STUDY OF AIR-SEA INTERACTION AND CO_2 EXCHANGE PROCESS BETWEEN THE ATMOSPHERE AND OCEAN USING ALOS/PALSAR (Study Cases of Wind Wave Bubbling Process in Badung and Lombok Straits)

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Abstrak

Peningkatan CO_2 di atmosfer yang berpotensi menghasilkan pemanasan global telah menjadi perhatian bagi kehidupan manusia. Lautan mengandung lima puluh kali lebih besar CO_2 daripada atmosfer dan menjadi penyangga yang membatasi konsentrasi CO_2 dalam atmosfer. CO_2 mengalami perubahan secara terus menerus antara udara-lautan dan konsentrasi CO_2 di dalam laut dikendalikan oleh parameter fisika, kimia, dan biologi. Perubahan konsentrasi CO_2 antara udara-lautan dapat ditentukan dari interaksi gas dan perbedaan konsentrasi CO_2 antara udara-lautan. Perubahan CO_2 antara udara-lautan dapat dikaji dari studi kecepatan angin, koefisien gesekan kecepatan angin yang diperoleh dari satelit ALOS/PALSAR di daerah Selat Badung dan Selat Lombok, salinitas, dan juga dengan SST yang diperoleh dari satelit MODIS.
Hasil analisis menunjukkan bahwa koefisien perubahan CO_2, perbedaan tekanan CO_2 antara udara-lautan, dan CO_2 flux antara udara-lautan secara berturut-turut yaitu 0.303±0.006 (rata-rata±standar deviasi) (mol m^{-2} $month^{-1}$ μatm^{-1}), 17.94±10.79 ìatm, and 5.35±3.26 (mol m^{-2} $month^{-1}$), dengan nilai maksimum dan minimum dari koefisien perubahan CO_2 secara berturut-turut terjadi pada bulan Agustus dan Februari.

Kata kunci: CO_2, koefisien, suhu, laut.

1. Introduction

Carbon dioxide (CO_2) is principal greenhouse gas (Frankignoulle et al., 1998). The direction of CO_2 gas movement depends on the CO_2 concentration gradient between air and surface water (Schimel et al., 2001). The amount of CO_2 exchange is related to the gas exchange coefficient. All water areas (Oceans, Straits, Lake, etc), with their big or small area but large atmospheric CO_2 flux are important to understand the CO_2 fluxes in continent (Meybeck, 1993). Fluxes, sources, and mechanisms of CO_2 in ocean have been previously studied and compared (Sugimori and Zhao, 1995 and Hope et al., 1996).

Meanwhile, the world ocean plays an important role in the earth climate. It is not only absorbs heat from the sun, but plays a major role in carbon cycle processes (Akiyama, 2002). Ocean contains more than fifty times carbon in the atmosphere and can be taken as a buffer limiting the concentration of CO_2 in atmosphere (Sugimori and Zhao, 1995). For long term climate forecasts, knowledge of the heat, momentum, and substance exchange between the atmosphere and the ocean is essential because the time constants and capacities of the ocean are much larger than those of the atmosphere.

Carbon dioxide (CO_2), as the main greenhouse gas in the atmosphere, has been studied for many years. An increase in the atmospheric concentration of carbon dioxide (CO_2) has been directly observed over the past 40 years in Hawaiian Island from 315 PPMV (part per million in volumes) to 358 PPMV in 1994 (Keeling, 1995) and in 2004 become 380 PPMV. Pre-industrial concentration at 270-280 PPMV and there is no doubt that the carbon dioxide (CO_2) concentration in the atmosphere will continue to increase in the future. Some numerical models have been developed to describe the climate response as carbon dioxide (CO_2) concentration increases, and the results show that globally average temperature on the earth surface would increase from 1.5 to 5 Celsius degree due to different model, if the carbon dioxide (CO_2) concentration will be produced to be double of the recent concentration (Keeling, 1995).

Since the growth rate of carbon dioxide (CO_2) in atmosphere is less than the rate of carbon release, some released carbon dioxide must be absorbed by either the terrestrial biosphere or the oceans.

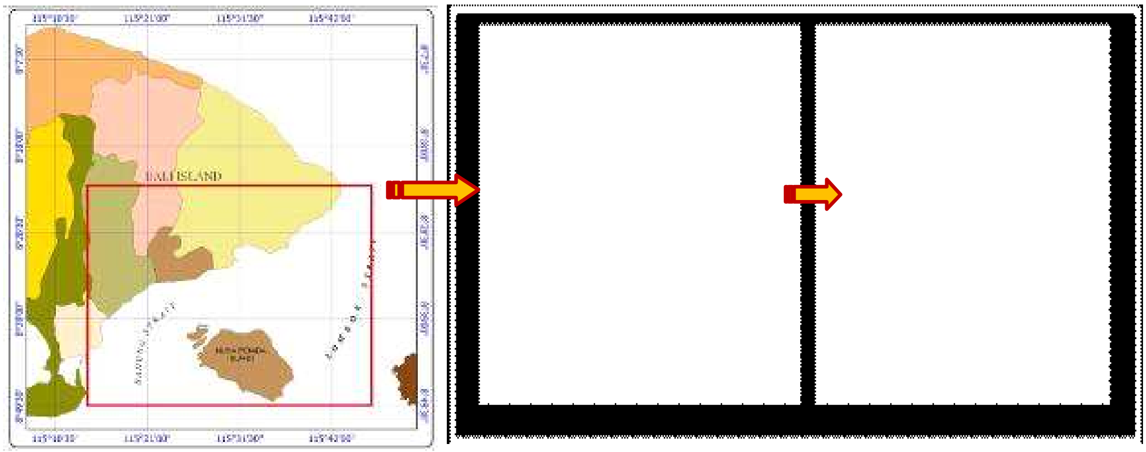
Wind speed and wind friction velocity are not only the factor influencing the gas (CO_2) transfer velocity, turbulence, wave breaking, and bubbling are also the main factor in gas exchange (Sugimori and Zhao, 1995). The determination of wind speed and wind friction velocity from satellite-derived wind data will take an important role for air sea interaction in the ocean (Suzuki *et al,* 2002). Ocean wave directional spectrum is much more important parameter for describing the essential structure of ocean wave. It is generally agreed that additional wave information such as wavelength, wave direction, and perhaps wave height are contained in Synthetic Aperture Radar wave image (JAXA, 2005).

PALSAR is an active microwave sensor using L-band frequency to achieve cloud-free and day-and-night land observation (JAXA, 2005). It provides higher performance than the JERS-1's synthetic aperture radar (SAR). This research, study of wind wave bubbling process is located in Badung and Lombok Straits, because those areas are important places for the transportation between Bali and Lombok, and also near from land. The image data should be taken in deep water related to the main wavelength, so the wind wave parameters could be found easily. The Lombok strait, a small sea channel between the islands Bali and Lombok, is the second most important trans-section in southern part of the Indonesian through-flow. The aims of this research are to know the air-sea interaction at sea surface and the CO_2 exchange process between the atmosphere and the ocean using ALOS/PALSAR.

2. Materials And Methods

Research Location

The research location are in Badung and Lombok Straits with the geographical position is $8^0$25'30.3"S/$115^0$15'30"E - $8^0$90'30,19"S/$116^0$2'00". The location of research is shown in Figure 1.



(a) **(b)**

Figure 1. Location of Research in Badung and Lombok Straits
(a) Location of Research and
(b) Directional Wind Wave Spectrum in area of Badung and Lombok Straits after Fast Fourier Transform.
Digital image of ALOS/PALSAR at January 6^{th} 2007.

Research Procedures

Digital image processing

The image from ALOS/PALSAR is processed in GIS software. The digital image processing is divided into three steps there were: data selection, geometric correction, and Fast Fourier Transform (FFT).

Data Calculation

1) Spectral Form of Wind Wave in High Frequency

$$S(\omega) = 2\pi\alpha g u_* \omega^{-p} \quad (1)$$

Spectral form of wind wave in high frequency can be expressed as follows:
Where: = Wind wave energy density, g = gravity acceleration (ms^{-2}), u* = coefficient of friction velocity, = a constant = 0.0214, = Peak Frequency, Where, p = 1.538 to 6 (Toba and Chaen, 1973). From Equation (1) wind friction velocity (u*) is calculated.

2) The estimation of Whitecap coverage (W)
The fraction of whitecap coverage due to the wave breaking has been investigated for many years such as by Monahan and Spillane (1984), Toba and Chaen (1973), and Wu (1988). Generally, whitecap coverage (W) is related to the wind speed or wind friction velocity. Area ratio of whitecap on Whitecap Model can be expressed as follows: W = 0.066 U* (2)

3) Carbon dioxide (CO_2) calculation

a) Air-sea CO_2 gas transfer velocity
Air-sea CO_2 gas transfer velocity can be calculated as follows (Monahan and Spillane, 1984):

$K_{radon} = K_m (1\text{-}W) + K_e W$ (3a)

Where, K_m = transfer velocity associated without Whitecap area = 9.58 cm/hr, K_e = transfer velocity related a turbulent Whitecap area = 475.07 cm/hr, W = area ratio of whitecap on Whitecap model, K_{radon} = transfer function of gas (cm/hr), Carbon dioxide gas transfer velocity can be calculated as follows:

$$K_{CO_2} = K_{radon}\left(\frac{Sc_{CO_2}}{Sc_{radon}}\right)^{-n} \quad (3b)$$

Where: K_{CO2} = CO_2 gas transfer velocity,

Sc_{CO2} = 2073.1 - 125.62T + 3.6276T^2 - 4.3219 x 10^{-2}T^3

Sc_{radon} = 3412.8 – 224.30T + 6.7954T^2- 8.3x10^{-2}T^3

b) Air-sea CO_2 gas exchange coefficient
Air-sea CO_2 gas exchange coefficient calculation with equation (Akiyama, 2002):

$$E_{CO_2} = K_{CO_2} * L_{CO_2} \quad (4)$$

Where: = CO_2 gas exchange coefficient (cm/hr), = CO_2 transfer velocity cm/hr), = CO_2 gas solubility (mol/liter atm).

c) Carbon dioxide (CO_2) gas solubility
Weiss (1974) provided an empirical formula to estimate CO_2 gas solubility L on the basis of data fitting between the solubility, temperature, and salinity as follows:

$$\ln L = A1 + A2(100/T_{abs}) + A3\ln(T_{abs}/100) + S\left[(B1 + B2(T_{abs}/100) + B3(T_{abs}/100)^2\right] \quad (5)$$

Where, T_{abs} = absolute temperature (K) = (273.15 + T^o Celsius) K, S = salinity (psu),

d) Carbon dioxide (CO_2) flux calculation
The carbon dioxide flux can be calculated as follows (Akiyama, 2002):

F = * ($pCO_{2\ atmosphere}$ - $pCO_{2\ seawater}$) (6)

F = * ΔpCO_2 (7)

Where, F: CO_2 flux (μmol/kg), $pCO_{2atmosfer}$: CO_2 partial pressure in atmosphere (μatm), $pCO_{2seawater}$: CO_2 partial pressure in seawater (μatm), Δ pCO_2: Carbon dioxide partial pressure.

e) Carbon dioxide partial pressure (The ΔpCO_2) distribution derived from sea surface temperature (SST)
The Δ p CO_2 is a function of temperature, total inorganic CO_2 concentration (T CO_2), alkalinity, and salinity. Metzl et al. (1995) tried to derive pCO_{2water} from the relation with sea surface temperature (SST) in Indian Ocean. As $pCO_{2\ air}$ in the atmosphere varies slowly in both spatial and temporal scale, Zhou (1995) derived the difference of CO_2 partial pressure between air and sea

(ΔpCO_2) from sea surface temperature. The relationship between ΔpCO_2 and SST is investigated using in situ data and MODIS data monthly in year 2007. Due to data limitation, related to summer and winter period are derived using least square fit method and the relation between ΔpCO_2 and SST can be expressed as:

$$\Delta pCO_2 = 0.0147T^3 - 0.1241T^2 - 12.3453T + 115.5879 \quad (4.8)$$

(In summer period)

Where, T = Sea Surface Temperature (Celsius).

In this study, the average value of wind friction velocity (u*) is 0.00565 (Table 2). Under a continuous influence of wind, waves grow and eventually become unstable locally, the wave then break to dissipate excess energy provided by the wind (Wu, 1988). The breaking is marked by whitecaps.

The fraction of whitecap coverage due to the wave breaking has been investigated for many years (Monahan and David, 1989; Toba and Chaen, 1973; Wu, 1988; Zhao, 1995). Generally, whitecap coverage (W) is related to the wind speed or wind friction velocity. Monahan and David (1989) used ordinary least square fitting (OLS) and robust bi weight fitting technique (RBF) to analyze the data set of Toba and Chaen (1973). By the way, Wu (1979) proposed that the whitecap coverage, W, should be related to the wind stress or wind friction velocity on the basis of theoretical analysis. Waves break after wind wave is supplied excessive energy by wind. Whitecap coverage (W), the fraction of the sea surface covered by whitecaps, is related to the energy flux from wind (Wu, 1988). However, the conclusion, whitecap coverage (W) should be proportional to the cube of wind friction velocity, seems to have been accepted by the scientific community (Wu, 1988).

In this work, some data of directional wind wave spectrum image have been taken in the inland sea, Badung and Lombok Straits. The data is digitized by Fast Fourier Transform in the computer. Toba and Chaen (1973) and Monahan (1984) are also reprocessed after friction velocity is re-estimated on the basis of wind speed logarithmic profile. Finally, the result to determined the wind friction velocity in order to calculated whitecap coverage (W) by the modified whitecap model hereafter, $W = 0.066\, u^{*3}$ (Zhao, 1995). From u*, the area ratio of whitecap on Whitecap Model can be calculated, $W = 1.19 \times 10^{-8}$. The whole value of U*, W, and K_{radon}, are shown in Table 5.1.

After the whitecap coverage coefficient is found, the processes are continued to find the transfer velocity of gas transfer associated without whitecap area (K_{radon}) with Monahan Model calculation ($K_{radon} = K_m (1-W) + K_e W$), from this equation the value of K_{radon} is found (K_{radon} = 9.58 cm hour^{-1}). From the K_{radon} value, the calculation processes are continued to get the CO_2 transfer velocity (K_{CO_2}) also follows the Monahan model calculation ($K_{CO_2} = K_{radon}(\frac{Sc_{CO_2}}{Sc_{radon}})^{-n}$). Result is shown in Figure 6 (a).

The calculation processes are continued to get the CO_2 gas solubility (L), after the CO_2 transfer velocity is estimated. L coefficient then combine with CO_2 transfers velocity (K_{CO_2}), so the CO_2 gas exchange coefficient (E_{CO_2}) is estimated.

The calculation processes are continued to get ΔpCO_2. After the ΔpCO_2 is estimated, the calculation processes are continued to get CO_2 flux combining with CO_2 gas exchange coefficient

(Flux = $E_{CO_2} * \Delta pCO_2$).

Table 5.1 Wind Friction Velocity (U*), W, and K_{radon} Calculation

S(ω)	ω (Hz)	π	α	g (ms^{-2})	ω_p^{-2}	u *	$W=0.066\ u*^3$	K_{radon}
67	0.006098	3.14	0.0214	9.8	3.72E-05	0.002	4.47E-10	9.58000021
108	0.005587	3.14	0.0214	9.8	3.12E-05	0.003	1.11E-09	9.58000052
188	0.005682	3.14	0.0214	9.8	3.23E-05	0.005	6.46E-09	9.58000301
278	0.005618	3.14	0.0214	9.8	3.16E-05	0.007	1.95E-08	9.58000908
338	0.006211	3.14	0.0214	9.8	3.86E-05	0.009	6.41 E-08	9.58002982
379	0.006173	3.14	0.0214	9.8	3.81E-05	0.011	8.70 E-08	9.58004050
293	0.005882	3.14	0.0214	9.8	3.46E-05	0.008	3.01 E-08	9.58001401
213	0.005780	3.14	0.0214	9.8	3.34E-05	0.005	1.04 E-08	9.58000485
188	0.005682	3.14	0.0214	9.8	3.23E-05	0.005	6.46 E-09	9.58000301
180	0.005848	3.14	0.0214	9.8	3.42E-05	0.005	6.74 E-09	9.58000314
257	0.006173	3.14	0.0214	9.8	3.81E-05	0.007	2.71 E-08	9.58001261
223	0.006993	3.14	0.0214	9.8	4.89E-05	0.008	3.75 E-08	9.58001744
209	0.006897	3.14	0.0214	9.8	4.76E-05	0.008	2.84 E-08	9.58001321
150	0.006897	3.14	0.0214	9.8	4.76E-05	0.005	1.05 E-08	9.58000488
93	0.006993	3.14	0.0214	9.8	4.89E-05	0.003	2.72 E-09	9.58000127
195	0.006803	3.14	0.0214	9.8	4.63E-05	0.007	2.12 E-08	9.58000988
80	0.006536	3.14	0.0214	9.8	4.27E-05	0.003	1.15 E-09	9.58000054
241	0.006061	3.14	0.0214	9.8	3.67E-05	0.007	2.00 E-08	9.58000933
105	0.007353	3.14	0.0214	9.8	5.41E-05	0.004	5.29 E-09	9.58000246
251	0.005348	3.14	0.0214	9.8	2.86E-05	0.005	1.07 E-08	9.58000497
182	0.005814	3.14	0.0214	9.8	3.38E-05	0.005	6.73 E-09	9.58000313
124	0.005814	3.14	0.0214	9.8	3.38E-05	0.003	2.13 E-09	9.58000099
114	0.007143	3.14	0.0214	9.8	5.1E-05	0.004	5.68 E-09	9.58000265
167	0.007042	3.14	0.0214	9.8	4.96E-05	0.006	1.64 E-08	9.58000764
					Average	0.006	1.78 E-08	9.58000829

3. Result And Discussions

SST MODIS Data Monthly Year 2007

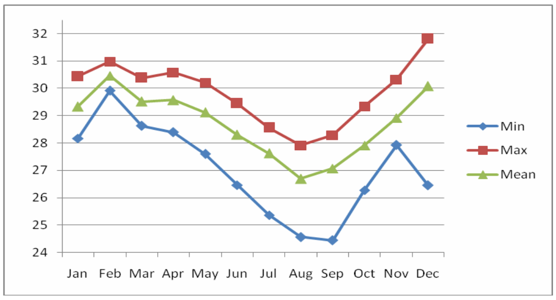


Figure 2 Graphic of annual SST value from January until December in 2007

Figure 2 shows data monthly of MODIS data year 2007 from January until December, under the temperature from 24.43⁰C to 31.80⁰C. The lowest and highest temperature could be seen on August and February, with average temperature 26.69⁰C and 30.46⁰C. The minimum SST value is from 24.43⁰C in September to 29.92⁰C in February. The maximum SST value is from 28.29⁰C in September to 30.98⁰C in February. Also, the average SST is from 26.69⁰C in August to 30.46⁰C in February. The lowest average SST is found in August and the highest is found in February 2007. Distributions of SST are shown in Figure 6 (b).

Distribution Data of Monthly Δ pCO_2 between the Atmosphere and Ocean in 2007

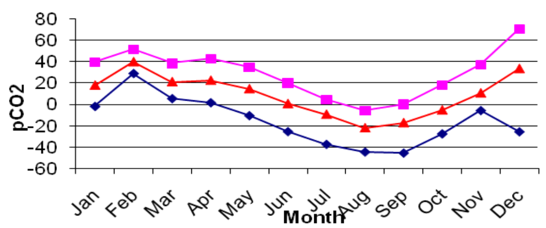


Figure 3 Graphic of Monthly Δ CO_2 from January until December in 2007

Figure 3 shows monthly data of ∆ pCO_2 year 2007 from January until December, under ∆ pCO_2 from -44.66 µatm to +28.78 µatm. The lowest and highest ∆ pCO_2 could be seen on February and August, with average ∆ pCO_2 -2.05 µatm and +39.95 µatm. The positive value of ∆ pCO_2 indicates the transfer of partial pressure is from the ocean to the atmosphere which is shown in January until June and November until December during high SST in year 2007. The negative value of ∆ pCO_2 indicates the transfer partial pressure is from atmosphere to the ocean which is shown in July until October during low SST in year 2007. Result shows the negative ∆ pCO_2 value which indicates transfer of ∆ pCO_2 into the ocean is from -22.05 µatm on August to -5.42 µatm on October. The positive ∆ pCO_2 value which indicates transfer of ∆ pCO_2 into the atmosphere is from 0.64 µatm on June to 39.95 µatm on February. Measurements of the atmospheric CO_2 concentration indicate that it has been increasing at a rate about 50% of that which is expected from all industrial CO_2 emissions (Takahashi *et al.,* 1997).

Result also shows that the mean annual ∆ pCO_2 values (area weighted) for the inland sea are positive (+39.95 ± 5.21 µatm) in February, and negative (-22.05 ± 9.86 µatm) in August. This means that the oceans are, as a whole, nearly in equilibrium with atmospheric CO_2, although they are locally out of equilibrium. This suggests that the oceanic uptake of CO_2 depends sensitively on the wind speed distribution where large negative ∆ pCO_2 and high wind speeds prevail. The result is comparable with Takahashi climatologically data set in equator area. The result is not much different within Takahashi result. The annual mean ∆ pCO_2 in this study is +34.74 µatm in February and -12.19 µatm in August. This exchange coefficient correspond Takahashi et al (1997) result +27.90 µatm in February and -11.20 µatm, in August (really not much different), which is global mean value of CO_2 estimated from air-sea water equilibrium methods (Takahashi et al., 1997). Distributions of "pCO_2 are shown in Figure 6 (c).

Distribution Monthly Data of CO_2 Exchange Coefficients (The Transfer Velocity of Carbon dioxide) between the Atmosphere and Ocean in 2007

Figure 4 shows distribution monthly data of CO_2 exchange coefficients between the atmosphere and ocean in 2007 from January until December, under the carbon dioxide exchange coefficients from 0.27 (mol m^{-2}month^{-1}µatm^{-1}) to 0. (mol m^{-2}month^{-1}µatm^{-1}). The lowest and highest transfer velocity of carbon dioxide could be seen on February and on August, with average CO_2 exchange transfer velocity 0.28 (mol m^{-2}month^{-1}µatm^{-1}) and 0.32 (mol m^{-2}month^{-1} µatm^{-1}). The CO_2 transfer velocity which is determined from a turbulent whitecap area and sea surface temperature become lower if SST and the area of whitecap coverage are smaller.

Result shows the minimum CO_2 exchange coefficients are from 0.27 (mol m^{-2} month^{-1}µatm^{-1}) on December to 0.31 (mol m^{-2}month^{-1}µatm^{-1}) on August. The maximum CO_2 exchange coefficients are from 0.29 (mol m^{-2}month^{-1}µatm^{-1}) on February to 0.34 (mol m^{-2}month^{-1}µatm^{-1}) on September. Also, the average CO_2 exchange coefficients are from 0.28 (mol m^{-2}month^{-1}µatm^{-1}) on February to 0.32 (mol m^{-2}month^{-1}µatm^{-1}) on August. The lowest average CO_2 exchange coefficient is found on February and the highest is found on August 2007.
(mol m^{-2} month^{-1}µatm^{-1})

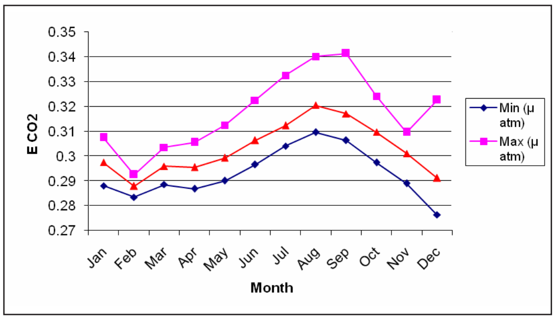


Figure 4 Distribution Monthly Data of CO_2 Exchange Coefficients between the Atmosphere and Ocean in 2007

In this study, the distribution of gas exchange coefficient obtained by the modified whitecap method from ALOS/PALSAR data in 2007 and SST data estimated from MODIS monthly data in 2007. The annual mean CO_2 gas exchange coefficient is 0.303 mol m^{-2} month^{-1}µatm^{-1} or 2.525 x 10^{-2} (mol m^{-2}month^{-1}µatm^{-1}). This exchange coefficient corresponds Zhao (1995) result 5.7 x 10^{-2} (mol m^{-2}month^{-1}µatm^{-1}) (or 19.7 cm hour^{-1}) which is little smaller than 6.1 x 10^{-2} (mol m^{-2}month^{-1}µatm^{-1}) (or 21 cm hour^{-1}), which is global mean value of CO_2 estimated from C^{14} data (Broecker *et al.,* 1986 in Zhao, 1995). The seasonal variation can be seen clearly; especially the mean exchange coefficient varies much in May to October compared with November to April. Distributions of CO_2 exchange coefficients are shown in Figure 6 (d).

Distribution Monthly Data of CO_2 Flux in 2007

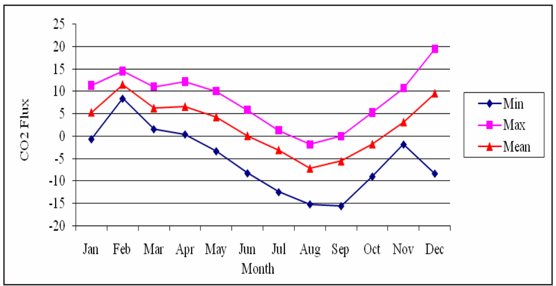
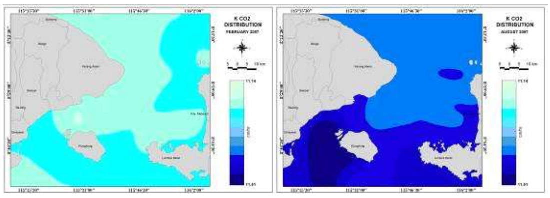
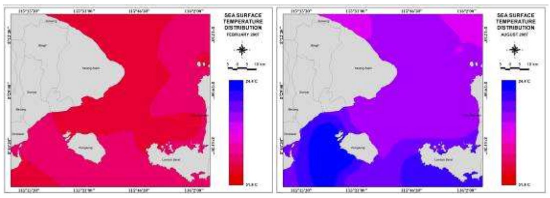


Figure 5 Distribution Monthly Data of CO_2 Flux in 2007

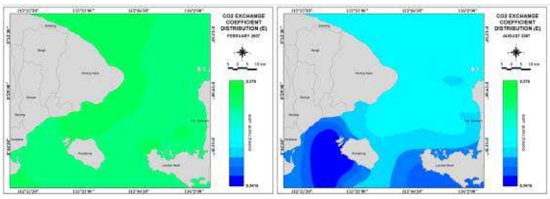
Figure 5 shows distribution monthly data of CO_2 flux between the atmosphere and ocean in 2007 from January until December, under the carbon dioxide flux value from -15.58 (mol m^{-2} $month^{-1}$) to 19.45 (mol m^{-2} $month^{-1}$). The lowest and highest transfer velocity of carbon dioxide could be seen on August and on February, with average CO_2 flux -7.14 (mol m^{-2} $month^{-1}$) and 11.49 (mol m^{-2} $month^{-1}$). The CO_2 flux which is determined from CO_2 transfer velocity (E) and Δ p CO_2 becomes lower if SST, Δ pCO_2, and the CO_2 flux transfer velocity are smaller. Result shows the negative CO_2 flux value indicates the flux into the ocean is from -7.14 (mol m^{-2} $month^{-1}$) on August to 11.49 (mol m^{-2} $month^{-1}$) also on February. The positive CO_2 flux value indicates the flux into the atmosphere is from 0.44 mol m^{-2} $month^{-1}$ on April to 19.45 mol m^{-2} $month^{-1}$on December. The following areas are strong sources for atmospheric CO_2 (positive Δ pCO2 values): i) the northwestern of Badung Strait (due to seasonal warming upwelling) and (ii) a few patchy areas near Lombok Barat regency (local upwelling). The average distributions of CO_2 flux in this month become positive value; this indicates the flux into the atmosphere in this month. In August, the strong source areas include (i) the central Lombok Strait (upwelling) and (ii) the northern area of Lombok Strait temperate gyre (seasonal warming). The average distributions of CO_2 flux in this month become negative value; this indicates the flux into the ocean during the low SST in this month. Distributions of CO_2 flux are shown in Figure 6 (e).



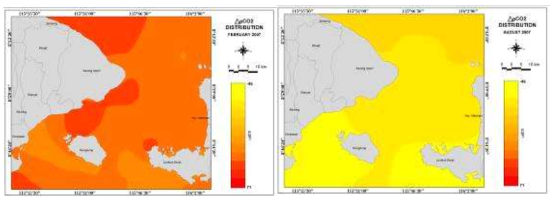
(a) Distribution of K CO_2



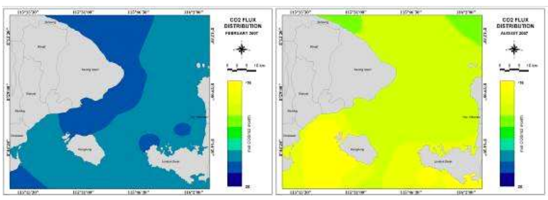
(b) Distribution of SST



(c) Distribution of CO_2 exchange coefficients



(d) Distribution of ΔpCO_2



(e) Distribution of CO_2 flux

Figure 6 (a, b, c, d, e) show the distributions variations of KCO_2, SST, CO_2 exchange coefficients, "pCO_2, and CO_2 flux, respectively, in Badung and Lombok Straits variety in February and August

4. Conclusions and Sugestion

Conclutions

Within ALOS/PALSAR data, the air-sea interaction at sea surface is determinate by directional wind wave and wind friction velocity from satellite-derived wind data which takes an important role for air sea interaction in the ocean.

Within ALOS/PALSAR data, the CO_2 exchange process between the atmosphere and the ocean at sea surface is determinate by carbon dioxide flux, which is due to some factor, such as: ΔpCO_2, ECO_2, SST, and total carbon acid.

Sugestion

For the future study, it is recommended the deeper study using difference method on the calculation of the difference CO2 partial pressure between air and ocean, Δ pCO2, and on the calculation CO2 flux in ocean or in wider sea area with satellite and ground truth data.

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