CO₂ Sink/Source Characteristics in the Tropical Indonesian Seas

A. R. Kartadikaria¹,², A. Watanabe³, K. Nadaoka³, N. S. Adi⁴, H. B. Prayitno⁵, Suharsono⁵, M. Muchtar⁵, I. Triyulianti⁶, A. Setiawan⁶, Suratno⁵, and E. N. Khasanah⁵
1 Study Program of Oceanography, Bandung Institute of Technology, Jl. Ganesha 10, 40132, Indonesia

2 Division of Physical Sciences and Engineering, King Abdullah University of Science and Technology, Thuwal, 23955, Kingdom of Saudi Arabia

3 Department of Mechanical and Environmental Informatics, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo, 152-8552, Japan

4 Research Center for Marine and Coastal Resources, Agency for Marine and Fisheries Research and Development, Ministry of Marine Affairs and Fisheries, Indonesia, Jl. Pasir Putih I Ancol Timur, Jakarta 14430, Indonesia

5 Research Center for Oceanography, Indonesian Institute of Sciences, Jl. Pasir Putih I Ancol Timur, Jakarta 11048, Indonesia

6 Institute for Marine Research and Observation, Ministry of Marine Affairs and Fisheries, Indonesia, Jl. Baru Perancak, Negara-Jembrana, Bali, 82251, Indonesia
Abstract.

Two distinct CO$_2$ sink/source characteristics are found in the tropical Indonesian seas from the compilation of observed data for the period 1984-2013. The western region persistently emits CO$_2$ to the atmosphere, whereas the eastern region is dynamic and acts either as a small source or sink of CO$_2$ to the atmosphere, depending on sites. The segregation is proximal to the Makassar Strait, which is located over the continental shelf and is one of the main routes of the Indonesian Throughflow (ITF). Lower salinity and higher silicate were found in the western region, suggesting a terrestrial influence in this area. Temperature has a limited influence in controlling different CO$_2$ sink/source characteristics in the west and east. However, an SST change of -2.0 $^\circ$C during La Niña events effectively reduces the pCO$_2$ difference between the atmosphere and surface seawater by 50% compared to normal year conditions. During La Niña events, higher wind speeds double the CO$_2$ flux from the ocean to the atmosphere compared to that of a normal year. In the continental shelf area where the CO$_2$ sink area was found, data of over 29 years show that the seawater pCO$_2$ increased by 0.6-3.8 $\mu$atm yr$^{-1}$. Overall, the seawater pCO$_2$ of the Indonesian Seas is supersaturated relative to the atmosphere by 15.9 $\pm$ 8.6 $\mu$atm and thus acts as a source of CO$_2$ to the atmosphere.
1. Introduction

Research on seawater CO\textsubscript{2} is in demand in Indonesia due to the lack of reliable and well-documented ocean CO\textsubscript{2} data. Global maps of sea surface partial pressure of CO\textsubscript{2} [Takahashi et al., 2009; Bakker et al., 2014] and inventories of anthropogenic CO\textsubscript{2} [Sabine et al., 2004] show Indonesian seas as a blank spot for CO\textsubscript{2} measurement. As a country with one of the longest coastlines, Indonesia possesses an extensive coastal ocean region, but so far little attention has been given to its carbon budget and what role this plays in global carbon cycle [e.g., Borges et al., 2005]. Many parts of the Indonesian coastal ocean receive large amounts of terrestrial organic matter and nutrient inputs [Sasai et al., 2011]. Other parts (e.g., the Makassar and Lombok Straits) are strongly influenced by throughflow of water masses from the Pacific to the Indian Ocean, known as the Indonesian Through Flow (ITF) [Gordon et al., 1999, 2008; Susanto et al., 2007; Kartadikaria et al., 2011b]. Considering this setting, complex air-water CO\textsubscript{2} interactions can be expected, and extensive measurements are required to determine the CO\textsubscript{2} sink/source characteristics of the Indonesian seas, including the role of the oceans surrounding Indonesia in terms of binding excessive atmospheric CO\textsubscript{2}.

According to Laruelle et al., [2014], a new global CO\textsubscript{2} sink estimate of 0.19 ± 0.05 Pg C yr\textsuperscript{-1} in continental shelf seas falls in the low end of previous estimates, i.e., 0.18-0.45 Pg C yr\textsuperscript{-1}, implying overestimation of the earlier studies of the continental shelf CO\textsubscript{2} sink process. Several studies have concluded that for certain continental shelves, the shallow zone (< 200 m) [Tsunogai et al., 1999; Frankignoulle and Borges, 2001; Thomas et al., 2004], slope-shelf zone [Walsh et al., 1985] and deeper zone, especially in the Atlantic
Ocean, all act as sinks, i.e., they take up atmospheric CO\textsubscript{2}. In the open ocean, tropical seas are natural sources of CO\textsubscript{2} [Takahashi et al., 2002; Feely et al., 2006]; however, high latitude oceans have an opposing role [Sabine et al., 2004]. These reasons have motivated us to map the sea surface partial pressure of CO\textsubscript{2} (SSpCO\textsubscript{2}) that spatially represent the primary Indonesian seas. Here, we present measured SSpCO\textsubscript{2} from tropical Indonesian seas based on the observed data and discuss a possible CO\textsubscript{2} sink/source mechanism, the influence of La Niña on air-sea CO\textsubscript{2} exchange, and annual trends of oceanic CO\textsubscript{2} in the region.

2. Materials and Methods

Locations and archived CO\textsubscript{2} data – The study area was located within 12°S-5°N, 104-130°E. Six datasets were obtained by direct measurements of SSpCO\textsubscript{2} over four years (2010-2013). These were mostly collected during the austral summer season (Table 1). Six additional datasets of the mole fraction of CO\textsubscript{2} in surface seawater (xCO\textsubscript{2}) from the CDIAC-LDEO database V2009 (http://cdiac3.ornl.gov/waves/underway/) and AOML-Xuelong expedition (http://www.aoml.noaa.gov/ocd/gcc/index.php) were downloaded and analyzed in conjunction with the data collected as part of this study. The atmospheric xCO\textsubscript{2}\textsuperscript{ATM} data were obtained from the NOAA/ESRL database (http://ds.data.jma.go.jp/gmd/wdcgg/jp/wdcgg_j.html). We selected the nearest location of atmospheric xCO\textsubscript{2}\textsuperscript{ATM} data that were available during the listed cruises in Table 1. The atmospheric xCO\textsubscript{2}\textsuperscript{ATM} data were used to calculate the pCO\textsubscript{2} difference between the surface ocean and atmosphere (\(\delta p\text{CO}_2\)). The method of calculating pCO\textsubscript{2} from xCO\textsubscript{2} is explained in the next subsection. In total, CO\textsubscript{2} data from 12 cruises were
used for this study. This is one of the most comprehensive CO$_2$ data compilations for the Indonesian archipelago (Table 1).

*In situ measurements* - One- to ten-minute recordings of sea surface temperatures (SST), sea surface salinity (SSS), chlorophyll-a (Chl-a), turbidity, and dissolved oxygen (DO) were obtained using Compact sensors (JFE Advantech Co. Ltd., Japan). An onboard weather station was utilized to measure air temperature, humidity, solar radiation, wind direction and wind speed, and air pressure (Onset Computer Corporation, US). Starting from the EWIN cruise in 2010, continuous measurements were collected by pumping sea surface water into a plastic container. A fast, continuous, and portable CO$_2$ analyzer capable of measuring the in situ xCO$_2$ in the water and atmosphere was utilized in our observations (C02-09, Kimoto Electric Co. Ltd., Japan). For one hour of continuous measurements of xCO$_2$ (equal to one cycle), we measured the xCO$_2$ every minute in the water for 50 minutes and then continued to measure the xCO$_2$ in the air for 5 minutes and xCO$_2$ in the CO$_2$-free gas (air fed through a soda-lime column) for 5 minutes. The CO$_2$ analyzer was pre-calibrated with a known concentration of CO$_2$ in dry air (250, 500, 797, and 1100 ppm) and was intended to measure the mole fraction of xCO$_2$ in gas form [Saito et al., 1995]. In water, the xCO$_2$ level was measured as a fraction of the CO$_2$ in dry air because the membrane filter (Gore-Tex) in the pCO$_2$ analyzer was able to equilibrate the CO$_2$ in seawater and air after removing the water vapor. With this machine, a direct pCO$_2$ value was not obtained; this value must be calculated from the measured xCO$_2$ value with the following equation:

$$pCO_2 = xCO_2 \left( P_{eq} - P_w \right).$$

(1)
where $P_{eq}$ is the total pressure of the carrier gas measured in the equilibrator chamber, and $P_w$ is the saturation vapor pressure of water at the equilibrium temperature, $T_{eq}$. $P_w$ can be calculated from the equation following the methods of Weiss and Price [1980] [Körtzinger 1999]. The accuracy of the pCO$_2$ analyzer was estimated at 7 $\mu$atm [Saito et al., 1995].

Discrete oceanographic samples were also collected using a CTD and *rosette sampler*. The seawater that was collected from certain depths by the *rosette sampler* was then used for the following analyses: (1) CO$_2$ system parameters (total alkalinity (TA), dissolved inorganic carbon (DIC), pH, and salinity); (2) nutrients; (3) suspended solids (SS); and (4) Chl-a. For the treatment of TA, DIC, and pH, we placed the sampled water into a 250-mL *Schott Duran* bottle according to standard procedures outlined in Dickson et al., [2007], and preserved the sample with 200 $\mu$L of a saturated HgCl$_2$ solution to halt any biological activity. In the treatment for nutrients, a 10-mL sample was collected in two acrylic tubes and frozen in a scientific freezer (temperature $<-2$ °C) for further laboratory analysis. One liter of water was filtered with a 47-mm diameter GF/F filter to collect the SS data, and 200 mL of water was filtered with a 25-mm diameter filter to collect the Chl-a data. The 47-mm GF/F filters for SS were dried and weighed in advance, stored in a freezer after the filtration, and then dried and weighed again in the laboratory. The 25-mm GF/F filters for Chl-a were immediately placed in a tube that contained 6 mL of *N-N dimethylformamide* and preserved in a freezer until analysis.

*Laboratory analyses* – For each 250-mL *Schott Duran* bottle sample, we conducted CO$_2$ and salinity analyses. For the CO$_2$ analysis in the laboratory, we used a carbonate system analyzer (Kimoto Electric Co., Ltd., Japan) containing a flow-through-type analyzer that
could accurately analyze TA, DIC and pH [Kimoto et al., 2001, 2002; Watanabe et al., 2004]. Each sample was continuously fed into the analyzer, which trifurcated the flow to the TA, DIC and pH lines, and each reading was determined by the appropriate detectors.

Table 2 summarizes the list of parameters measured using the instruments and their accuracies relative to Certified Reference Materials (CRMs) for both in situ and ex situ measurements. We analyzed the nutrient samples to obtain the NO$_3$, NO$_2$, NH$_4$, PO$_4$, and SiO$_2$ values using the QuAAtro-SFA analyzer (SEAL analytical Ltd.), and we measured the discrete Chl-a concentration using a 10-AU fluorometer from Turner designs. For TA and DIC analyses, CRMs from the Scripps Institution of Oceanography were used. For all nutrients except for NH$_4$, reference materials from KANSO Japan were used (http://www.kanso.co.jp/eng/index.html). We did not have CRMs for Chl-a; therefore, we calibrated our analysis against a standard that was prepared from pure chlorophyll powder. Calculated pCO$_2$ values from combinations of DIC, TA, and pH inevitably have errors due to error propagation from DIC, TA, and pH themselves. DIC and TA were measured with 2-3 μmol kg$^{-1}$ accuracy and precision, and pH was measured in total scale with 0.002 precision and 0.005 accuracy. The calculated pCO$_2$ has an accuracy and precision of ~10 μatm from TA-DIC and 5 μatm from TA-pH or DIC-pH (evaluated based on Chapter 8 in Grasshoff et al., 1999). The direct measurement has an accuracy of ~7 μatm and precision with a similar range or better. The purpose of comparing calculated pCO$_2$ from TA-DIC and direct measured pCO$_2$ was to check the internal consistency (i.e., to evaluate whether all of the parameters were measured accurately). Furthermore, the merit of measuring TA-DIC is that these measurements can
describe more information about biogeochemical processes occurring in the system (such as photosynthesis, respiration, calcification, etc.).

Data validation and assessment – The final data were compiled at oneminute intervals based on the temporal resolution of the SSpCO₂ data. Five minutes of weather data and ten minutes of DO data were interpolated to one-minute data. One-minute SST, SSS, Chla, and SS data can be directly used after being re-calibrated according to accurate discrete data (i.e., CTD). The assessment of underway data deletion was performed when the SST and SSS values collected by the CTD/rosette instrument (i.e., direct sea surface water measurement) had significant errors compared with the continuous underway SST and SSS data collected by the Compact-CT/Infinity-CT and Compact-CLW/Infinity-CLW instruments (i.e., pumping water measurement). The error usually originated from the mixture of old and new water inside the container that needed to be cleaned depending on water clarity. In addition, when the water discharge fell far below the ideal water flow rate (1 L sec⁻¹), data were then discarded.

Sink/Source (net flux) calculation - We estimated the sink/source of CO₂ from the result of Equation 1 by first subtracting the calculated pCO₂ value for seawater (pCO₂SW) from the mean calculated pCO₂ value of the atmosphere (pCO₂ATM) of each cruise using the following equation:

\[
\delta pCO₂ = pCO₂^{SW} - pCO₂^{ATM}
\]  

(2)

Because the pCO₂ analyzer did not measure the xCO₂ in the atmosphere concurrently with the measurements of the xCO₂ in seawater, we could not instantaneously obtain the \( \delta pCO₂ \) value. Therefore, we calculated the mean value of pCO₂ATM from the average of...
one cruise and subtracted the averaged $pCO_2^{ATM}$ data from each of the $pCO_2^{SW}$ values. This assumption was valid because the atmospheric $CO_2$ values did not show significant temporal variability and was spatially homogeneous and less variable, especially during the limited duration of the cruise. For example, the standard deviation of SSp$CO_2$ was recorded smallest at 1.2 $\mu$atm during the EWIN2010 cruise and highest at 5.0 $\mu$atm during the EWIN2013 cruise. The $\delta pCO_2$ information was further analyzed to estimate the $CO_2$ flux; the net air-sea $CO_2$ flux ($F_{CO_2}$) (mol m$^{-2}$ yr$^{-1}$) can be estimated using the following equation:

$$F_{CO_2} = k_{CO_2} \times S_0 \times \delta pCO_2$$

(3)

where the above equation is a function of the transfer velocity ($k_{CO_2}$), the solubility of $CO_2$ ($S_0$) and the sea-air $pCO_2$ difference ($\delta pCO_2$). The transfer velocity of $CO_2$ (cm hour$^{-1}$), which is commonly parameterized as a function of the mean wind speed ($U_{10}$) (m s$^{-1}$) and the solubility of $CO_2$ in seawater (mol kg$^{-1}$ atm$^{-1}$), followed the general solubility of a non-ideal gas according to Weiss [1974]:

$$\ln S_0 = A_1 + A_2 \left(\frac{100}{T}\right) + A_3 \ln \left(\frac{T}{100}\right) + S \left[ B_1 + B_2 \left(\frac{T}{100}\right) + B_3 \left(\frac{T}{100}\right)^2 \right]$$

(4)

where the $A$ and $B$ constants can be obtained directly in the manuscript of Weiss [1974], $T$ is the temperature (Kelvin), and $S$ is the salinity (psu).

The quantification of the $CO_2$ flux between the ocean and atmosphere was explained by McGillis et al., [2004]. There was no concise information on the selection of kinematic transfer for the region. Here, without giving constraint to the final $CO_2$ flux result, we...
adopted well-known variety types of kinematic transfer velocities for CO$_2$ gas that ranged from low to high $k_{CO_2}$ estimations depending on the $U_{10}$ (wind speed at 10 m altitude).

$$k_{CO_2} = \begin{cases} 
0.39U_{10}^2(Sc/660)^{-0.5} & \text{(a)} \\
0.22U_{10}^2 + 0.33U_{10} & \text{(b)} \\
(3.3 + 0.026U_{10}^{-3})(Sc/660)^{-0.5} & \text{(c)} 
\end{cases} \quad (5)$$

Equations 5a, 5b and 5c refer to Wanninkhof [1992], Nightingale et al., [2000] and McGillis et al., [2001], respectively. $Sc$ is the Schmidt number, which describes the ratio between the kinematic viscosity and diffusivity process of CO$_2$ and is a function of temperature [Jähne et al., 1987; Wanninkhof, 1992]. Detailed results of the CO$_2$ sink/source for each cruise are explained in the following section.

3. Cruise Results

3.1. Spatial $\delta$pCO$_2$ and pCO$_2$

The complete compiled distribution of $\delta$pCO$_2$ in the Indonesian seas for the period 1984-2013 is depicted in Figure 1a. Here, we interpolated the underway data to 15-minute pixel grids with a radius of approximately 150 km because the largest interval between stations was 20-30 minutes during the EWIN cruise in 2010. In this study, the data spanned from 1984 to 2013. The CO$_2$ data not only showed high seasonal variability, but also gradually increased inter-annually for the duration of the measurements. For measurements with a wide temporal range, Takahashi et al. [2002, 2009] normalized pCO$_2$ data to a single reference year of 2000 by identifying the rates of pCO$_2$ change and the seasonal correction factor in various areas of the global ocean. Following this concept, a normalization technique has been applied to Figure 1b of this study. Our method to generalize the distribution of $\delta$pCO$_2$ is described in the Appendix.
these figures, the obvious pattern from the above results indicates that the inner western region of the Indonesian seas (Java Sea) had higher $\delta p$CO$_2$ compared to the eastern region (Flores and Banda Seas). The Java Sea is part of the shallow Sunda continent, but the bathymetry increases toward the continental shelf. In the Makassar Strait, where the continental shelf is located, we observed CO$_2$ sink areas. A considerable CO$_2$ sink area was also found in the Banda Sea. However, the mean observed $\delta p$CO$_2$ from each mission indicated that the overall region act as a CO$_2$ source to the atmosphere; the mean value along the track during the February 2010, April 2010, April 2011, June 2011, November 2012 and May 2013 cruises were +15.6, +11.7, +20.6, +11.5, +34.3, and +17.2 $\mu$atm, respectively. Consequently, the SSpCO$_2$ level was generally higher with respect to the observed mean atmospheric CO$_2$ level. The difference of SSpCO$_2$ to the atmosphere is approximately 11 - 34 $\mu$atm and taking into account the average of SSpCO$_2$ from the other open-source datasets generate $+15.9 \pm 8.6 \mu$atm uptake of atmospheric CO$_2$. On the other hand by taking a broader view, the regions were situated between appreciable CO$_2$ sink regions located in the Pacific (ITF entrance) and Indian Oceans (ITF outlet) (Figure 1). Therefore, the CO$_2$ characteristics were observed to change as the water flowed through the Indonesian seas.

Insights into the characteristic differences between the western and eastern regions of the Indonesian seas can be obtained by analyzing the data collected during the April 2010, June 2011 and June 2013 cruises. The cruise tracks covered the west and central/east regions of the Indonesian seas. In April 2010, the average of SSpCO$_2$ level was higher compared to the observed mean atmospheric CO$_2$ level of 379.2 $\pm$ 1.2 $\mu$atm (Figure 2), but with considerable variability. The observed mean SSpCO$_2$ level was 387.4 $\pm$ 49.7
μatm. In this case, under similar wind conditions, the Java Sea can potentially release a larger amount of CO₂ to the atmosphere than the amount contributed by the other seas. In contrast, SSpCO₂ significantly decreased in the continental slope region around the Surabaya and Lombok Strait (δpCO₂ ≈ -40 μatm), and the SSpCO₂ level was lower than the atmospheric CO₂ in this area. In the Flores and Banda Seas, the SSpCO₂ level steadily increased; it was slightly higher than the atmospheric CO₂ level but less than 420 μatm. A maximum δpCO₂ ≈ 100 μatm was observed in the Java Sea, whereas in the Flores and Banda Seas, the difference in pCO₂ between the ocean and atmosphere was 40 μatm.

From the end of June to the beginning of July 2011, the average SSpCO₂ level was 388.3 ± 16.4 μatm, whereas the observed mean atmospheric CO₂ level was 376.3 ± 2.9 μatm (Figure 3a). A majority of the high positive SSpCO₂ was located in the Java Sea, and the shallow areas of the Flores Sea (close to Makassar) exhibited higher values of δpCO₂ (≈ 30 μatm) compared to the Banda Sea (Figure 3b). In this time period, the temperature in the Java Sea was higher and the salinity was lower; however, this condition gradually changed toward the Banda Sea (Figure 3c). Temperatures slightly decreased and salinity increased by 1-2 units. The DO values were relatively lower (≈ 5 mg L⁻¹) than the normal value (6-7 mg L⁻¹) (Figure 3d). This low DO trend was independently verified using iodometric titration (Winkler method) and the DO sensors in the CTD and Compact instruments. All of these measurements and calculations suggest that the DO during this cruise was relatively low compared with the normal surface DO levels. Nutrient measurements in the Java Sea indicated that the surface silica concentration was
higher in the Java Sea than in the Banda Sea (Figure 3e). One surface silica measurement on June 26th was recorded at 29.9 μmol L⁻¹ (not shown in the graph).

In June 2013, the cruise mission was aimed at the Makassar Strait area next to the Java Sea. The SSpCO₂ level was generally higher with respect to the observed mean atmospheric CO₂ level (383.3 μatm ± 5.0 μatm) (Figure 4). The average δpCO₂ was +17.2 μatm, which showed that the Java Sea contributed higher CO₂ emissions compared to the other seas. Temperature was lower in the center of the Makassar Strait and higher elsewhere.

3.2. Increasing pCO₂ in the Makassar Strait

The Makassar Strait area is a potentially important region for CO₂ studies in that we found a mixture of CO₂ sinks and sources advected from the Java Sea and Pacific Ocean. Using our data, we examined the possible changes in pCO₂ in this area (Figure 5). There were four cruise tracks that crossed the Makassar Strait (cruises in 1984, 2007, 2008 and 2013); however, two additional tracks (cruises in 2010 and 2011) from south of the Makassar Strait were also used to investigate the pCO₂ trend over this time period. The selected underway cruise data (denoted with a colored dashed line) were then extrapolated to a radius of up to 150 km. We performed a transect slice (denoted by the black dashed line) through the Strait and compared the pCO₂ levels from 1984 to 2013, as calculated from Equation 1. No de-seasonalization or normalization methods were applied in Figure 5.

Based on the cruise tracks that crossed the Makassar Strait, the pCO₂ level was clearly observed as increasing from 354.5 μatm in 1984 to 390.7 μatm in 2013. At a latitude of 5°S, where all data existed, the pCO₂ level in 2010 was smaller than that in 2008.
However, in general, we found an increasing trend of pCO₂ in the Makassar Strait. The linear regression for the years 1984 to 2007 was \( y = 1.01x + 9.53 \) (\( R^2 = 0.75 \)); however, if we include data for the year 2008, the regression was \( y = 0.66x - 956.84 \) (\( R^2 = 0.89 \)). Then, for the period 1984-2007/2008, the pCO₂ increased at a rate of 0.6-1.0 μatm yr⁻¹. The trend was more apparent in the period 2007-2013 in which the linear regression was \( y = 3.82x - 7288.3 \) (\( R^2 = 0.89 \)); the pCO₂ level increased 3- to 6-fold. Table 3 explains in more detail the underway-averaged pCO₂ levels from the diagonal dashed black line in Figure 5. A 35.5 μatm increase was observed within the last 29 years; however, the trend has been dramatic in recent years. With a degree of confidence of \( R^2 > 0.75 \), the increasing trend in CO₂ was calculated as approximately ± 1.0 μatm yr⁻¹.

3.3. CO₂ source areas

The SSpCO₂ distribution in the Java Sea indicates that this area is a major contributor of CO₂ to the atmosphere (Figure 6). From the four cruises conducted in April 2010, April 2011, June 2011, and November 2012, evidence of persistent positive δpCO₂ was found. By comparing the EWIN2010 (April 2010) and EWIN2011 (April 2011) data only for the Java Sea, it is evident that the area averaged value of δpCO₂ decreased from 58.9 μatm in 2010 to 20.6 μatm in 2011. In the June 2011 data, recorded after the La Niña event, the δpCO₂ increased again to 25.1 μatm. During the onset of the northwest monsoon in November 2012, the δpCO₂ was 34.3 μatm. All of the δpCO₂ values in the Java Sea fall in the high-end level of the mean δpCO₂ range in the Indonesian seas.

The CO₂ fluxes for all cruises were calculated according to Equation 3 and are shown as the black line in Figure 6. From our observations, the average CO₂ fluxes indicated the average CO₂ emissions from the sea to the air during the total cruise periods of the
February 2010, April 2010, April 2011, November 2012 and May 2013 cruises were +1.3, +2.2, +5.3, +5.8 and +2.9 mol m$^{-2}$ yr$^{-1}$, respectively. As we did not measure the wind data in June 2011, we could not determine the average CO$_2$ fluxes during this period. Our results suggest that during our cruises, the Java Sea acted as a main source of CO$_2$ to the atmosphere.

4. Discussion

The physical and biogeochemical properties of the Indonesian seas are characterized by large temporal and spatial variability. Specifically, our study showed that the spatial distribution of SSpCO$_2$ was different between the western and eastern regions, with proximal segregation occurring at the Makassar Strait. This transition zone coincides with the "Wallace line", a virtual line segregating the terrestrial and marine flora and fauna, which is also located in the continental shelf of the Makassar Strait [Barber et al., 2000]. In general, the Indonesian archipelago acts as a source of CO$_2$ to the atmosphere, which is consistent with the findings of Gruber N. [2015] and Laruelle et al. [2014], which indicated that low latitude coastal regions release CO$_2$ to the atmosphere.

4.1. Physical and biogeochemical aspects related to the SSpCO$_2$ distribution

Both temperature and salinity affect pCO$_2$. A one-degree warming increased the pCO$_2$ by approximately 13 µatm, whereas a 1 psu increase in salinity resulted in a pCO$_2$ increase of 9 µatm [Takahashi et al., 1993; Keeling et al., 2004]. Our data showed that the surface layer salinity and temperature varied greatly between the west and the east. In the western part, the surface salinity was lower, while temperature was higher compared to that in the eastern Indonesia seas. The SSS varied around two units between west and
east, whereas the SST varied slightly about one degree Celcius between west and east. The spatial change in salinity and temperature was followed by an observed change in SSpCO$_2$, with more prominent change was reflected by the change in salinity.

The SSpCO$_2$ source pattern (red color in Figures 2-4) not only showed a tendency to correlate negatively with salinity as explained above, but also depicted a positive correlation with silica. For instance, when the positive $\delta$pCO$_2$ was high, the salinity was low and silica concentration was high, and when the positive $\delta$pCO$_2$ was low, the salinity was relatively high and silica concentration was low. This is an indication of freshwater and nutrient input from the land. Silica concentrations were high in shallow waters, such as in the Java Sea, which could have been caused by freshwater input from adjacent lands supplying silica. The similar condition of high silica was also found during the EWIN 2013 cruise. Normalized TA (NTA) and SiO$_2$ were positively correlated during this cruise (not shown). This is evidence that relatively high NTA water was brought by rivers together with SiO$_2$. The EWIN 2013 cruise was targeted to take samples along rivers in Kalimantan Island, especially at the second largest delta in Indonesia, which is called Mahakam Delta. Therefore, larger surface NTA data were found during the EWIN 2013 cruise than was mostly observed in the Makassar Strait (Figure 7). Observing water quality of mining areas was one of the aims during the Banggai 2011 cruise, and relatively higher NTA was also found during this cruise. This evidence indicates a potentially strong terrestrial influence in the Indonesian seas. Yet, in straits connecting to the Pacific or Indian Oceans, the change in pCO$_2$ could be caused by ocean advection or changes in salinity and temperature of the outside waters.
Other physical and biogeochemical factors, such as temperature and DO, also showed differences between the western and eastern regions; however, they were not as significant as the differences in salinity and silica. Based on the Chl-a data, all of the measurements were collected during non-phytoplankton bloom conditions; therefore, we were not able to examine and determine the quantitative correlation of Chl-a (and DO) on the SSpCO$_2$ distribution during bloom conditions.

From the preceding discussion, even though differences in the salinity characteristics influenced the spatial SSpCO$_2$ differences, we found that salinity did not have a significant correlation with the increasing SSpCO$_2$ trend in the Makassar Strait for the period 1984-2013 (not shown). This was also true for the SST, as the scatter in the data for the Makassar Strait showed that the time series of SST did not present the clear increasing trend, such as that of pCO$_2$. However, this explanation should be further analyzed and clarified by obtaining fixed long-term time-series data for Indonesian seas.

4.2. Possible influence of terrestrial input to pCO$_2$

In addition to section 4.1, we carefully analyzed the influence of salinity, especially the role of nutrients input from land to the pCO$_2$ distribution in the Indonesian seas. Using CO2SYS software, the observed SST and SSS in April 2010 were used to reconstruct the SSpCO$_2$ distribution of the western and eastern parts of the Indonesian seas. We selected the dissociation constant from Mehrbach et al., [1973], which was refitted by Dickson and Millero [1987], the KSO$_4$ constant from Dickson [1990], and pH based on the total scale, as the main constant parameters. We calculated pCO$_2$ from in situ SST and SSS data obtained during the cruise and from normalized TA (NTA) and DIC (NDIC). NDIC and NTA were calculated from the following equation:
\[ NTA(NDIC) = NTA_0(NDIC_0) \times 35.0 / SSS \] (6)

where \( NTA_0 \) and \( NDIC_0 \) are the offshore end-member values, as determined below. Samples taken from the far-ocean sites in the eastern Indonesian seas (Flores or Banda Seas) were averaged and normalized at \( S = 35 \), then used as NTA and NDIC (2290 and 1964 μmol kg\(^{-1}\), respectively). In the eastern regions, water was less influenced from terrestrial inputs, which can clearly be observed at higher salinities, and water can be regarded as an offshore end-member. If TA and DIC were changed solely from freshwater input/output through rainfall/evaporation, the observed pCO\(_2\) should match the pCO\(_2\) calculated from this method. If not, other factors influencing TA and DIC (i.e., river discharge with significant TA and DIC, calcification and photosynthesis, upwelling of deep-sea water, gas-exchange, etc.) should be considered. The calculated pCO\(_2\) showed that the temperature and salinity did not fully explain the pCO\(_2\) variability that was observed in the Java Sea; however, the calculation sufficiently depicted the variability at the Flores/Banda Seas (Figure 8). In the Java Sea, a deviation of more than 44.0 μatm occurred between the calculated and observed pCO\(_2\), whereas in the Flores/Banda Seas, this deviation was only 1.1 μatm. The high pCO\(_2\) in the Java Sea can be explained from higher terrestrial organic matter inputs in this region. Thus, the large discrepancies were attributable to greater terrestrial impacts due to shallower water depth and to more densely populated cities in the western region. This theoretical approach suggested that a small change in salinity could influence the distribution of pCO\(_2\) levels. However, the discrepancy that was found in the theoretical calculation using CO2SYS software showed that the pCO\(_2\) condition at the surface was complex and influenced by many factors,
including the carbonate system, water-mass characteristics, nutrients, organic matter and atmospheric conditions.

4.3. Influence of temperature during La Niña on CO₂ emissions

Although the role of temperature was not as significant as salinity and silica, in this subsection, we show the influence of the interannual variability of temperature on the CO₂ conditions in the Indonesian seas, especially in the Java Sea. We describe an interesting feature of the \( \delta pCO_2 \) and CO₂ flux that was observed in the Java Sea. April 2011 was the termination period for the La Niña event of 2010. We found that the \( \delta pCO_2 \) decreased by approximately 50% in April 2011 compared to its value in 2010. This decrease was associated with the lowest averaged SST in the region.

The SST in April 2011 was lower than that in April 2010 by 1-2 °C, which was similar to the condition that occurred in February 2010 during the peak austral monsoon. Additional information collected from the NCEP/NCAR data for the SST and wind speed during the cruise missions is listed in Figure 9. The wind was stronger in April 2011 than in 2010; during this cruise, the La Niña event occurred, and its effects were prolonged in the Pacific Ocean, where strong winds with heavy rains and a typhoon were recorded before the cruise. These occurrences suggest that the cruise was not conducted during a normal year. The weather conditions in April 2011 resulted in lower SST values, which contributed to lower \( \delta pCO_2 \) values (because of the thermodynamics) compared to those from the EWIN2010 (April 2010) data obtained from the Java Sea during normal conditions. It is clear that \( \delta pCO_2 \) decreases during La Niña events. Thus, in the absence of a La Niña event, the April 2011 levels of \( \delta pCO_2 \) would have been higher than those during the austral winter.
conditions (June-August) because, in general, the temperature during the austral summer is higher than during the austral winter.

Although the $\delta$pCO$_2$ was lower during the April 2011 cruise (20.6 $\mu$atm) as a result of lower SST distributions, the CO$_2$ flux during the EWIN 2011 cruise (5.29 mol m$^{-2}$ yr$^{-1}$) was 1.7 times larger than that of the EWIN 2010 cruise (3.1 mol m$^{-2}$ yr$^{-1}$). This phenomenon occurred because the wind speeds during the April 2011 cruise (4.4 $\pm$ 2.3 m s$^{-1}$) were higher than those during the April 2010 cruise (3.4 $\pm$ 1.3 m s$^{-1}$) (Figure 9); however, the CO$_2$ flux was proportional to a second- and higher-order wind speed, suggesting that during the La Niña conditions, the CO$_2$ flux to the atmosphere increased.

5. Summary

This study demonstrates the first region wide compilations of the regional surface oceanic pCO$_2$ levels in the tropical Indonesian seas. The subsequent discussions focused on the different distribution of SSpCO$_2$ between the shallow Java Sea and deep Flores/Banda Seas. The results of these analyses revealed evidence that the Indonesian seas act as a source of CO$_2$, contributing approximately 3.7 $\pm$ 2.2 mol m$^{-2}$ yr$^{-1}$, especially during the austral summer season. The results also showed that the shallow Java Sea released more CO$_2$ to the atmosphere than the deep Flores/Banda Seas, and the high SSpCO$_2$ in this region was associated with higher freshwater and nutrient input from land. Along the main ITF routes, we found that in the Makassar Strait, the SSpCO$_2$ trend over the past 29 years showed an average unit increase per year but a more appreciable increase in recent years. Despite the strong influence of salinity on the changes in pCO$_2$, the impact of temperature is more significant on a temporal (inter-annual) scale rather than a spatial scale, e.g., the changes in CO$_2$ emissions in the shallow Java Sea during La Niña

D R A F T  October 30, 2015, 8:26am  D R A F T

This article is protected by copyright. All rights reserved.
years. An SST change of -2.0 °C could effectively impact δpCO$_2$ and the CO$_2$ flux. The analysis presented in this study supports the notion that no single factor controlled the CO$_2$ dynamics in this region and that each parameter had its own specific influence either spatially or temporally, though salinity, silica, and TA appeared to control the SSpCO$_2$ through freshwater supply from adjacent lands. The authors believe that the ITF variability may contribute to the SSpCO$_2$ distribution; therefore, this topic should be considered a valuable subject for future research by the scientific community.

Appendix

To eliminate biases due to sampling year and seasonal changes, we normalized the data to last years data in 2013 by assuming that pCO$_2$ increases are associated with SST increases. This assumption is driven by the discovery that SST best fits the seasonal pattern of oceanic SSpCO$_2$. The SST model output of 1993-2007 [Kartadikaria et al., 2011a] was used to obtain the weighted average factor for the austral summer and winter seasons. We considered the seasonal factor of 0.96 and 1.04 for the austral summer and austral winter, respectively. The regression function that was used to normalize pCO$_2$ data to a single reference year was derived from the Hawaii Ocean Time-series (HOT) surface CO$_2$ time series data [Dore et al., 2009] with a rate of pCO$_2^{HOT}$ change of 0.43 μatm per season. In Figure 1b, the normalized SSpCO$_2$ data were de-seasonalized using the seasonal factor (w) and de-trended using the rate of pCO$_2$ change (m), as mentioned previously, as follows:

$$SSpCO_2|_{t_{ref}} = SSpCO_2(t) \times w(t) + \left[ m \cdot \left( pCO_2^{HOT}(t) - pCO_2^{HOT}|_{t_{ref}} \right) \right]$$ (7)
When the data were reanalyzed (normalized), the atmospheric pCO$_2$ in 2013, at a level of 383.3 µatm, was selected to obtain the δpCO$_2$ value.

Acknowledgments.

This work was funded by the Global Environment Research Fund (F-082) of the Ministry of the Environment, Japan, and a Grant-in-Aid for Scientific Research (A) (No. 18254003 and No. 21254002) of the JSPS (Japan Society for the Promotion of Science). This work is a joint-research project in cooperation with the Tokyo Institute of Technology, the Research Center for Oceanography-Indonesian Institute of Sciences, and the Research Center for Marine and Coastal Resources - Ministry of Marine Affairs and Fisheries of Indonesia. The authors gratefully acknowledge the underway pCO$_2$ data from the CDIAC-LDEO from Columbia University and the Xuelong expedition that was managed by the Third Institute of Oceanography, China; the University of Georgia and the AOML ocean carbon group; the xCO$_2$ atmospheric data from the CRISO and NOAA/ERSL; and the captain and crews of the R/V Baruna Jaya VIII. We benefited considerably from the facilities offered by the Kayanne Laboratory, the University of Tokyo, and from fruitful discussion with Dr. Takashi Nakamura. The first author received grant support from a postdoctoral JSPS for foreign researchers. pCO$_2$ data collection can be requested from the corresponding authors: a.r.kartadikaria@oceanography.itb.ac.id and watanabe.a.ah@m.titech.ac.jp.

References


Dickson, A.G. (1990), Thermodynamics of the dissociation of boric acid in synthetic seawater from 273.15 to 318.15K, Deep-Sea Research, 37, 755-766.


Mehrbach, C., C.H. Culberson, J.E. Hawley, and R.M. Pytkowicz (1973), Measurement of
the apparent dissociation constants of carbonic acid in seawater at atmospheric pressure,

Nightingale, P. D., P. S. Liss, and P. Schlosser (2000), Measurements of airsea gas
transfer during an open ocean algal bloom, Geophys. Res. Lett., 27(14), 2117–2120,

Sabine C. L., Richard A. Feely, Nicolas Gruber, Robert M. Key, Kitack Lee, John L.
Bullister, Rik Wanninkhof, C. S. Wong, Douglas W. R. Wallace, Bronte Tilbrook, Frank
J. Millero, Tsung-Hung Peng, Alexander Kozyr, Tsueno Ono, and Aida F. Rios (2004),

oxide-based multicomponent catalysts for methanol synthesis from carbon dioxide and

Sasai, Y., A. R. Kartadikaria, Y. Miyazawa and K. Nadaoka (2011), Marine Ecosystem
Simulation in the Indonesian Seas, Interdisciplinary Studies on Environmental Chem-
istryMarine Environmental Modeling & Analysis, Eds., TERRAPUB, pp. 1117.

Susanto, R.D., A. L. Gordon and J. Sprintall, (2007), Observation and proxies of the
surface layer throughflow in the Lombok Strait, J. Geophys. Res. Vol. 112, No. C3,
C03S92, 10.1029/2006JC003790.

Seasonal variation of CO$_2$ and nutrients in the high-latitude surface oceans: A compa-


<table>
<thead>
<tr>
<th>No.</th>
<th>Cruise</th>
<th>Start (ddmmmyy)</th>
<th>Finish (ddmmmyy)</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Condition</th>
<th>Location</th>
<th>Interannual SSxCO₂ data</th>
<th>Atmospheric CO₂ data</th>
<th>No. of Station</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Makassar Strait</td>
<td>09Feb84</td>
<td>11Feb84</td>
<td>9.0°S</td>
<td>115.5°E</td>
<td>Normal</td>
<td>CDIAC-LDEO</td>
<td>Normal</td>
<td>Normal</td>
<td></td>
<td>This study</td>
</tr>
<tr>
<td>2</td>
<td>Savu Sea</td>
<td>11Mar92</td>
<td>20Mar92</td>
<td>8.5°S</td>
<td>120.0°E</td>
<td>El Niño</td>
<td>CDIAC-LDEO</td>
<td>Normal</td>
<td>Normal</td>
<td></td>
<td>This study</td>
</tr>
<tr>
<td>3</td>
<td>Sunda Strait</td>
<td>01Nov95</td>
<td>03Nov95</td>
<td>7.0°S</td>
<td>104.0°E</td>
<td>La Niña</td>
<td>CDIAC-LDEO</td>
<td>Normal</td>
<td>Normal</td>
<td></td>
<td>This study</td>
</tr>
<tr>
<td>4</td>
<td>Celebes Sea</td>
<td>25Jan96</td>
<td>25Jan96</td>
<td>0.0°S</td>
<td>115.0°E</td>
<td>La Niña</td>
<td>CDIAC-LDEO</td>
<td>Normal</td>
<td>Normal</td>
<td></td>
<td>This study</td>
</tr>
<tr>
<td>5</td>
<td>24th China</td>
<td>24Nov07</td>
<td>23Nov07</td>
<td>12.0°S</td>
<td>115.0°E</td>
<td>La Niña</td>
<td>AOML-XUELONG</td>
<td>Normal</td>
<td>Normal</td>
<td></td>
<td>AOML-XUELONG</td>
</tr>
<tr>
<td>6</td>
<td>24th China</td>
<td>04Apr08</td>
<td>10Apr08</td>
<td>12.0°S</td>
<td>115.0°E</td>
<td>Normal</td>
<td>AOML-XUELONG</td>
<td>Normal</td>
<td>Normal</td>
<td></td>
<td>This study</td>
</tr>
<tr>
<td>7</td>
<td>Sby-Mks Exp.</td>
<td>14Feb10</td>
<td>15Feb10</td>
<td>4.5°S</td>
<td>112.0°E</td>
<td>Normal</td>
<td>NOAA/ESRL (Bukit Kota Tabang)</td>
<td>Normal</td>
<td>Normal</td>
<td></td>
<td>This study</td>
</tr>
<tr>
<td>8</td>
<td>EWIN2010</td>
<td>22Apr10</td>
<td>01May10</td>
<td>5.0°S</td>
<td>106.0°E</td>
<td>Normal</td>
<td>NOAA/ESRL (Bukit Kota Tabang)</td>
<td>Normal</td>
<td>Normal</td>
<td></td>
<td>This study</td>
</tr>
<tr>
<td>9</td>
<td>EWIN2011</td>
<td>12Apr11</td>
<td>23Apr11</td>
<td>3.5°S</td>
<td>106.0°E</td>
<td>La Niña</td>
<td>This study</td>
<td>This study</td>
<td>This study</td>
<td></td>
<td>This study</td>
</tr>
<tr>
<td>10</td>
<td>Banggai Exp.</td>
<td>24Jun11</td>
<td>06Jul11</td>
<td>5.0°S</td>
<td>106.0°E</td>
<td>Normal</td>
<td>This study</td>
<td>This study</td>
<td>This study</td>
<td></td>
<td>This study</td>
</tr>
<tr>
<td>11</td>
<td>SITE2012</td>
<td>22Nov12</td>
<td>30Nov12</td>
<td>6.0°S</td>
<td>106.0°E</td>
<td>Normal</td>
<td>This study</td>
<td>This study</td>
<td>This study</td>
<td></td>
<td>This study</td>
</tr>
<tr>
<td>12</td>
<td>EWIN2013</td>
<td>05Jun13</td>
<td>20Jun13</td>
<td>6.0°S</td>
<td>111.0°E</td>
<td>Normal</td>
<td>CDIAC-LDEO</td>
<td>Normal</td>
<td>Normal</td>
<td></td>
<td>This study</td>
</tr>
</tbody>
</table>

Table 1. Available underway SSxCO₂ data (1984-present) during the austral summer season in the Indonesian seas.
Table 2. Underway and discrete measured parameters.

<table>
<thead>
<tr>
<th>No.</th>
<th>Parameter</th>
<th>Main instruments</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Name</td>
<td>Output used</td>
</tr>
<tr>
<td>1.</td>
<td>Carbonate system</td>
<td>portable pCO$_2$ analyzer SSsCO$_2$, atm. pCO$_2$</td>
<td>In situ</td>
</tr>
<tr>
<td>2.</td>
<td>Temperature</td>
<td>Compact CT</td>
<td>SST</td>
</tr>
<tr>
<td>3.</td>
<td>Salinity</td>
<td>Compact CT</td>
<td>SSS</td>
</tr>
<tr>
<td>4.</td>
<td>Chlorophyll-a</td>
<td>Compact CLW or Surface chlorophyll-a</td>
<td>In situ</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Infinity CLW</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>Dissolved Oxygen (DO)</td>
<td>Compact DOW or Surface DO</td>
<td>In situ</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Infinity AROW</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>Nutrient</td>
<td>Auto analyzer</td>
<td>NO$_3$, NO$_2$, NH$_4$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PO$_4$ and SiO$_2$</td>
</tr>
<tr>
<td>7.</td>
<td>Suspended Sediment (SS)</td>
<td>Compact CLW or Surface SS</td>
<td>In situ</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Infinity AROW</td>
<td></td>
</tr>
</tbody>
</table>

Note: CTD used is CTD Sea-Bird SBE 911
Table 3. Underway (snapshot) averaged level of pCO$_2$ in the Makassar Strait.

<table>
<thead>
<tr>
<th>No.</th>
<th>Year (x variable)</th>
<th>Average level (y variable)</th>
<th>Regression function</th>
<th>mean pCO$_2^{ATM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>1984</td>
<td>354.6 ± 7.2 μatm</td>
<td>$y = 1.01x + 9.53$</td>
<td>344.8 μatm</td>
</tr>
<tr>
<td>2.</td>
<td>2007</td>
<td>366.5 ± 10.7 μatm</td>
<td>$y = 3.82x - 7288.3$</td>
<td>366.5 μatm</td>
</tr>
<tr>
<td>3.</td>
<td>2008</td>
<td>373.3 ± 8.6 μatm</td>
<td></td>
<td>365.4 μatm</td>
</tr>
<tr>
<td>4.</td>
<td>2010</td>
<td>386.4 ± 10.2 μatm</td>
<td></td>
<td>381.9 μatm</td>
</tr>
<tr>
<td>5.</td>
<td>2011</td>
<td>387.6 ± 3.8 μatm</td>
<td></td>
<td>376.3 μatm</td>
</tr>
<tr>
<td>6.</td>
<td>2013</td>
<td>390.0 ± 13.4 μatm</td>
<td></td>
<td>383.3 μatm</td>
</tr>
</tbody>
</table>
Figure 1. Compilation of the available δpCO₂ data (in μatm) from 1984-2013 according to cruise tracks (upper figure). Smaller-sized dots in the upper panel were obtained from expeditions other than those in this study. In the lower figure, the interpolation uses a 30-min grid and 150-km radius. Positive δpCO₂ values indicate that the ocean has a pCO₂ concentration that is significantly higher than the atmospheric pCO₂.
Figure 2. Time series of the surface parameters measured during the EWIN 2010 cruise. From the upper to lower panel: (a) oceanic and atmospheric pCO$_2$ values; (b) δpCO$_2$; (c) SST and SSS values; (d) Chl-a values and DO values; and (e) NO$_3$, PO$_4$ and SiO$_2$ concentrations. The Surabaya and Lombok Strait areas are located between the Java Sea and Flores-Banda Sea and are indicated with a blue line. The red line in (b) separates the pCO$_2$ sinks (negative) and sources (positive).
Figure 3. Time series of the surface parameters measured during the Banggai cruise (June-July 2011). From the upper to lower panel: (a) oceanic and atmospheric pCO$_2$ values; (b) δpCO$_2$; (c) SST and SSS values; (d) Chl-a values and DO values; and (e) NO$_3$, PO$_4$ and SiO$_2$ concentrations. The Bali and Kangean areas are located between the Java Sea and Flores-Banda Sea and are indicated with a blue line. The red line in (b) separates the pCO$_2$ sinks (negative) and sources (positive).
Figure 4. Time series of the surface parameters measured during the EWIN 2013 cruise (June 2013). From the upper to lower panel: (a) oceanic and atmospheric pCO$_2$ values; (b) δpCO$_2$; (c) SST and SSS values; (d) Chl-a values and DO values; and (e) NO$_3$, PO$_4$ and SiO$_2$ concentrations.
Figure 5. Interpolated deseasonalized pCO$_2$ values for the Makassar Strait, which shows an increasing trend of pCO$_2$ trend of 35.5 $\mu$atm over 29 years (Figures A-F). The pCO$_2$-latitude plot is extracted from the interpolated cruise tracks (denoted by colored dots) and only uses the data from along the diagonal dashed black line.
Figure 6. Time series of the $\delta pCO_2$ and CO$_2$ flux values (left panel) and spatial pCO$_2$ levels (right panel) around the Java Sea. The cruise tracks on the right panel correspond to the time series for the left panels, which originated from Jakarta port. The left figures show the time series of the $\delta pCO_2$ and CO$_2$ flux values for the cruises in the 2000s. At the end of the La Niña event in April 2011, the ocean emitted less CO$_2$ gas to the atmosphere, whereas during a normal season, the Java Sea emitted $\sim$40 $\mu$atm CO$_2$. The black dotted line denotes $\delta pCO_2 = 50 \mu$atm.
Figure 7. Deffeyes diagram for the normalized surface TA and DIC values from different cruises denoted with different colors. The unit is in $\mu$mol kg$^{-1}$. The calculated pCO$_2$ contour was calculated using the average SSS (=32.4 psu) and SST (=29.6 °C) of five cruises.
Figure 8. Time series of the measured (black line) and calculated (red line) \( pCO_2 \) values during the EWIN 2010 cruise. The calculated \( pCO_2 \) time series was measured as a function of the observed SST, SSS, NTA and NDIC. The NTA was normalized to TA(SSS=35)=2290, and the NDIC was normalized to DIC(SSS=35)=1964 \( \mu \text{mol kg}^{-1} \).
Figure 9. Distribution of the sea surface temperatures (shaded) and 10-m wind above the ocean surface (vector) during the northwest monsoon season in (a) February 2010, (b) April 2010, and (c) April 2011. Wind and SST data are plotted from the averaged 6-hour NCEP/NCAR data obtained during the cruises. Temperature and wind speed units are in °C and m s$^{-1}$, respectively.
This article is protected by copyright. All rights reserved.
This article is protected by copyright. All rights reserved.