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The Partial Pressure of CO_2 and Fluxes of CO_2 in Semarang Bay, Indonesia

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Abstract

The CO_2 characteristics of the Semarang Bay system on the Northern coast of Java were investigated to understand the roles in carbon dioxide flux. The flux of carbon dioxide at the sea surface between seawater and atmosphere is essential for mitigating atmospheric CO_2. The aims of this study were to assess the variation of CO_2 partial pressure seawater (pCO_{2sea}) and CO_2 flux and to analyse the water quality variable which has the larger influence on CO_2 flux in the waters of Semarang Bay. The variables in this study were temperature, pH, salinity, and DO. Different methods were adopted in the analysis of water samples: spectrophotometric to measure chlorophyll-a and phosphate and titration method to measure Total Alkalinity (TA) and Dissolved Inorganic Carbon (DIC). A CO_2 meter was used to measure the CO_{2atm}. The lowest CO_2 flux value was (1.86 mmol CO_2 m^{-2} day^{-1}) during the morning period while the pCO_{2sea} reached 461.04 µatm and CO_2 flux 83.79 mmol CO_2 m^{-2} day^{-1} at night. At noon time, with increased temperature, pCO_{2sea} was 461.04 µatm, and CO_2 flux was 83.79 mmol CO_2 m^{-2} day^{-1}. The high concentration of chlorophyll-a ranged between 3.55–4.11 mg.L^{-1}. This chlorophyll-a concentration has a negative correlation with CO_2 flux, and it was found that TA and DIC concentrations have no relationship with CO_2 flux. Based on PCA analysis, it was found that the variability of CO_2 flux in Semarang Bay is influenced by the variability of pCO_{2sea}, sea surface temperature and k_{wa} (affected by wind speed).

Keywords: *CO_2 flux, pCO_2 seawater, Dissolved Inorganic Carbon, Semarang Bay*

Introduction

The oceans have an essential role as the most significant anthropogenic CO_2 sink, larger than land-based sinks. CO_2 diffusing through the sea surface changes form becoming into dissolved carbon dioxide, carbonic acid, bicarbonate, and carbonate, which is then utilised by phytoplankton and other autotrophic organisms and converted into organic carbon during the process of photosynthesis. This mechanism is known as the biological pump. Marine and coastal ecosystems play an important role in the global CO_2 cycle by capturing and storing carbon and redistributing it (Nehren and Wicaksono, 2018). Through the biological pump, the oceans sequester large amounts of particulate organic carbon (POC) while sinking to the bottom of the waters (Cavan *et al.*, 2019). At sea level, CO_2 changes into *free aqueous* CO_2, carbonic acid ($H_2CO_3^-$), bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) (Borges *et al.*, 2014; Akhand *et al.*, 2021). The concentration of free aqueous CO_2 in seawater is proportional to the partial pressure of CO_2 in seawater (pCO_{2sea}). The difference between the partial pressure of CO_2 in seawater and in the atmosphere determines the direction of CO_2. The partial pressure of CO_2 shows more significant ocean variations than the atmosphere. Thus the movement of CO_2 flux is controlled primarily by changes in ocean pCO_2 (Zeebe, 2012; Delaigue *et al.*, 2020). The partial pressure of CO_2 in seawater is determined by sea surface temperature and biological processes in the ocean, such as photosynthesis. Thus, these two parameters determine the sink (uptake) and source (release) of CO_2 by the ocean (Feely *et al.*, 2001; Cavan *et al.*, 2019). Various researches have been carried out to determine the effects of sea surface temperature (Takahashi *et al.*, 2002; Zhai *et al.*, 2007; Zhu *et al.*, 2009; Chierici *et al.*, 2009) and of biological processes (Takahashi *et al.*, 2002; Hülse *et al.*, 2017; Cavan *et al.*, 2019) on seawater pCO_2 and sea-atmosphere CO_2 flux distribution (Takahashi *et al.*, 1997; Takahashi *et al.*, 2002; Zhai *et al.*, 2007; Chierici *et al.*, 2009; Kartadikaria *et al.*, 2015; Li *et al.*, 2018; Brady *et al.*, 2019; Friedlingstein *et al.*, 2020).

Roy-Barman and Jeandel (2016), states that at low latitudes/equator the warm waters can reduce the solubility of CO_2 causing CO_2 to be released back into the atmosphere (source CO_2). At high latitudes with cold waters, the solubility of CO_2 is high which can increase the dissolution of gas into

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seawater causing CO_2 absorption (sink CO_2) to occur. This is supported by other studies which conclude that high-latitude seas/oceans with four seasons and relatively cold temperatures function as CO_2 absorbers (Takahashi *et al.*, 1997; Takahashi *et al.*, 2002; Cai *et al.*, 2006; Yasunaka *et al.*, 2016; Arnone *et al.*, 2017; Ito *et al.*, 2018; Tian *et al.*, 2020) while low latitudes seas function as a source of CO_2 due to warm waters (Fitranti *et al.*, 2013; Kartadikaria *et al.*, 2015; Afdal, 2016; Yan *et al.*, 2018; Latifah *et al.*, 2020). Several studies in Indonesia, however, show that the sea can function as sinks of CO_2 (Fachri *et al.*, 2015; Latifah *et al.*, 2019). These studies focused on waters with seagrass and coral reef ecosystems. Studies of CO_2 flux in waters which do not have seagrass ecosystems and coral reefs surrounded by urban settlements and industries are still lacking. The waters of Semarang Bay do not have seagrass ecosystems, or coral reefs and are surrounded by many industries and settlements which necessitates a comprehensive study of the CO_2 flux. Seagrass meadows and coral reefs are essential for carbon storage representing a vital ecosystem service (Guerra-Vargas *et al*,, 2020). In coastal waters, tropical seagrass meadows are connected to coral reefs, and since the reef barrier disperses waves, which accelerates sediment accretion and avoids erosion. Therefore, coral reefs might enhance the seagrass meadows' capacity as a blue carbon sink. The first study to investigate the spatiotemporal distribution of CO2 flux in the Java Sea (Wirasatrya *et al*., 2020) which also the first study to examine the key parameters at the sea surface (i.e., SST, Chl_a, sea surface salinity, and surface wind) to obtain the most influencing parameter for CO2 flux in the Java Sea. This indicates a limited number of studies on CO2 flux in the Java sea. Moreover, the once dense mangrove forests around the bay have largely been lost, and with them an important CO_2 sink. Therefore, a comprehensive study on the CO_2 flux in the bay is required.

The aims of the present study are 1) to determine the variation of CO_2 partial pressure (pCO_2) and CO_2 flux in the waters of Semarang Bay; 2) to analyze the water quality variables that have the most influence on CO_2 flux.

Materials and Methods

The research was conducted in August 2021 during the southeast monsoon, when the wind blows from the Australian to the Asian Continent (Muskananfola *et al.*, 2021b). In Indonesia, including Semarang Bay, this is the dry season (Muskananfola *et al.*, 2021a). The monsoon winds blow through the Maritime Continent or the Indonesian seas, mainly over the seas along the routes formed by the coastline of the large islands and the chains of the small islands (Alifdini *et al*., 2021. In the Indonesian seas, the monsoon wind is a key factor affecting the regional climate and oceanographic conditions (Susanto *et al*., 2006).

Field data collection was conducted on 21 August 2021 (3 stations), 22 August 2021 (4 stations), and 23 August 2021 (3 stations) (Figure 1.). Station selection was based on their representativeness of the entire Semarang Bay area.

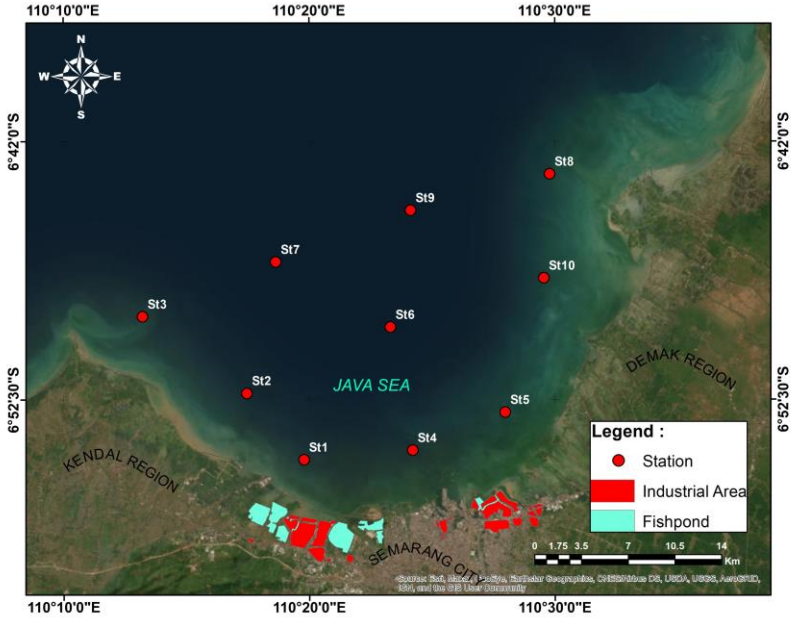

Figure 1. Study sites at Semarang Bay.

Sample collection

Using a Nansan Water Sampler, samples were collected near the sea water surface and put into several bottles: 1). 250 ml glass bottles (Dissolved Inorganic Carbon (DIC) and Total Alkalinity (TA) analysis using the titrimetric method); 2). 1,500 ml (chlo-a analysis using the spectrophotometric method); and 3). 600 ml (nitrate and phosphate using the spectrophotometric method). Measurements of temperature, pH, and salinity were done using a DO meter and pH meter, measurement of Atmospheric CO_2 using a CO_2 meter, and water CO_2 using the titrimetric method.

Determination of the partial pressure of CO_2

Seawater CO_2 partial pressure was calculated using the following formula (Dickson *et al.,* 2007):

$$fCO_2 = [CO_2] / Ko$$
$$pCO_2 \text{ sea } (\mu atm) = fCO_2 (\mu atm) * [1.00436 - 4.669*10^{-5}*SST(^oC)]$$

where $[CO_2]$ is the seawater CO_2 concentration; Ko is the CO_2 solubility of seawater

The partial pressure of atmospheric CO_2 was calculated using the following formula (Dickson *et al.*, 2007):

$$pCO_2atm = xCO_2atm\ (pb - pH_2O)$$

Where pb = air pressure (atm); xCO_2atm (ppm) is the molar fraction of CO_2 air in the troposphere obtained from https://disc.gsfc.nasa.gov/datasets/AIRX3C2M_V005/summary, pH_2O is the water vapour pressure at the air-sea boundary obtained from Weiss *et al.* (1980):

$$pH_2O = \exp(24.4543 - 67.4509 \times (100/Tk)) - 4.8489 \times \ln(Tk / 100) - 0.000544 \times S$$

where: T is sea surface temperature (Kelvin); S is sea surface salinity (‰).

Estimation of the sea-air CO_2 Flux

Calculation of CO_2 flux or CO_2 gas flow exchange is calculated using a formula (Takahashi *et al.*, 2002; Du *et al.*, 2015; Fachri *et al.*, 2015; Takahashi and Sutherland, 2017):

$$\text{Flux } CO_2 = K_h \times k_{wa} \times (\Delta pCO_2)$$
$$\Delta pCO_2 = pCO_{2sea} - pCO_{2atm}$$

Where Flux CO_2 is a carbon dioxide flux (mmol.m^{-2}.day^{-1}); Kh= solubility of CO_2 in mol L^{-1} atm^{-1} is derived from Weiss (1974); k_{wa} = CO_2 gas transfer velocity in m s^{-1} using the RC01 and B04 formula (Raymond and Cole, 2001; Borges *et al.*, 2004); ΔpCO_2= the partial pressure difference of CO_2 in the seawater and the atmosphere.

Results and Discussion

Partial pressure of CO_2

The partial pressure of carbon dioxide (pCO_2) is influenced by water temperature. The results of this study show that the pCO_{2sea} value in Semarang Bay in August 2021 ranges from 378–438 µatm with a temperature range of 28–35 ^oC (Figure 2.). The partial pressure of ocean carbon dioxide (pCO_{2sea}) increases with increasing water temperatures, with a correlation value of 0.88 (Figure 2.). Lakshmi (2000), stated that warm ocean waters , generally at low latitudes, reduced the solubility of CO_2, increasing the partial pressure of sea carbon dioxide (pCO_{2sea}), which is in agreement with the results of Figure 2. Temperature and coastal ecosystems (estuaries, mangroves, coral reefs and seagrasses) are the main factors that cause variations in pCO_{2sea} values and CO_2 flux (Afdal *et al.*, 2020). Other studies (Arnone *et al.*, 2017; Ito *et al.*, 2018) found that relatively cold water temperatures reduced seawater pCO_2 and the sea acted as a CO_2 sink. The partial pressure of carbon dioxide (pCO_2) and primary ocean productivity are important keys in the biological pump mechanism.

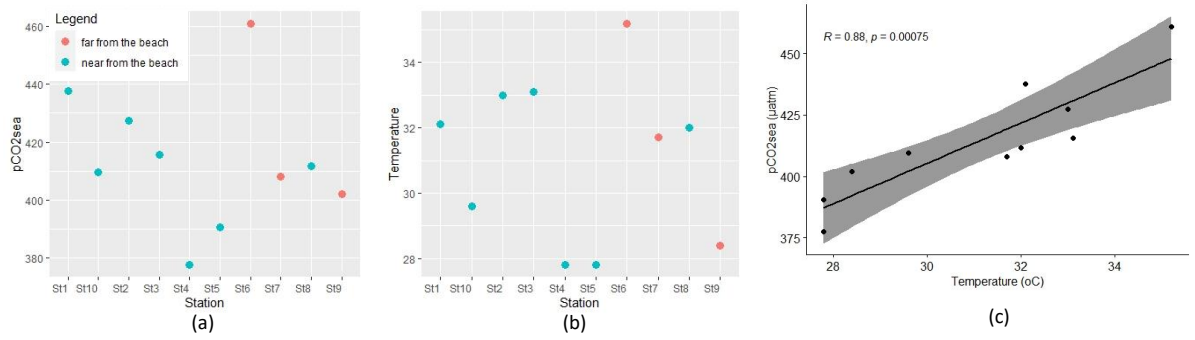

Figure 2. Distribution and relationship of pCO_2 sea and sea surface temperature

Variations in pCO_{2sea} are caused not only by the sea surface temperature but also by the concentration of DIC (Dissolved Inorganic Carbon) and Total Alkalinity (TA). The present study, however, indicates that pCO_{2sea} has no significant relationship with DIC or TA (Figures 3 and 4.). DIC in surface water is affected by freshwater input, biological transformations, the CO_2 exchange with the atmosphere and precipitation of calcium carbonate likewise with TA is mainly altered by the formation and dissolution of calcium carbonate (Honkanen *et al.*, 2021). The precipitation and dissolution of calcium carbonate $CaCO_3$ affect both DIC and TA. Calcium carbonate is formed in a slow precipitation process by specific calcifying organisms such as coral reef (Zhang *et al.*, 2023), certain types of phytoplankton (Honkanen *et al.*, 2021), macroalgae in seagrass meadow (Macreadie *et al.*, 2017; Howard *et al.*, 2018). So, in this study in Semarang Bay, specific calcification organisms were not found. Therefore, maybe that's why DIC and TA have no significant effect on pCO_{2sea}. These results were also found in a study (Honkanen *et al.*, 2021) in the Baltic Sea that DIC and TA do not change with related pCO_{2sea} change by the hourly temperature change.

$$CO_2 \text{ (gas)} \leftrightarrow CO_2 \text{ (dissolved)}$$
$$CO_2 + H_2O \leftrightarrow (H_2CO_3) \leftrightarrow HCO_3^- + H^+$$
$$HCO_3^- \leftrightarrow CO_3^{2-} + H^+$$

The concentration of DIC in surface waters ranges from 2,000 µmol kg^{-1}, while the solubility of CO_2 does not exceed 23 µmol kg^{-1}. In this study, DIC concentrations are less than 2,000 µmol kg^{-1} ranging from 1700–2000 µmol kg^{-1}, with a solubility of CO_2 ranging 6–13 µmol kg^{-1}. Most of the DIC is in the form of bicarbonate (87 %), and others in the form of carbonate (10 %) and carbon dioxide (0 %) (Figure 5.). In seawater, the composition of dissolved CO_2 is only 1% of the total DIC, while the most abundant are bicarbonate ions (HCO_3^-) at 89% and carbonate ions (CO_3^{2-}) at 10% (Roy-Barman and Jeandel 2016). According to Williams and Follows (2011), most of the carbon dioxide in the ocean was in the form of 90% bicarbonate ions, 9% carbonate ions and the remaining 1% as dissolved carbon dioxide. DIC (dissolved inorganic carbon) is more than 99% composed of bicarbonate and carbonate ions, which can increase the capacity of the oceans as sinks/reservoirs/storage of carbon more than 100 times to 38,000 Pg C.

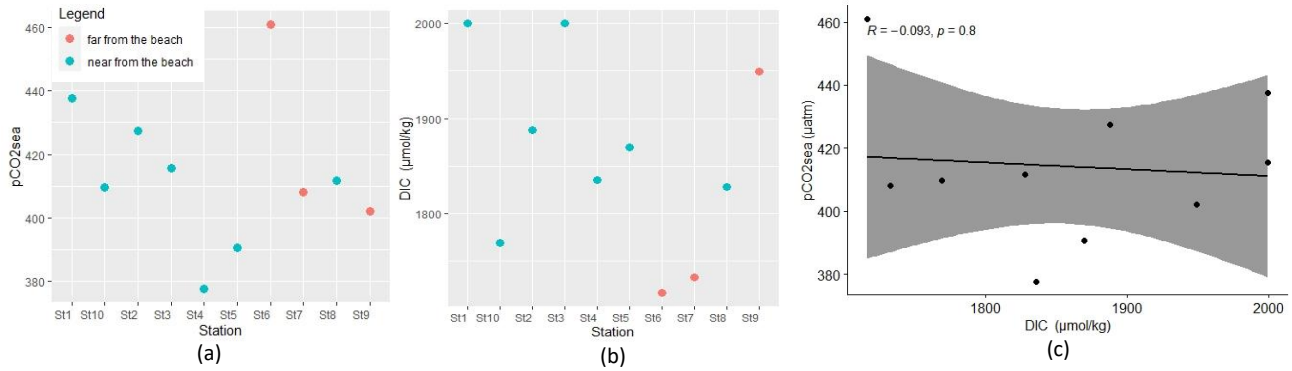

Figure 3. Distribution and relationship of pCO_{2sea} and DIC (Dissolved Inorganic Carbon)

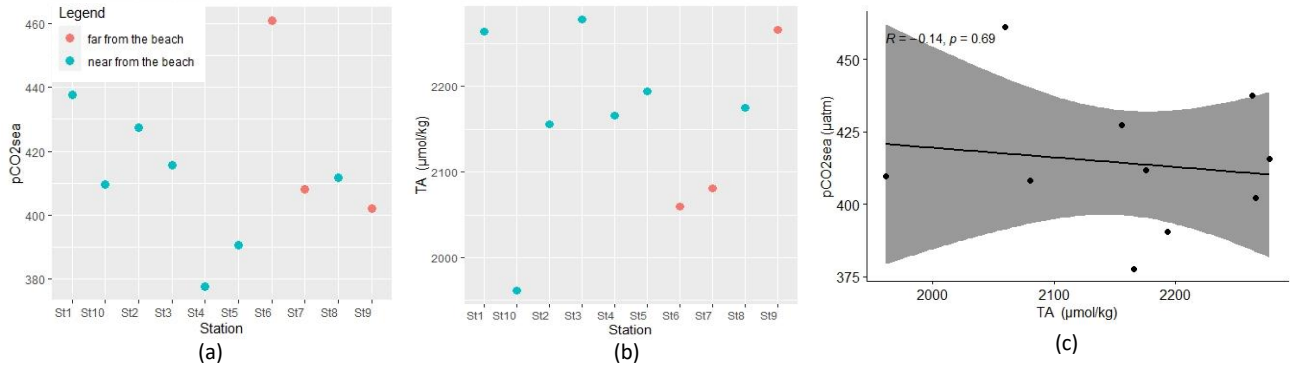

Figure 4. Distribution and relationship of pCO_{2sea} and TA (Total Alkalinity)

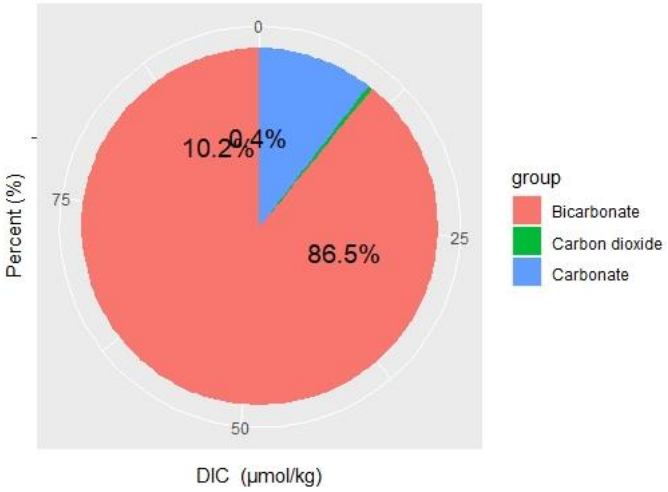

Figure 5. Average composition of the DIC distribution

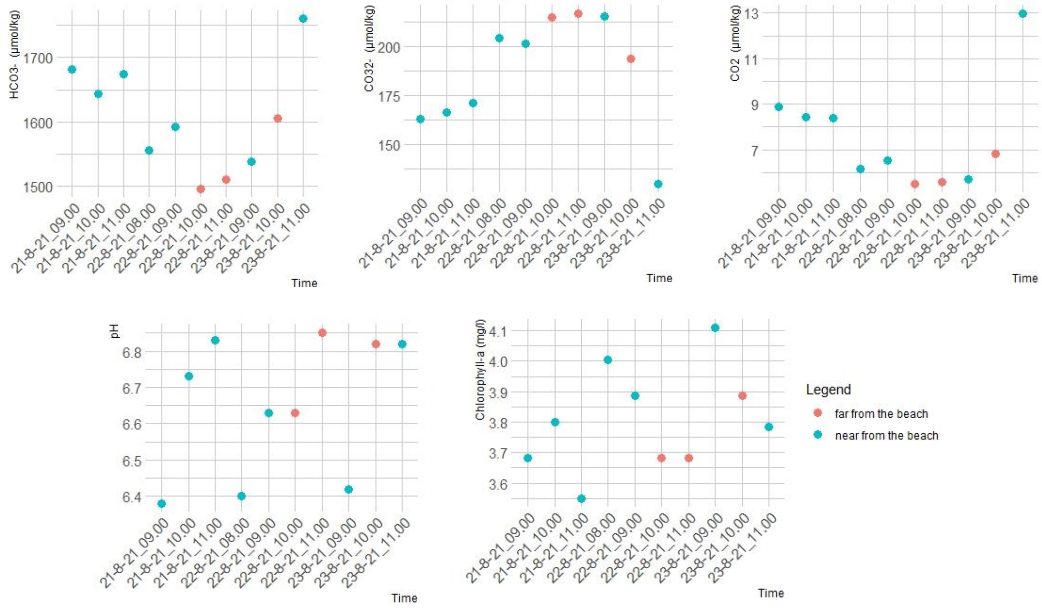

Figure 6. The concentration of bicarbonate, carbonate, carbon dioxide, pH and chlorophyll-a

Figure 6 shows that the smaller the HCO_3^- the higher the pH and vice versa. This is due to changes in the composition of phytoplankton in waters that utilise bicarbonate (HCO_3^-). The high chlorophyll-a content in the waters represents the abundance of phytoplankton in this case. The high chlorophyll-a concentration indirectly indicates the quantity of phytoplankton, causing more consumption of HCO_3^- bicarbonate (for the photosynthesis process). So, smaller HCO_3^- in the waters will reduce the number of H^+ ions and increase the pH. According to Williams and Follows (2011) and Millero (2010), a decrease in pH which is caused by an increase in consumption of HCO_3^- will reduce the number of H^+ ions and increase the pH.

Alkalinity is the ability of water to neutralize acids (Acid-Neutralizing Capacity/ANC) due to the presence of anions in water that can neutralize hydrogen cations. Alkalinity is also called buffer capacity because of its ability to buffer changes in the pH of the seas. According to Effendi (2003), the constituents of water alkalinity consist of hydroxide anions (OH^-), carbonates (CO_3^{2-}), silicates ($HSiO_3^-$), bicarbonates (HCO_3^-), sulfides (HS^-), borates ($H_2BO_3^-$), and phosphates (HPO_4^{2-} and $H_2PO_4^-$). In natural waters, the high constituent anion of alkalinity is bicarbonate which is the result of the ionization of carbonic acid, especially in waters with a high concentration of carbon dioxide. TA concentrations in this study ranged from 1961 – 2266 µmol kg^{-1}. TA

is form dissolution of calcium carbonate, biological and mixing processes. According to Honkanen *et al.*, (2021), TA is not affected by the sea–air CO2 exchange, however calcifiers may have an effect on the carbon cycle in the benthic zone.

Fluxes of CO_2

CO_2 flux is the rate at which CO_2 dissolves into the waters or evaporates back into the atmosphere. At equilibrium, the net flux will be zero (Latifah *et al.*, 2021). The results of CO_2 flux calculations suggest that Semarang Bay waters form source of CO_2 releasing CO_2 back into the atmosphere after being absorbed by the oceans through a diffusion process and is used for photosynthesis. The CO_2 flux values in Semarang Bay (August 2021) range from 2–84 mmol CO_2 m^{-2} day^{-1} (Figure 7.). This flux is higher than in other waters such as the Java Sea. Measurements in October 2015 showed a maximum CO_2 flux value of 5 mmol CO_2 m^2 day^{-1} (source CO_2) in the western part of the Java Sea, and in August 2015 a maximum weight of 17 mmol CO_2 m^{-2} day^{-1} (source CO_2) in its eastern part (Wirasatriya *et al.*, 2020). The Bintan Sea in April functioned as an CO_2 source (0.46±0.28 mmol m^{-2} day^{-1}) and as a CO_2 sink in August (-0.27±0.10 mmol m^{-2} day^{-1}) (Afdal *et al.*, 2020); The inner waters of Sekotong Bay had a range of CO_2 flux values of CO_2 0.07–0.52 mmol m^{-2} day^{-1}, and the seas acted as a source (Afdal, 2016). Another study (Macklin *et al.*, 2019) in Gilimanuk Bay showed that the average CO_2 flux in mangroves, seagrasses, and corals ecosystems was 9.8±6.0 mmol m^{-2} day^{-1} (source CO_2) in average. In mangrove ecosystems, the CO_2 flux is greater (substantial source CO_2) than in seagrass ecosystems (weak source CO_2). Figure 7 shows that the CO2 flux distribution at stations 4 and 5 (22 August 2021 at 08.00 and 09.00 WIB) have the lowest values (1.89 and 12.19 mmol CO_2 m^{-2} day^{-1}) because the sea surface temperature was measured 27.8°C. (Figure 8.) When it rained at night the pCO_{2sea} was low (377.58 dan 390.64 µatm). Whereas on the same day, the surface temperature of the waters began to rise (35.2 °C), and the wind speed was high (7.38 m s^{-1}) so that the pCO_{2sea} was high at 461.04 µatm.

The high value of CO_2 flux (1.89–46.73 mmol CO_2 m^{-2} day^{-1}) in the waters of Semarang Bay may result from the high value of pCO_{2sea} (377.58–461.04 µatm) due to the high concentration of k_{wa} (21.89–38.69) caused by the wind speed (5.87 – 7.38 m s^{-1}). The wind speed variability on the calculated gas transfer rates and possible chemical enhancement of CO_2 exchange has significant effects at low wind speeds over the ocean (Wanninkhof, 1992). The high flux of CO_2 in Semarang Bay is also caused by the variations in sea surface temperature (Figure 8.). At stations 4 and 5 (22 August 2021 at 08.00 and 09.00 WIB), low surface temperatures (27.8°C) and high chlorophyll-a (3.88–4.00 mg L^{-1}) resulted in low pCO_{2sea} (377.58 and 390.64 µatm) and low CO_2 flux (1.88 and 12.19 mmol CO2 m^{-2} day^{-1}). The study by Wirasatriya *et al.* (2020) stated that wind speed played a vital role in determining the variability of CO_2 flux in the Java Sea. More substantial wind speeds (0–40 m s^{-1}) and lower temperatures (higher chlorophyll-a) during El Nino (in August 2015) increased k_{wa} so that pCO_{2sea} and CO_2 flux increased (Wirasatriya *et al.*, 2020). According to Kartadikaria *et al.* (2015), overall, pCO_{2sea} in the Indonesian seas is supersaturated relative to the atmosphere of 15.9 ± 8.6 µatm to act as a source of CO_2 / releases CO_2 into the atmosphere.

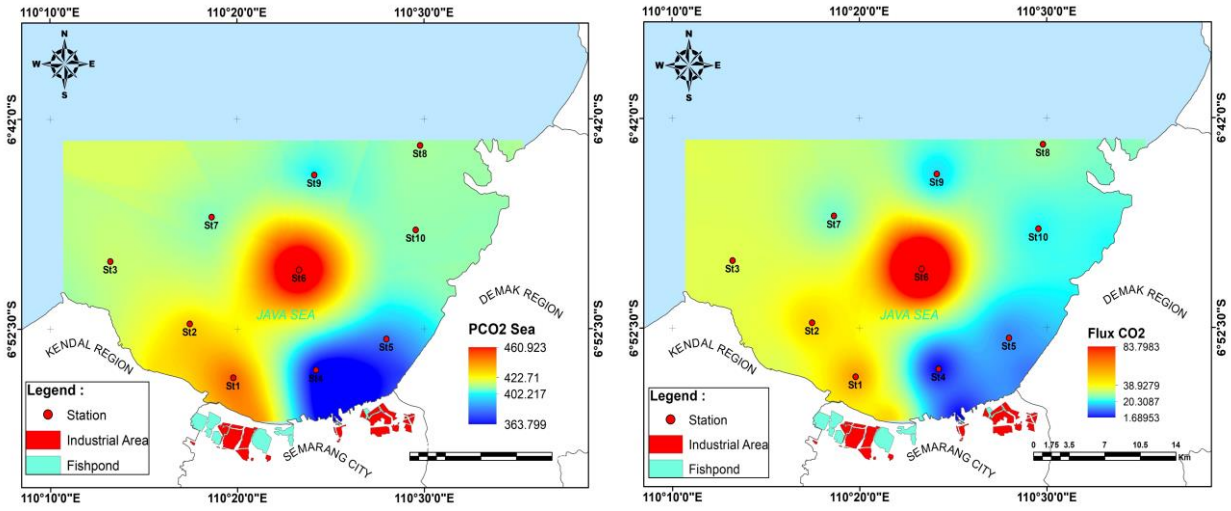

Figure 7. Distribution of pCO_{2sea} and CO_2 flux in August 2021 in Semarang Bay

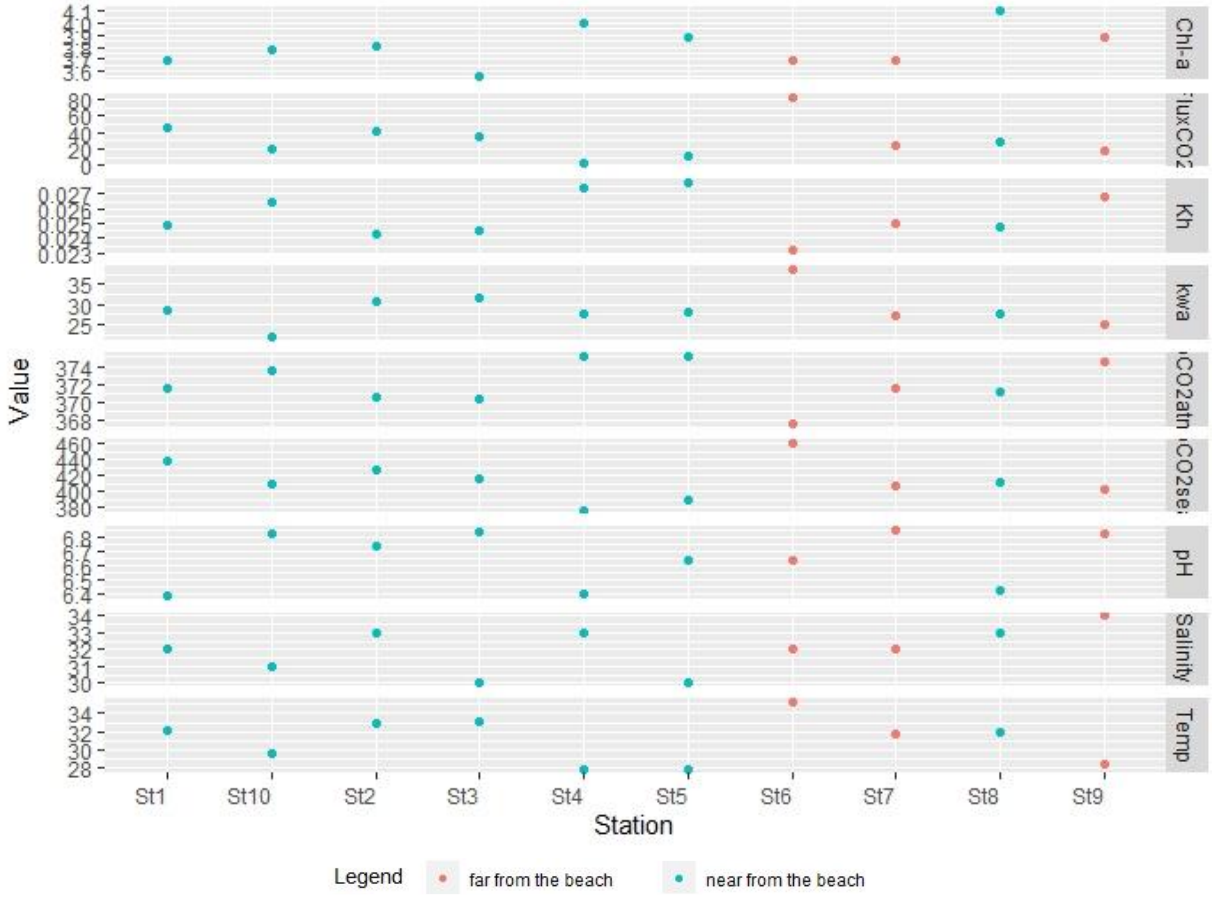

Figure 8. Fluxes of CO_2 and other variables

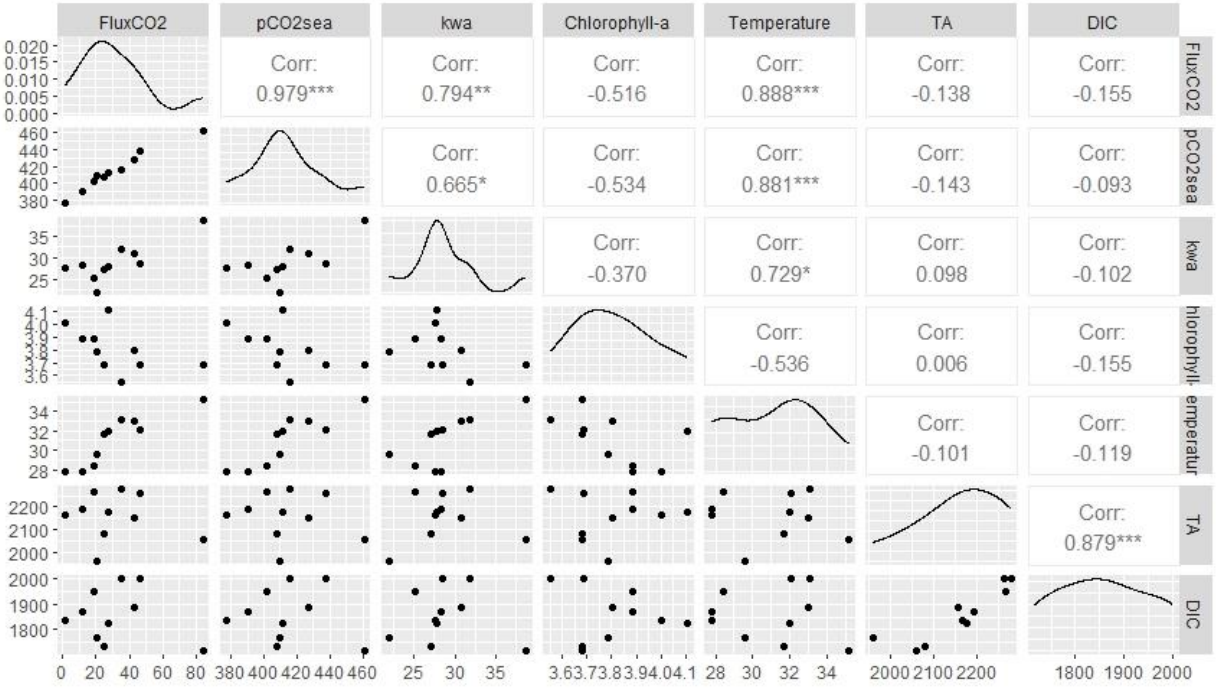

Figure 9. Spearman correlation of CO_2 flux with other variables

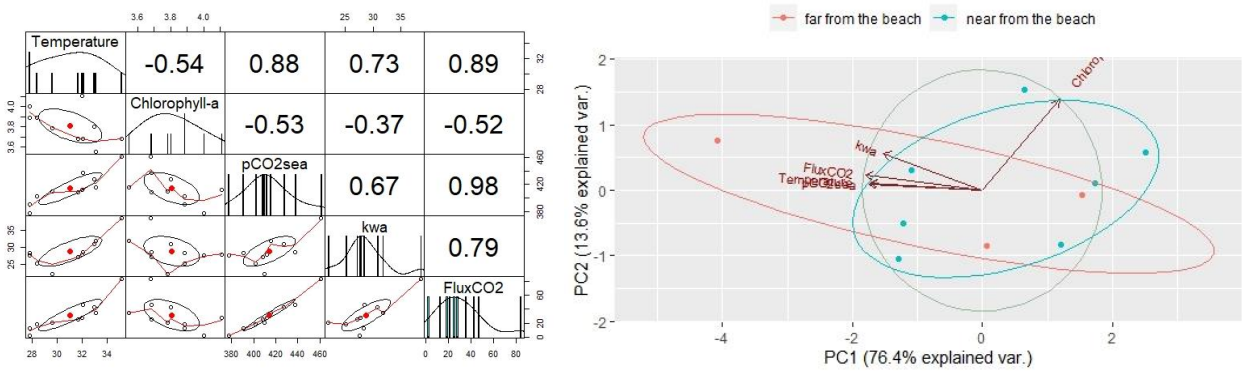

Figure 10. The results of PCA (Principal Component Analysis)

Water quality variables that affect CO_2 Flux

Previous studies (Takahashi *et al.*, 1997; Takahashi *et al.*, 2002; Cai *et al.*, 2006; Takahashi *et al.*, 2009; Otero *et al.*, 2013; Yasunaka *et al.*, 2016; Arnone *et al.*, 2017; Ito *et al.*, 2018; Tian *et al.*, 2020) showed that in waters in middle and high latitudes with low temperatures, the oceans acted as CO_2 sinks. While studies conducted at low latitudes with high (warm) temperatures (Fitranti *et al.*, 2013; Kartadikaria *et al.*, 2015; Afdal, 2016; Yan *et al.*, 2018; Latifah *et al.*, 2020) showed that the oceans served as a source of CO_2. Warm surface water causes CO_2 to be returned to the atmosphere by the oceans (outgassing of CO_2). If the cold surface water causes CO_2 to dissolve easily, CO_2 transfer from the atmosphere to the surface occurs (uptake of CO_2).

Several variables, including pCO2sea, pCO2atm, kwa, kH, sea surface temperature, chlorophyll-a, salinity, wind, pH, DIC, TA influence the role of these waters as a CO2 sink or CO2 source. The determination of these variables is based on the CO_2 calculation formula, which requires the values of the variables pCO_{2sea}, pCO_{2atm}, seawater solubility (k_H) calculated as a function of temperature and salinity, gas transfer rate (k_{wa}) calculated as a function of the wind speed, and the Schmidt number which is affected by sea surface temperature (Weiss, 1974; Wanninkhof, 1992; Takahashi *et al.*, 2002; Zhu *et al.*, 2009; Robbins *et al.*, 2010; Kartadikaria *et al.*, 2015; Du *et al.*, 2015; Takahashi and Sutherland, 2017; Yan *et al.*, 2018; Wirasatriya *et al.*, 2020). Based on the results of Spearman's correlation (Figure 9.) it shows that CO_2 flux has a strong positive significant relationship with pCO_{2sea} (r= 0.98), temperature (r= 0.88) and k_{wa} (r= 0.79), while chlorophyll-a (r= -0.52), has a moderate negative correlation, while TA (r= -0.14), and DIC (r= -0.15) have a weak negative relationship with CO_2 flux. Therefore, the following analysis uses PCA where the predictor variables used are temperature, chlorophyll-a, pCO2sea and kwa to determine the effect on the CO_2 flux variable.

Based on the results of PCA analysis (Figure 10.), among these variables, the most influencing CO_2 flux is the ocean CO_2 partial pressure (pCO_{2sea}), temperature and k_{wa}. Temperature, pCO_{2sea}, and k_{wa} have the same direction as the CO_2 flux. According to Afdal *et al.* (2020), the temperature in coastal ecosystems (estuaries, mangroves, seagrasses, and coral reefs) is the main factor causing variations in CO_2 flux in Bintan waters in April as a source of CO_2 and in August as a sink of CO_2, both spatially and temporally. In Figure 10, it can also be seen that the CO_2 flux at stations far from the beach is more influenced by temperature, pCO_{2sea} and k_{wa}. While and at the station close to the beach, the chlorophyll-a factor is more dominant.

Conclusion

With a CO_2 flux value of 1.88–83.79 mmol CO_2 m^{-2} day^{-1}, Semarang Bay functions as a CO_2 source. At stations 4 and 5 during morning sampling, with locations close to the coast and surrounded by many settlements and industries, the CO_2 flux value was the lowest (1.86 mmol CO_2 m^{-2} day^{-1}). The value was also affected by low water temperatures (27.8°C) due to rain at night. On the same day at noon, the temperature increased again to the highest (35.2°C) measurement. Station 6 has high pCO_{2sea} (461.04 µatm) and CO_2 flux (83.79 mmol CO_2 m^{-2} day^{-1}). The high concentration of chlorophyll-a (3.55–4.11 mg L^{-1}) is also visible from the colour (green) of the waters of Semarang Bay during sampling indicating that there is an abundance of green microalgae. This chlorophyll-a concentration has a negative correlation with CO_2 flux. The concentrations of TA and DIC show no relationship with CO_2 change. TA concentrations range from 1,961.20 to 2,277.51 µmol kg^{-1}, and DIC

concentrations range from 1,716.68 to 1,999.70 µmol kg^{-1}. Based on PCA analysis, the variability of CO_2 flux in Semarang Bay during August 2021 is influenced by the variability of pCO_{2sea}, sea surface temperature and k_{wa} (affected by wind speed).

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References

Afdal, A. 2016. Fluks CO_2 Di Perairan Pesisir Pulau Lombok, Nusa Tenggara Barat CO_2 Flux in the Coastal Waters of Lombok, West Nusa Tenggara. *Oseanol. Limnol. Indonesia,* 1(2): 91–103.

Afdal, A., Prayitno, H,B., Wahyudi, A.J. & Lastrini, S. 2020. Variasi Fluks CO2 Udara-Laut Di Perairan Pesisir Pulau Bintan. *Oseanol. Limnol. Indonesia,* 5(3): 145. https://doi.org/10.1203/oldi.2020.v5i3.266.

Akhand, A., Watanabe, K., Chanda, A., Tokoro, T., Chakraborty, K., Moki, H., Tanaya, T., Ghosh, J. & Kuwae, T. 2021. Lateral Carbon Fluxes and CO_2 Evasion from a Subtropical Mangrove-Seagrass-Coral Continuum. *Sci. Total Environ.,* 752: 1–14. https://doi.org/10.1016/j.scitotenv.2020.142190.

Alifdini, I., Shimada, T. & Wirasatriya, A. 2021. Seasonal distribution and variability of surface winds in the Indonesian seas using scatterometer and reanalysis data. *Int. J. Climatol.,* 41(10): 4825-4843. https://doi.org/10.1002/joc.7101

Arnone, V., González-Dávila, M. & Santana-Casiano, J.M. 2017. CO_2fluxes in the South African Coastal Region. *Mar. Chem.,* 195: 41–49. https://doi.org/10.1016/j.marchem.2017.07.008.

Borges, A.V., Morana, C., Bouillon, S., Servais, P., Descy, J.P. & Darchambeau, F. 2014. Carbon Cycling of Lake Kivu (East Africa): Net Autotrophy in the Epilimnion and Emission of CO2 to the Atmosphere Sustained by Geogenic Inputs. *PLoS ONE,* 9(10): 1–16. https://doi.org/10.1371/journal.pone. 0109500.

Borges, A. V., Vanderborght, J.P, Schiettecatte, L.S., Gazeau, F., Ferrón-Smith, S., Delille, B. & Frankignoulle, M. 2004. Variability of the Gas Transfer Velocity of CO_2 in a Macrotidal Estuary (the Scheldt). *Estuaries,* 27(4): 593–603. https://doi.org/10.1007/BF02907647.

Brady, R.X., Lovenduski, N.S., Alexander, M.A., Jacox, M. & Gruber, N. 2019. On the Role of Climate Modes in Modulating the Air – Sea CO_2 Fluxes in Eastern Boundary Upwelling Systems. *Biogeosciences,* 16(2): 329-346.

Cai, W.J., Dai, M. & Wang, Y. 2006. Air-Sea Exchange of Carbon Dioxide in Ocean Margins: A Province-Based Synthesis. *Geophys. Res. Lett.,* 33(12): 2–5. https://doi.org/10.1029/2006GL026219.

Cavan, E.L., Laurenceau-Cornec, E.C., Bressac, M. & Boyd, P.W. 2019. Exploring the Ecology of the Mesopelagic Biological Pump. *Prog. Oceanogr.,* 176: p.102125. https://doi.org/10.1016/j.pocean.2019.102125.

Chierici, M., Olsen, A., Johannessen, T., Trinañes, J. & Wanninkhof, R. 2009. Algorithms to Estimate the Carbon Dioxide Uptake in the Northern North Atlantic Using Shipboard Observations, Satellite and Ocean Analysis Data. *Deep-Sea Res. II: Top. Stud. Oceanogr.,* 56(8–10): 630–639. https://doi.org/10.1016/j.dsr2.2008.12.014.

Delaigue, L., Thomas, H. & Mucci, A. 2020. Spatial Variations in CO2 Fluxes in the Saguenay Fjord (Quebec, Canada) and Results of a Water Mixing Model. *Biogeosciences,* 17(2):547–566. https://doi.org/10.5194/bg-17-547-2020.

Dickson, A G., Sabine, C.L. & Christian, J.R. 2007. Guide to Best Practices for Ocean CO_2 Measurements. Vol. 3. Sidney: North Pacific Marine Science Organization.

Du, Z., Fang, L., Bai, Y., Zhang, F. & Liu, R. 2015. Spatio-Temporal Visualization of Air-Sea CO 2 Flux and Carbon Budget Using Volume Rendering. *Comput. Geosci.,* 77: 77–86. https://doi.org/10.1016/j.cageo.2015.01.00 4

Effendi, H. 2003. Telaah Kualitas Air: Bagi Pengelolaan Sumber Daya Dan Lingkungan Perairan. Yogyakarta: Kanisius.

Fachri, F.R., Afdal, A., Sartimbul. & Hidayati, N. 2015. Fluks CO_2 Di Perairan Pesisir Timur Pulau Bintan, Propinsi Kepulauan Riau. *J. Segara* 11 (1): 57–66.

Feely, R. A., Sabine, C.L. Takahashi, T. & Wanninkhof, R. 2001. Uptake and Storage of Carbon Dioxide in the Ocean. *Oceanography,* 14(4): p.18.

Fitranti, B.A., Sunarto., Prihadi, D.J. & Herunadi, B. 2013. Potensi Pelepasan dan Penyerap Co2 Kaitannya dengan Suhu dan Salinitas di Perairan Teluk Banten. *J. Akuatika,* 4(2):174-182.

Friedlingstein, P., O'Sullivan, M., Jones, M.W., Andrew, R.R., Hauck, J., Olsen, A. & Peters, G,P 2020. Global Carbon Budget 2020. *Earth Syst. Sci. Data,* 12(4): 3269–3340. https://doi.org/10.5194/essd-12-3269-2020.

Guerra-Vargas, L.A., Gillis, L.G. & Mancera-Pineda, J.E. 2020. Stronger Together: Do Coral Reefs Enhance Seagrass Meadows "Blue Carbon" Potential? *Front. Mar. Sci.* 7:628. https://doi.org/10.3389/fmars.2020.00628

Hülse, D., Arndt, S., Wilson, J.D., Munhoven, G. & Ridgwell, A. 2017. Understanding the Causes and Consequences of Past Marine Carbon Cycling Variability through Models. *Earth Sci. Rev.* 171: 349–82. https://doi.org/10.1016/j.earscirev.2017.06.004.

Ito, R.G., Tavano, V.M., Mendes, C.R.B. & Garcia, C.A.E. 2018. Sea-Air CO2 Fluxes and PCO2 Variability in the Northern Antarctic Peninsula during Three Summer Periods (2008–2010). *Deep Sea Res. Part II Top. Stud. Oceanogr.,* 149: 84–98. https://doi.org/10.1016/j.dsr2.2017.09.004.

Kartadikaria, A. R., Watanabe, A., Nadaoka, K., Adi, N.S., Prayitno, H.B., Soemorumekso, S., Muchtar, M., Triyulianti, I., Setiawan, A., Suratno, S. & Khasanah. E.N. 2015. CO_2 sink/source characteristics in the tropical Indonesian seas. *J. Geophys. Res. Oceans.,* 120: 7842–7856. https://doi.org/10.10 02/2015JC010925.

Lakshmi, V. 2000. "Is the Temperature Rising?: The Uncertain Science of Global Warming. S. George Philander. *Quarterly Rev. Biolog.,* 75(4): 485–485. https://doi.org/10.1086/393713.

Latifah, N., Endrawati, H. & Febrianto, S. 2019. Distribusi Spasial Fluks Karbon Dioksida Di Perairan Karimunjawa, Indonesia. *J. Ilmu Teknol. Kelautan Tropis,* 11(2): 357–68. https://doi.org/10.29244/jitkt.v11i2.23692.

Latifah, N., Febrianto, S., Wirasatriya, A. & Endrawati, H. 2021. Interaksi Lautan Dan Atmosfer : Tekanan Parsial Dan Fluks Karbondioksida. Semarang: Undip Press.

Latifah, N., Febrianto, S., Wirasatriya, A., Endrawati, H., Zainuri, M., Suryanti, S. & Hidayat, A.N. 2020. Air-Sea Flux of CO_2 in the Waters of Karimunjawa Island, Indonesia. *Saintek Perikanan : Indonesian J. Fisheries Sci. Technol.,* 16(3): 171–78. https://doi.org/10.14710/ijfst.16.3.171-178.

Li, J.L., Zhai, X., Zhang, H.H. & Yang, G.P. 2018. Temporal Variations in the Distribution and Sea-to-Air Flux of Marine Isoprene in the East China Sea. *Atmos. Environ*., 187: 131–43. https://doi.org/10.1016/j.atmosenv.2018.05.054.

Macklin, P.A., Suryaputra, I.G.N.A., Maher, D.T., Murdiyarso, D. & Santos, I.R. 2019. Drivers of CO2 along a Mangrove-Seagrass Transect in a Tropical Bay: Delayed Groundwater Seepage and Seagrass Uptake. *Continental Shelf Res.,* 172: 57–67. https://doi.org/10.1016/j.csr.2018.10.008.

Millero, F.J. 2010. History of the Equation of State of Seawater. *Oceanograp.,* 23(3): 18–33. https://doi.org/10.5670/oceanog.2010.21.

Muskananfola, M.R., Erzad, A.F. & Hartoko, A., 2021a. Hydro-oceanographic characteristics and sedimentation in the waters of Kemujan Island. *AACL Bioflux,* 14: 2866–2877.

Muskananfola, M.R., Jumsar. & Wirasatriya, A., 2021b. Spatio-temporal distribution of chlorophyll-a concentration, sea surface temperature and wind speed using aqua-modis satellite imagery over the Savu Sea, Indonesia. *Remote Sens. Appl. Soc. Environ.* 22: p.100483. https://doi.org/10.1016/j.rsase.2021.100483

Nehren, U. & Wicaksono, P. 2018. Mapping Soil Carbon Stocks in an Oceanic Mangrove Ecosystem in Karimunjawa Islands, Indonesia. *Estuarine, Coast. Shelf Sci.,* 214: 185–93. https://doi.org/10.1016/j.ecss.2018.09.022.

Otero, P., Padin, X.A., Ruiz-Villarreal, M., García-García, L.M., Ríos, A.F. & Pérez, F.F., 2013. Net Sea-Air CO_2 Flux Uncertainties in the Bay of Biscay Based on the Choice of Wind Speed Products and Gas Transfer Parameterizations. *Biogeosciences,* 10(5): 2993–3005. https://doi.org/10.5194/bg-10-2993-2013.

Raymond, P.A., & Cole, J.J. 2001. Technical Notes and Comments: Gas Exchange in Rivers and Estuaries: Choosing a Gas Transfer Velocity.

Estuaries, 24(2): 312–17. https://doi.org/10.2307/1352954.

Robbins, L.L., Hansen, M.E., Kleypas, J.A. & Meylan, S.C. 2010. CO2calc: A User Friendly Carbon Calculator Foe Windows, Mac OS X and IOS (IPhone). *United States Geological Survey* 1280: 1210–80. https://doi.org/10.3133/OFR20101280.

Roy-Barman, M. & Jeandel, C. 2016. Marine Geochemistry: Ocean Circulation, Carbon Cycle and Climate Change. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780198787495.001.0001.

Susanto, R.D., Moore, T.S. & Marra, J. 2006. Ocean color variability in the Indonesian Seas during the SeaWiFS era. *Geochem. Geophys. Geosyst.* 7(5): Q05021. https://doi.org/10.1029/2005GC001009.

Takahashi, T., Feely, R.A., Weiss, R.F., Wanninkhofs, R.H. Chipman, D.W., Sutherland, S.C. & Takahashi, T.T. 1997. Global Air-Sea Flux of CO 2 : An Estimate Based on Measurements of Sea – Air PCO 2 Difference. *Proc. Natl. Acad. Sci. USA,* 94: 8292–8299.

Takahashi, T. & Sutherland, S.C. 2017. Global Ocean Surface Water Partial Pressure Of CO_2 Database: Measurements Performed During 1957–2016 (Version 2016). *NOAA/NCEI/OCADS* 4 (Version 2016): 1–16.

Takahashia, T., Sutherlanda, S.C., Sweeneya, C., Poissonb, A., Metzl, N., Tilbrookc, B., Bates, N., Wanninkhof, R., Richard, A.F., Sabine, C., Olafsson, J. & Nojiri, Y. 2002. Global sea–air CO2 flux based on climatological surface ocean pCO2, and seasonal biological and temperature effects. *Deep-Sea Res. II*, 49: 1601–1622.

Takahashi, T., Sutherland, S.C., Wanninkhof, R., Colm Sweeney, C., Feely, R.A., Chipman, D.W., Hales, B., Friederich, G., Chavez, F., Sabine, C., Watson, A., Bakker, D.C.E., Schuster, U., Metzl, N., Yoshikawa-Inoue, H., Ishii, M., Midorikawa, T., Nojiri, Y., Ko¨rtzinger, A., Steinhoff, T., Hoppema, M., Olafsson, J., Arnarson, T.S., Tilbrook, B., Johannessen, T., Olsen, A., Bellerby, R., Wong, C.S., Delille, B., Bates, N.R. & de Baar, H.J.W. 2009. Climatological mean and decadal change in surface ocean pCO2, and net sea–air CO_2 flux over the global oceans. *Deep-Sea Res. II,* 56: 554–577.

Tian, T., Xu, R.G., Canadell, J.G., Thompson, R.L., Winiwarter, W., Suntharalingam, P., Davidson, E.A. Ciais, P., Jackson, R.B., Janssens-Maenhout, G., Prather, M.J., Regnier, P., Pan, N., Pan, S., Peters, G.P., Shi, H., Tubiello, F.N., Zaehle, S., Zhou, F., Arneth, A., Battaglia, G., Berthet, S., Bopp, L., Bouwman, A.F., Buitenhuis, E.T., Chang, J., Chipperfield, M.P., Dangal, S.R.S., Dlugokencky, E., Elkins, J.W., Eyre, B.D., Fu, B., Hall, B., Ito, A., Joos, F., Krummel, P.B., Landolfi, A., Laruelle, G.G., Lauerwald, R., Li, W., Lienert, S., Maavara, T., MacLeod, M., Millet, D.B., Olin, S., Patra, P.K., Prinn, R.G., Raymond, P.A., Ruiz, D.J., van der Werf, G.R., Vuichard, N., Wang, J., Weiss, R.F., Wells, K.C., Wilson, C., Yang, J. & Yao, J. 2020. Nitrous oxide (N_2O), like carbon dioxide, is a long-lived greenhouse A comprehensive quantification of global nitrous oxide sources and sinks. *Nature,* 586(7828): 248–56. https://doi.org/10.1038/s41586-020-2780-0.

Wanninkhof, R. 1992. Relationship between Wind Speed and Gas Exchange over the Ocean. *J. Geophys. Res.* 97(C5): 7373–7382. https://doi.org/10.1029/92JC00188.

Weiss, R.F. 1974. Carbon Dioxide in Water and Seawater: The Solubility of a Non-Ideal Gas. *Mar. Chem.,* 2(3): 203–15. https://doi.org/10.1016/0304-4203(74)90015-2.

Weiss, R.F. & Price, B.A. 1980. Nitrous oxide solubility in water and seawater. *Mar. Chem.,* 8(4): 347-359. https://doi.org/10.1016/0304-4203(80)90024-9

Williams, R.G., & Follows, M.J. 2011. *Ocean Dynamics and The Carbon Cycle Principles and Mechanism*. Cambridge University Press.

Wirasatriya, A., Sugianto, D.N., Maslukah, L., Ahkam, M.F., Wulandari, S.Y. & Helmi, M. 2020. Carbon Dioxide Flux in the Java Sea Estimated from Satellite Measurements. *Remote Sens. Appl.: Soc. Environ.,* 20: p100376. https://doi.org/10.1016/j.rsase.2020.100376.

Yan, H., Yu, K., Shi, Q., Lin, Z., Zhao, M., Tao, S., Liu, G. & Zhang, H. 2018. Air-Sea CO 2 Fluxes and Spatial Distribution of Seawater PCO 2 in Yongle Atoll, Northern-Central South China Sea. *Cont. Shelf Res.,* 165: 71–77. https://doi.org/10.1016/j.csr.2018.06.008.

Yang, R., Xu, Z., Liu, S. & Xu, Y.J. 2019. Daily PCO2 and CO2 Flux Variations in a Subtropical Mesotrophic Shallow Lake. *Water Res.,* 153: 29–38. https://doi.org/10.1016/j.watres.2019.01.012.

Yasunaka, S., Murata, A., Watanabe, E., Chierici, M., Fransson, A., van Heuven, S., Hoppema, M.,

Ishii, M., Johannessen, T., Kosugi, N., Lauvset, S.K., Mathis, J.T., Nishino, S., Omar, A.M., Olsen, A., Sasano, D., Takahashi, T. & Wanninkhof, R. 2016. Mapping of the air–sea CO2 flux in the Arctic Ocean and its adjacent seas: Basin-wide distribution and seasonal to interannual variability. *Polar Sci.*, 10(3): 323-334. https://doi.org/10.1016 j.polar.2016.03.006.

Zeebe, R.E. 2012. History of Seawater Carbonate Chemistry, Atmospheric CO_2, and Ocean Acidification. *Annu. Rev. Earth Planet. Sci.,* 40 (1): 141–65. https://doi.org/10.1146/annurev-earth-042711-105521.

Zhai, W., Dai, M., Cai, W.J., Wang, Y. & Hong, H. 2007. The Partial Pressure of Carbon Dioxide and Air-Sea Fluxes in the Northern South China Sea in Spring, Summer and Autumn. *Mar. Chem.* 103(1–2): 209. https://doi.org/10.1016/j.marchem.2006.06.014.

Zhu, Y., Shang, S., Zhai, W. & Dai, M. 2009. Satellite-Derived Surface Water PCO2 and Air-Sea CO2 Fluxes in the Northern South China Sea in Summer. *Prog. Nat. Sci.,* 19(6):775–79. https://doi.org/10.1016/j.pnsc.2008.09.004.