrm{CO_2^{sea}}}{\partial \mathrm{SSS}} \cdot \Delta \mathrm{SSS} + \frac{\partial p\mathrm{CO_2^{sea}}}{\partial \mathrm{DIC}} \cdot \Delta \mathrm{DIC} + \frac{\partial p\mathrm{CO_2^{sea}}}{\partial \mathrm{TA}} \cdot \Delta \mathrm{TA}, \quad (1)$$

where the contributions of SST and SSS correspond to the thermodynamic effects, which include consideration of changes in the buffer factor. With regard to TA, nTA remained unchanged over the study region during the periods in question [*Midorikawa et al.*, 2010]. In addition, no significant change in nTA was detected for the periods of both 1984–1997 and 1999–2009 by the calculation using the observational data of pCO$_2^{\mathrm{sea}}$, DIC, SST and SSS although the data were limited to several latitudes. Then, it is assumed that the contribution of TA can be ignored. We evaluated the rates of changes in the remaining three parameters for the respective periods and determined the corresponding growth rate of pCO$_2^{\mathrm{sea}}$ for each under conditions with mean values for the other parameters (see Text S2 in the auxiliary material).

[12] We compared the rates of changes in the three parameters for the respective periods, converted to pCO$_2^{\mathrm{sea}}$ values, with those of pCO$_2^{\mathrm{sea}}$ at the respective latitudes (Figure 2). For the period 1984–1997, the largest contribution to the pCO$_2^{\mathrm{sea}}$ growth rate was from the DIC concentration, which enhanced the growth rates of pCO$_2^{\mathrm{sea}}$ over the latitudes 3–32°N. At many latitudes, we observed contributions from the rate of decreasing SST that reduced the growth rates of pCO$_2^{\mathrm{sea}}$, especially at 8–21°N. In contrast, at latitudes with a rate of increasing SST (22–24°N, 33°N), the temperature effects on

pCO$_2^{\mathrm{sea}}$ were not profound, but rather these latitudes showed lower growth rates of DIC. Although the overall contribution of salinity changes to pCO$_2^{\mathrm{sea}}$ growth rates was minor, it was relatively large at latitudes around 7–14°N.

[13] For the period 1999–2009, the contribution of changes in DIC concentration to the pCO$_2^{\mathrm{sea}}$ growth rate was generally small, leading to a reduction in the growth rate of pCO$_2^{\mathrm{sea}}$ at most latitudes. At 16°N, 21°N and 33°N, the rate attributable to changes of DIC concentration became negative. The contribution from SST changed from negative to positive at about half of the latitudes considered, and the decrease in the growth rate of DIC was large at these latitudes. With the decrease in the contribution from DIC concentration changes, the contribution from the decrease in SSS became relatively large; its negative effects reduced the growth rate of pCO$_2^{\mathrm{sea}}$ around 5–20°N. At 6°N, 15°N and 16°N, the rate of pCO$_2^{\mathrm{sea}}$ became negative.

[14] The recent deceleration of the pCO$_2^{\mathrm{sea}}$ increase could be attributable primarily to the reduction in the growth rate of DIC and these changes are likely linked to the concurrent SST rise (see Text S3 in the auxiliary material). The processes that could induce these changes in DIC and SST remain unclear, but possible candidates include a reduction in the uptake of atmospheric CO$_2$ and a reduction in the entrainment of DIC from deeper layers during autumn and early winter mixing. Preliminary calculations based on time series SST data for the months preceding the observations in late January and early February (Text S4) indicate that the changes in the CO$_2$ influx from increasing trends for 1984–1997 to decreasing trends for 1999–2009 over 10–20°N (Figure S8) are coincident with changes in the growth rates of DIC of −0.10 to −0.14 μmol kg^{-1} yr^{-1} (Text S5). This decrease in the growth rate of DIC is equivalent to rates of change for pCO$_2^{\mathrm{sea}}$ of −0.2 to −0.3 μatm yr^{-1} and accounts for 15–20% of the decline in the contribution of DIC concentration to the pCO$_2^{\mathrm{sea}}$ growth rate (average, −1.3 ± 0.4 μatm yr^{-1}; Figure S5g) from 1984–1997 to 1999–2009 for 10–20°N.

[15] In addition, comparisons of the rates of changes in sea-surface oceanographic properties between 1984–1997 and 1999–2009 exhibited recent changes in the oceanographic conditions in the upper water column at latitudes around 15°N—that is, warming of surface layers and deepening of 20–25°C isotherms (Figures 3 and S9). Corresponding deepening of the potential density surface, σ_θ, of 27 kg m^{-3} (Figure 3c) and a raising of the sea-surface dynamic height at these latitudes suggest the expansion of the western Subtropical Gyre towards the south (Text S6 and Figure S11b), leading to the thickening of the warm and DIC-poor surface layer and subsequent reduction of the entrainment of DIC from the underlying layer. These changes could depress the surface nDIC increase (Figure 3d) and also contribute to the recent slowdown of pCO$_2^{\mathrm{sea}}$ increase in the southern subtropical zone at 137°E.

[16] The slowdown of pCO$_2^{\mathrm{sea}}$ and nDIC increases after the late 1990s has also been observed at Hawaii Ocean Time-series Station ALOHA in the eastern Subtropical Gyre of the North Pacific [*Keeling et al.*, 2004] and in the western equatorial Pacific warm pool [*Ishii et al.*, 2009]. *Keeling et al.* [2004] suggested that the change in the trend around 1997 at Station ALOHA is a result of a large-scale shift in the climate of the North Pacific. The observations of the present study, together with the results from these other
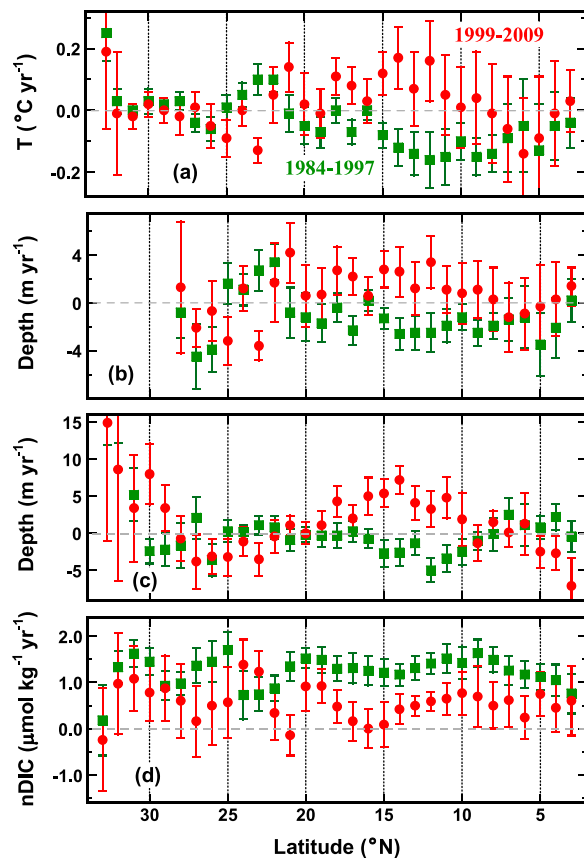
Figure 3. Latitudinal distributions of changes in oceanographic properties along 137°E in the North Pacific. Rates of changes in (a) average temperature at depths above 300 m, (b) the 20 °C isotherm depth, (c) the depth of $27\sigma_\theta$ surface, and (d) nDIC concentration. Green squares, 1984–1997; red circles, 1999–2009. Error bars represent 1σ values for the rates of change at each latitude. The rates of change in other properties are shown in Figure S9.

regions, suggest that the slowdown of pCO$_2^{sea}$ and nDIC increases is the trend over a broad expanse from the eastern to southwestern subtropics and further to the tropics that are likely to be connected by the circulation of the North Pacific Subtropical Gyre and its branch into the equatorial zone.

4. Concluding Remarks

[17] On the basis of the winter time-series data of pCO$_2^{air}$ and pCO$_2^{sea}$ along 137°E in the western North Pacific, we found that the growth rates of pCO$_2^{sea}$ for 1999–2009 were significantly lower than those for 1984–1997 at most latitudes, in spite of the acceleration of pCO$_2^{air}$ increase during 2000s. The recent notable slowdown of pCO$_2^{sea}$ increase in the southern subtropical zone is attributable to the reduction of the entrainment of DIC from deeper layers as well as the reduction of the CO$_2$ influx from the atmosphere. We postulate that the primary driver of these changes is the changes in the upper-layer oceanographic structure, i.e., the accumulation of surface warm DIC-poor water, as a result of water mass redistribution of the western Subtropical Gyre to the south.

[18] Since the circulation of the Subtropical Gyre shows the oscillatory behavior [e.g., *Qiu and Chen*, 2012], the growth rate of pCO$_2^{sea}$ might rebound in the coming decade. It is interesting to clarify how the reorganization of the North Pacific circulation drives the physical and biogeochemical shifts in the upper ocean and, consequently, alters its response to the rise in atmospheric CO$_2$.

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References

Canadell, J. G., et al. (2007), Contributions to accelerating atmospheric CO$_2$ growth from economic activity, carbon intensity, and efficiency of natural sinks, *Proc. Natl. Acad. Sci. U. S. A.*, *104*, 18,866–18,870, doi:10.1073/pnas.0702737104.

Dickson, A. G., C. L. Sabine, and J. R. Christian (Eds.) (2007), *Guide to Best Practices for Ocean CO$_2$ Measurements*, PICES Spec. Publ., *3*, 191 pp.

Gruber, N., et al. (2009), Oceanic sources, sinks, and transport of atmospheric CO$_2$, *Global Biogeochem. Cycles*, *23*, GB1005, doi:10.1029/2008GB003349.

Inoue, H. Y., M. Ishii, H. Matsueda, S. Saito, T. Midorikawa, and K. Nemoto (1999), MRI measurements of partial pressure of CO$_2$ in surface waters of the Pacific during 1968 to 1970: Re-evaluation and comparison of data with those of the 1980s and 1990s, *Tellus, Ser. B*, *51*, 830–848, doi:10.1034/j.1600-0889.1999.t01-3-00007.x.

Ishii, M., H. Y. Inoue, H. Matsueda, S. Saito, K. Fushimi, K. Nemoto, T. Yano, H. Nagai, and T. Midorikawa (2001), Seasonal variation in total inorganic carbon and its controlling processes in surface waters of the western North Pacific subtropical gyre, *Mar. Chem.*, *75*, 17–32, doi:10.1016/S0304-4203(01)00023-8.

Ishii, M., et al. (2009), Spatial variability and decadal trend of the oceanic CO$_2$ in the western equatorial Pacific warm/fresh water, *Deep Sea Res., Part II*, *56*, 591–606, doi:10.1016/j.dsr2.2009.01.002.

Keeling, C. D., H. Brix, and N. Gruber (2004), Seasonal and long-term dynamics of the upper ocean carbon cycle at Station ALOHA near Hawaii, *Global Biogeochem. Cycles*, *18*, GB4006, doi:10.1029/2004GB002227.

Le Quéré, C., et al. (2009), Trends in the sources and sinks of carbon dioxide, *Nat. Geosci.*, *2*, 831–836, doi:10.1038/ngeo689.

McKinley, G. A., A. R. Fay, T. Takahashi, and N. Metzl (2011), Convergence of atmospheric and North Atlantic carbon dioxide trends on multidecadal timescales, *Nat. Geosci.*, *4*, 606–610, doi:10.1038/ngeo1193.

Metzl, N. (2009), Decadal increase of oceanic carbon dioxide in southern Indian Ocean surface water (1991–2007), *Deep Sea Res., Part II*, *56*, 607–619, doi:10.1016/j.dsr2.2008.12.007.

Metzl, N., et al. (2010), Recent acceleration of the sea surface fCO$_2$ growth rate in the North Atlantic subpolar gyre (1993–2008) revealed by winter observations, *Global Biogeochem. Cycles*, *24*, GB4004, 13 pp., doi:10.1029/2009GB003658.

Midorikawa, T., K. Nemoto, H. Kamiya, M. Ishii, and H. Y. Inoue (2005), Persistently strong oceanic CO$_2$ sink in the western subtropical North Pacific, *Geophys. Res. Lett.*, *32*, L05612, doi:10.1029/2004GL021952.

Midorikawa, T., M. Ishii, K. Nemoto, H. Kamiya, A. Nakadate, S. Masuda, H. Matsueda, T. Nakano, and H. Y. Inoue (2006), Interannual variability of winter oceanic CO$_2$ and air-sea CO$_2$ flux in the western North Pacific for 2 decades, *J. Geophys. Res.*, *111*, C07S02, doi:10.1029/2005JC003095.

Midorikawa, T., M. Ishii, S. Saito, D. Sasano, N. Kosugi, T. Motoi, H. Kamiya, A. Nakadate, K. Nemoto, and H. Y. Inoue (2010), Decreasing pH trend estimated from 25-yr time series of carbonate parameters in the western North Pacific, *Tellus, Ser. B*, *62*, 649–659, doi:10.1111/j.1600-0889.2010.00474.x.

Midorikawa, T., M. Ishii, D. Sasano, N. Kosugi, H. Sugimoto, N. Hiraishi, S. Masuda, T. Suzuki, T. R. Takamura, and H. Y. Inoue (2011), Ocean acidification in the subtropical North Pacific estimated from accumulated carbonate data, *Pap. Meteorol. Geophys.*, *62*, 47–56, doi:10.2467/mripapers.62.47.

Qiu, B., and S. Chen (2012), Multidecadal sea level and gyre circulation variability in the northwestern tropical Pacific Ocean, *J. Phys. Oceanogr.*, *42*, 193–206, doi:10.1175/JPO-D-11-061.1.

Schuster, U., A. J. Watson, N. R. Bates, A. Corbiere, M. Gonzalez-Davila, N. Metzl, D. Pierrot, and M. Santana-Casiano (2009), Trends in North Atlantic sea-surface fCO$_2$ from 1990 to 2006, *Deep Sea Res., Part II*, *56*, 620–629, doi:10.1016/j.dsr2.2008.12.011.

Takahashi, T., S. C. Sutherland, R. A. Feely, and R. Wanninkhof (2006), Decadal change of the surface water pCO$_2$ in the North Pacific: A synthesis of 35 years of observations, *J. Geophys. Res.*, *111*, C07S05, doi:10.1029/2005JC003074.

Takahashi, T., et al. (2009), Climatological mean and decadal change in surface ocean pCO$_2$, and net sea-air CO$_2$ flux over the global oceans, *Deep Sea Res., Part II*, *56*, 554–577, doi:10.1016/j.dsr2.2008.12.009.

Watson, A. J., et al. (2009), Tracking the variable North Atlantic sink for atmospheric CO$_2$, *Science*, *326*, 1391–1393, doi:10.1126/science.1177394.