STUDY FOR ESTIMATION OF AIR-SEA $C0_2$ GAS TRANSFER BY WAVE BREAKING MODEL USING SATELLITE DATA — ESTIMATION OF THE FRICTION VELOCITY CONSIDERING WAVE EFFECT —

NAOYA SUZUKI[1], NAOTO EBUCHI[2], CHAOFANG ZHAO[3],
TAKAHIRO OSAWA[4], TAKASHI MORIYAMA[5]

Abstract

The determination of wind friction velocity from satellite-derived wind data will take an important role of key factors for computation of $C0_2$ flux transfer. It is necessary for relation between wind speed and wind friction velocity to determine that of relation between non-dimensional roughness length and wave age, included with all parameters (wind, wave).

In this study, we proposed a new method to estimate u„„ which is based on the new relationship between non-dimensional roughness and wave velocity, after considering fetch and wave directionality. Consequently, we obtained the new relationship between friction velocity and wind speed. Using this relationship, we estimated the wave frequency from two methods: 3/2 powers law (Toba, 1972) and WAM model (WAMDI, 1988). The results arc compared with the results estimated from Charnock formula (1955) and the above influence of wave effects on the wind stress is also discussed. A new relationship was established to determine CO. exchange coefficient based on whitecap model (Monahan and Spillane 1984), using $U_{|0}$-u, relationship in North Pacific Ocean, satellite data of NOAA/AVHRR (SST) and DMSP/SSM/I (wind speed) in Oct., Nov., and Dec. 1991. The $C0_2$ exchange coefficient estimated by other models (Wanninkhof, 1992; Liss and Merlivat, 1986; Tans et al., 1990) are also compared with these results. The results show the importance of wave breaking effect.

Key words: wind waves, friction velocity, $C0_2$ exchange coefficient, roughness length, wave age

I. Introduction

It is definitely getting to be more important to solve $C0_2$ circulation mechanism over whole earth, atmosphere, ocean and biosphere, in order to settle the problem of the earth warming. Now, we understand that the ocean occupies about 70% over the earth surface and attracts our attention due to its enormous reservoir for $C0_2$ in deep underwater, However, $C0_2$ circulation mechanism between atmosphere and ocean has not been solved well so far. In order to better understanding of $C0_2$ circulation between air-sea interfaces, it is necessary to estimate $C0_2$ flux

1 Division of Applied Marine Physics, Rosenstiel School of Marine and Atmospheric Science (RSMAS), University of Miami, 4600 Rickenbacker Causeway Miami, FL 33149 U.S.A. (E-mail: nsuzuki@rsmas.miami.edu).

2 Institute of Low Temperature Science, Hokkaido University, Kita-19, Nishi-8, Kita-ku Sapporo, 060-0819, Japan, (E-mail:ebuchi@lowtem. hokudai.ac.jp).

3 Ocean Remote Sensing Laboratory, Ocean University of China, 5, Yushan Road Qingdao, RR. China 266003, (E-mail: zhao_cf@21cn.com).

4 Center for Environmental Remote Sensing (CEReS), Chiba University, 1 -33 Yayoi Inage Chiba, 263-8522 Japan, (E-mail: osawa@ceres.cr.chiba-u.ae.jp).

5 National Space Development Agency of Japan (NASDA), 2-1-1 Tsukuba Sengen, 305-8505 Japan, (E-mail: moriyama.takashi@nasda.go.jp).

transferred at sea surface. Historically several models (Whitecap, Tans, Wanninkof, Liss & Merlivat model) has been proposed to determine the CO_2 exchange at sea surface. In their model, Whitecap model seems to be better one which can include wave breaking (area ratio of whitecap). Whitecap model, proposed by Monahan and Spilane (1984), is expressed as following,

$$K_{radon} = K_m(1 - W) + K_e W, \qquad (1.1)$$

where K_{radon} is the transport function of radon gas, K_m is the transfer velocity associated with no whitecap area, and K_e is the transfer velocity related with whitecap area. W is the function of sea surface covered by whitecaps due to wave breaking. Wu (1980) proposed W as function of friction velocity u.,

$$W = 0.2u*^3 \qquad (1.2)$$

K_m and K_e are estimated from GEOSECS and TTO radon data with the value of 9.58 cm/hr and 475.07 cm/hr. Carbon dioxide gas transfer velocity can be estimated from dependence of gas transfer velocity on Schmidt number Sc, which was proposed by Deacon (1977). Wind tunnel experiment showed K is proportional to $Sc^{3,2}$ at low wind speeds, and to $Sc^{1/2}$ at higher wind speed (Jahne et al, 1987). This relationship offers a method to estimate gas transfer velocities from one kind of gas to another. Then, CO_2 gas transfer velocity can be calculated by

$$K_{CO2} = K_{radon}(Sc_{CO2}/Sc_{radon})^n \qquad (1\text{-}3)$$

where n=2/3 for U < 3.6 m/s and n=l/2 for U>3.6 m/s. Schmeidt number for CO_2 and radon gas can be estimated from temperature (Wanninkhof, 1992)

$$Sc_{radon} = 3412.8 - 224.30T + 67.954T^2 - 8.3 \times 10^{-2}T^3 \qquad (1.4)$$

$$Sc_{CO2} = 2073.1 - 125.62T + 3.6276T^2 - 4.3219 \times 10^{-2}T^3 \qquad (1.5)$$

for radon gas and CO_2 gas in the seawater with salinity S=35%o.

Liss and Merlivat (1986) proposed a relationship between gas transfer velocity K and wind speed, based on tracer gas exchange experiment, wind tank data and field data in some lakes. This relation consists of three linear segments, related to smooth surface, rough surface and breaking wave regime.

$$K = 0.17U_{10} \quad \text{for } 0 \leq U_{10} < 3.6 \text{ m/s} \qquad (1.6a)$$

$$K = 2.85U_{10} - 9.65 \quad \text{for } 3.6 \leq U_{10} \leq 13 \text{ m/s} \qquad (1.6b)$$

$$K = 5.9U_{10} - 49.3 \quad \text{for } 13 \leq U_{10} \qquad (1.6c)$$

where U is wind speed at 10 m above sea surface.

Tans et al. (1990) provided a relation related to the gas exchange coefficient E and wind speed,

$$E = 0.016(U_{10} - 3.0) \quad \text{for } U_{10} \geq 3.0 \text{ m/s} \qquad (1.7a)$$

$$E = 0.0 \quad \text{for } U_{10} < 3.0 \text{ m/s} \qquad (1.7b)$$

Temperature effect is not considered based on that CO_2 gas solubility and Schmidt number have inversely temperature effect.

Wanninkhof (1992) compared the several transfer velocity equations with water tank, field data and proposed gas transfer velocity is related with a quadratic dependence of wind speed.

$$K = 0.39\,U_{av}^2(Sc/660)^{-1/2} \qquad (1.8a)$$

for long-term averaged wind speed

$$K = (2.5(0.5246 + 1.6256 \quad 10^{-2}T + 4.9946 \times 10^{-4}T^2) - 0.3U^2)(Sc/660)^{-1/2} \qquad (1.8b)$$

for short-term steady wind speed

Finally, CO_2 gas exchange coefficient E can be calculated using transfer velocity K_{C02} by multiplying CO_2 gas solubility. Weiss (1974, 1980) provided an empirical formula to estimate the CO_2 gas solubility L on the basis of data fitting between the solubility, temperature and salinity.

Area ratio of whitecap W is expressed by friction velocity u„. Satellite data can provide wind speed U_{10} at 10 m above sea surface only. Therefore, it is required relationship between friction velocity u, and wind speed at 10m above sea surface U . Relation between wind speed and wind friction velocity needs to determine the relationship between non-dimensional roughness length and wave age, included with all parameters (wind, wave). We estimated friction velocity including wave effect using improved this relationship and WAM model (WAMDI, 1988) to obtain the relationship between friction velocity u. and wind speed at 10m above sea surface U_{10} for satellite data. Subsequently, we calculated $C0_2$ gas exchange coefficient E, using Whitecap model.

II. The Relationship between Non-dimensional Roughness Length and Wave Age

Charnock (1955) proposed well known formula, as follows,

$$g z_0 / u_*^2 = \beta \qquad (2.1)$$

Eq. (1) has widely been utilized, where g is the acceleration of gravity, and is a constant. For the value of, there seems to be considerable disagreement among authors. For example, Charnock (1955) proposed 0.0068, Smith and Banke (1975) gave 0.0130, Garrat (1977) suggested 0.0144, and Wu (1980) proposed 0.0185. A possible reason for the disagreement might be poor quality and quantity of wind stress measurements. Also effects of waves on the wind stress should be considered explicitly.

Stewart (1974) presented a general formula for the wave dependence on the wind stress as a function of wave age,

$$g z_0/u_*^2 = f(C_p / u_*), \qquad \textbf{(2.2)}$$

where C_p is the phase speed of wind waves of the spectral peak frequency. By assuming the linear dispersion relationship of deep water waves, the wave age C_p/u, can be expressed as C_p/u,=(a u*/g)', where **o** is the angular frequency of wind-wave spectral peak. Toba and Koga (1986) proposed a formula involving the peak frequency of wind wave as,

$$z_0 / u_* = \gamma \qquad \textbf{(2.3)}$$

Furthermore, Masuda and Kusaba (1987) proposed a functional formula of Eq. (2.2) as non-dimensional roughness length and inverse wave age,

$$g z_0 / u_*^2 = a (\sigma_p u_*/g)^b \qquad \textbf{(2.4)}$$

where a and b are constants. The Charnock's (1955) formula in Eq.(2.1) corresponds to b - 0 and a = P in Eq.(2.4). Constants a and b is different from various investigations. Toba et al. (1990) took b=-0.5. Masuda and Kusaba (1987) took b=1.10. Donelan et al. (1993) took b=1.0. A negative value of the slope b is suggested from the data set ranging from laboratories to open oceans, even though the data points are scattered very widely (Refer to Fig. 1 in Suzuki et al., 2002). Thus, this relationship has been discussed whether to be positive or negative slope. In composite data set collected from previous studies, there has existed a lack of data at a range of wave age region between laboratory and open ocean waves. Suzuki et al.(1998) estimated this lack of data using eddy correlation method from the data of the Hiratsuka Tower of (Independent Administrative Institution) National Research Institute for Earth Science and Disaster Prevention (NIED) in Sagami Bay, Japan. Then a and b is expressed as a=0.020 and b= -0.697. However because of the large variation of the non-dimensional roughness length in this relationship, it is difficult to express wave influence by the single wave age. Ocean wave directional spectrum is much more important parameter for describing the essential structure of ocean wave. Consequently, in this study we observed wave heights in four wave gauges at the Hiratsuka Tower, and analyze directional wave spectra estimated from EMEP method (Hashimoto, 1997). As a result (Suzuki et al., 2002), the data sets were classified into two different groups according to the directional wave spectrum distribution (Fig. 1, Fig.2). In Case 1 only swell and wind waves exist and in Case 2 there exists wave components from several directions. It is shown that the case of multiple-directional component waves (Case 2) may affect the non-dimensional roughness length and friction velocity (Suzuki et al., 2002). Therefore, we proposed the new scheme of relationship between non-dimensional roughness and wave age by considering fetch F from this result and form of field data sets, as following,

$$gz_0/u_*^2 = f\left(gF/u_*^2 , \sigma p u_*/g\right) \qquad (2.5)$$

$$gz_0/u_*^2 = \alpha\left(\sigma p u_*/g\right)^{\beta}$$

$$\begin{cases} gz_0/u_*^2 = \alpha(2\pi)^{\beta-\varepsilon}\left(gF/u_*^2\right)_m^{-0.33(\beta-\varepsilon)} . \left(\sigma p u_*/g\right) \\ \left(gz_0/u_*^2\right)_m = \alpha(2\pi)^{\beta}\left(gF/u_*^2\right)_m^{-0.33\beta} \end{cases} \qquad (2.6)$$

we suggest a functional form of Eq.(2.5) as following.

where α, β, ε is constant. In Fig. 3, we obtained α=0.0214, β=-0.8792, and ε=2.0 (Refer to Suzuki et al., 2002 (Proc. PORSEC2002)).

III. Estimation of CO_2 Exchange Coefficient Considered with wave effect

The relationship between non-dimensional roughness length and wave age primitively require to know the angular frequency of wind-wave spectral peak. In order to relationship, the wave frequency was estimated from two methods: 3/2 powers law (Toba, 1972) and WAM model (WAMDI, 1988). In this study, ECMWF wind data was used in WAM model (WAMDI, 1988). This data of area is one of around Japan (20N to 50N, 120E to 150E). Time interval of this data is one hour. Period is October, November, and December 1991. We estimated the friction velocity u, including the wave effect in area of around Japan, and compared with the friction velocity u* not including the wave effect estimated by Charnock (1955) formula. As result, when the wind speed is more than 8 m/s, the friction velocity u- is estimated from our results owns large value, compared with the result of Charnock (1955) formula, and the maximum difference was about 30% (Fig. 4). Therefore it was shown that wave effect is very important for friction velocity. And we investigated wave effect for CO_2 exchange coefficient in numerical simulation using Whitecap model (Monahan and Spillane, 1984) and the new relationship between non-dimensional roughness length and wave age. The wave frequency was

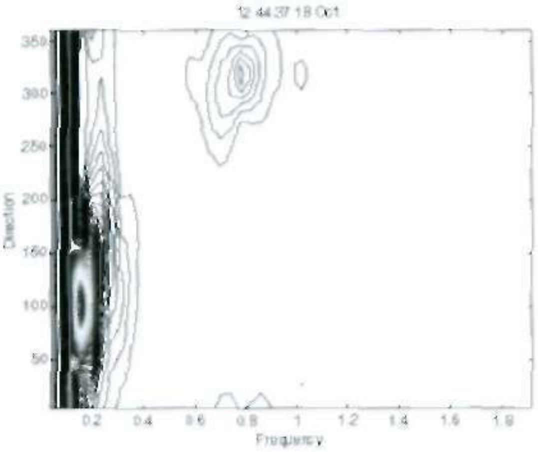

Fig. 1

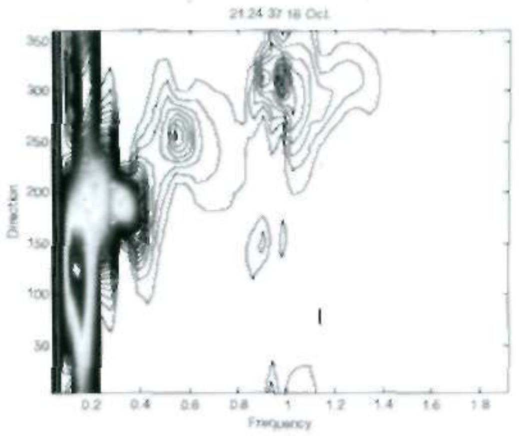

Fig-2

selected 0.1, 0.5, 1.0 Hz. The range of wind speed $U_{|0}$ is 0.0 m/s to 25.0 m/s, and sampling interval is 0.1 m/s. The temperature and salinity are 20! and 35%o constant. As a result, it was shown that C02 exchange coefficient is different value by wave period as wave effect (Fig. 5), and there is necessity to construct the new relationship between friction velocity and wind speed as considered wave effect.

Here, we are taken only wind speed at 10 m above sea surface U_{10} by satellite observation. Consequently, in this study, we estimated the relation between this difference A£ of the friction velocity (present result (Eq. 2.6) - Charnock's result) and wind speed U_{10} in each month (Fig. 6), and we could get the relationship, as following.

Oct. 1991,

$$\Delta\varepsilon = 0.0005U_{10}^3 - 0.0084U_{10}^2 + 0.0633U_{10} - 0.1577 \quad (U_{10} \geq 4.5)$$
$$-\Delta\varepsilon = -0.0049U_{10} + 0.0227 \quad (U_{10} < 4.5) \tag{3.1a}$$

Nov. 1991,

$$\Delta\varepsilon = 0.0002U_{10}^3 - 0.0024U_{10}^2 + 0.0217U_{10} - 0.063 \quad (U_{10} \geq 4.5)$$
$$-\Delta\varepsilon = -0.0044U_{10} + 0.0205 \quad (U_{10} < 4.5) \tag{3.1b}$$

Dec. 1991,

$$\Delta\varepsilon = 0.00004U_{10}^3 - 0.0007U_{10}^2 + 0.0003U_{10} - 0.0035 \quad (U_{10} \geq 4.5)$$
$$-\Delta\varepsilon = -0.0046U_{10} + 0.0152 \quad (U_{10} < 4.5) \tag{3.1c}$$

Furthermore, we added above equation to the Charnock's formula as the effect of a wave. Finally, we proposed new relationship between the friction velocity u_* and wind speed U_{10}, as following.

$$u_* = \sqrt{C_D}U_{10} \pm \Delta\varepsilon$$
$$C_D = \left(0.8 + 0.065U_{10}\right) \times 10^{-3} \tag{3.2}$$

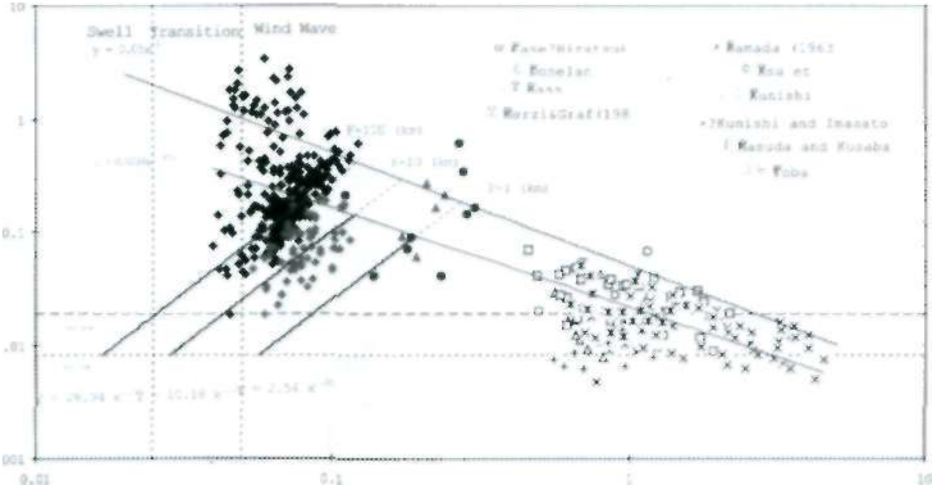

Fig. 3

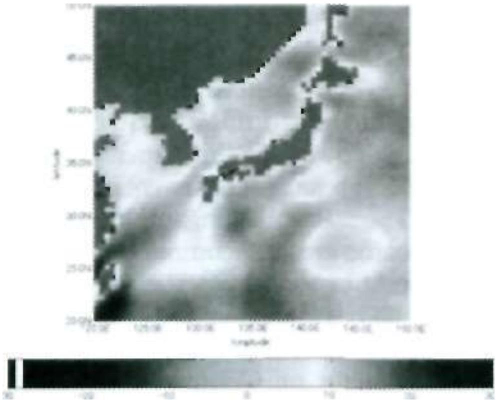

Fig. 4

where C_D is drag coefficient. We estimated the friction velocity u, using this equation (3.1), and estimated the difference between this result and result of the relationship between non-dimensional roughness length and wave age. As a result, the difference was smaller than 10 %. The wind speed of this period is including wind speed from low to high. Consequently, we think that this new relationship is can use global area, and we estimated $C0_2$ exchange coefficient by Whitecap model (Monahan and Spilane, 1984), Liss and Merlivat (1986) model, Wanninkhof (1992) model, and Tans et al. (1990) model in Pacific ocean using satellite data. The temperature and wind speed are used monthly composite data of NOAA/AVHRR and DMSP/SSM/I. The ratio of whitecap W is estimated empirically coefficient by using equation of Wu (1980), as following,

$$W = 0.13u,^{2} \qquad \textbf{(3.3)}$$

In Fig. 7, we show that distribution of $C0_2$ exchange coefficient by Whitecap model (Monahan and Spilane, 1984), Liss and Merlivat (1986) model, Wanninkhof (1992) model, and Tans et al. (1990) model on Oct. 1991. The result shows that the $C0_2$ exchange coefficient has large value as wind speed in increase (Especially it is high latitudes). Wanninkhof's result is much larger compared with Whitecap's result especially in equator area. The reason of problem for this difference is due to whitecap coverage very low in light wind.

Presently, the decision is difficult which model is high accuracy. It is reason of problem $C0_2$ is different by the observation place and a season. However, we were able to indicate importance of wave effect for $C0_2$ transfer velocity.

TV. Summary

In this study, we analyzed the wave effect

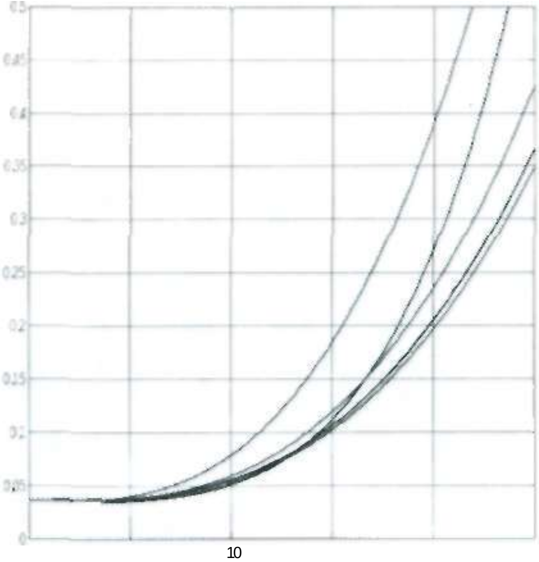

Fig. 5

of the friction velocity u, for the area ratio of whitecap by Whitecap model. WAM model (WAMDI, 1988) is used to get wave height data for the new relationship between non-dimensional roughness length and wave age, and estimate the friction velocity including the wave effect. It was shown that the difference is 30 % for the friction velocity not including wave effect. Consequently, it was shown that the friction velocity depends on sea surface conditions (wave) in addition to only the wind speed. But we can get a practical data wind speed U_{10} from satellite. Therefore, we proposed the new relationship between the friction velocity and wind speed including wave effect as the difference, based on this result. The satellite data, NOAA/AVHRR (SST) and DMSP/SSM/I (wind speed) are used in this study. We estimated $C0_2$ exchange coefficient using Whitecap model in the North Pacific Ocean using the new relationship, and other model (Wanninkhof, Liss and Merlivat, Tans) was also estimated it to compare. The each model gives same pattern of $C0_2$ exchange coefficient in the North Pacific Ocean with wind speed. However, Whitecap model is low value of $C0_2$ exchange coefficient in the equator area. The wave breaking are hardly exists in the equator area. This model uses whitecap, but other models use the wind speed. Presently, CO is many took in bubble of wave breaking, and wave breaking pay attention to important factor on $C0_2$ exchange. Consequently, Whitecap model is fairly suitable considering whitecap. Furthermore, we think that the accuracy of the estimation of $C0_2$ exchange coefficient is improved by using satellite data and our new relationship between the friction velocity and wind speed that considered an effect of wave.

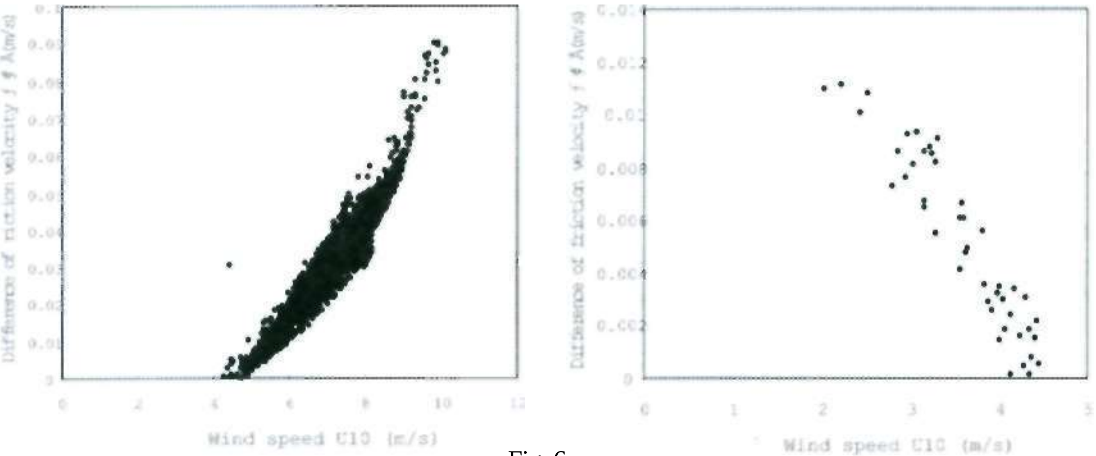

Fig. 6

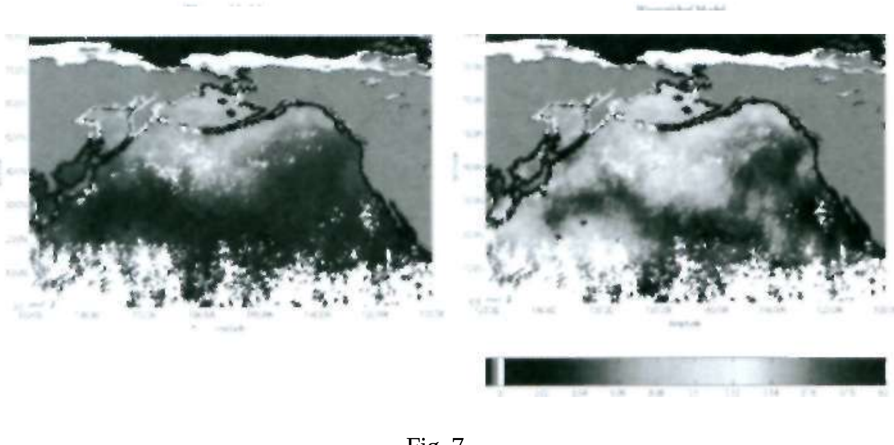

Fig. 7

In this study, we used modified Wu (1980) equation for the equation of area ratio of whitecap. However, if we used the friction velocity including wave effect, we have to also change the equation of area ratio of whitecap. Because of Wu (1980) equation is not including wave effect. Therefore, in the future, the estimation of CO, exchange coefficient will be able to more improved considering wave effect for the equation of the area ratio of whitecap on the Whitecap model.

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