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ESTIMATION OF THE SEA SURFACE DRAG COEFFICIENT BASED ON WAVE DATA

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ABSTRACT: The sea surface drag coefficient, an important parameter for the energy transfer process in wave prediction model, is generally expressed by a linear function of wind speed. However, it seems inadequate to apply these equations for strong wind conditions because these equations were deduced from the observational or the experimental data under wind speed of lower than 25m/s at fastest. To solve this problem, a wave prediction model ADWAM which includes a data assimilation method seems effective. For the purpose of clarifying the appropriate values of the sea surface drag coefficient in high wind speed, the ADWAM was modified to estimate the sea surface drag coefficients as its control variables of the model. In this study, the sea surface drag coefficient was deduced from the actual wave observation data. As a results, the sea surface drag coefficient, unknown parameter, was confirmed to be modified from arbitrary initial value to an appropriate value. Also, it was confirmed that the sea surface drag coefficient under stormy condition can be estimated based on the wave data observed outside the storm if the waves propagated from the storm were observed.

Keywords: Wave model, sea surface drag coefficient, data assimilation

INTRODUCTION

The sea surface drag coefficient C_D is one of the important parameter for the energy transfer from winds to waves in wave prediction model.

$$\tau = \rho_a u_*^2 = \rho_a C_D U_{10}^2 \tag{1}$$

Here τ is the wind stress at the surface, ρ_a is the air density, U_{10} is the mean wind speed at the 10 m height and u_* is the friction velocity. Generally, C_D is expressed by a increasing linear function of wind speed such as Wu (1980) and Honda & Mitsuyasu (1982) shown in Eq.(2) and Eq.(3) respectively.

$$C_D(U_{10}) = \begin{cases} 1.2875\times10^{-3} & (U_{10} < 7.5m/s) \\ (0.8+0.065\times U_{10})\times10^{-3} & (U_{10} \geq 7.5m/s) \end{cases} \tag{2}$$

$$C_D(U_{10}) = \begin{cases} (1.28-0.0242\times U_{10})\times10^{-3} & (U_{10} < 8m/s) \\ (0.581+0.0626\times U_{10})\times10^{-3} & (8m/s \leq U_{10}) \end{cases} \tag{3}$$

However, it seems inadequate to apply these equations for strong wind conditions because these equations were deduced from the observational or the experimental data under wind speed of lower than 25m/s at fastest. Actually, Powell et al (2003) reported that the sea surface drag coefficient begins to decrease when the wind speed exceeds 30m/s from the observed vertical wind profile amid hurricane. Andreas (2004) proposed a saturated sea surface drag coefficients in high winds by considering the spray generation from wave crests.

To clarify the energy transfer mechanism under strong wind conditions that exceeds 30m/s, wave observation directly under a severe typhoon or the experimental measurement seems to be difficult. As an alternative method, a wave prediction model ADWAM (Hersbach, 1998) which includes a data assimilation method is considered to be effective. It is a kind of remote sensing for deducing the internal structure of such complicated phenomenon through the model from observation data. An advantage of the adjoint method utilized in ADWAM is that it can trace back the data with respect to space and time. Therefore, it may be possible to estimate the model parameters under the storm conditions if the waves propagated through the storm were observed even if the observation point is outside the storm.

For the purpose of clarifying the appropriate values of the sea surface drag coefficient in high wind speed, the ADWAM was modified to deduce sea surface drag coefficients from observational wave data (Yokota et.al, 2011a). The new adjoint WAM was already validated through numerical experiments (Yokota et.al, 2011b). The aim of this study is to estimate the sea surface drag coefficient with the adjoint WAM from the actual wave observation data.

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AFFECT OF SRUFACE DRAG COEFFICIENT

Fig.1 compares the three types of the sea surface drag coefficients proposed as a function of wind speed. Affect of the difference in the sea surface drag coefficient were examined by comparing the wave height computed with WAM cycle 4. In order to use the sea surface drag coefficient in the computation, the energy transfer term in WAM Cycle 4 was modified to use drag coefficient from Janssen's quasi linear method (Janssen, 1991). The condition of the simulation is that a typhoon passes through a sea area from the south toward the north. The grid interval is 0.5 degree. The sea surface wind was estimated by an empirical parametric typhoon model. To reproduce strong winds that exceed 40m/s, we assumed the central atmospheric pressure 900hPa, the maximum wind speed radius 100km and migration velocity 50km/h.

Time series of wave height computed with these three types of the sea surface drag coefficients are shown in Fig.2. The maximum wave height computed with the equation of Mitsuyasu & Honda or that of Wu's equation are larger than that of the Andreas equation which consider the spray generation under strong wind conditions although these two equations are known to moderate the development of waves in strong wind condition compared with Janssen's method. This result suggests that the sea surface drag coefficient in high wind speed needs to be reexamined for an accurate forecast of high waves caused by an intense typhoon.

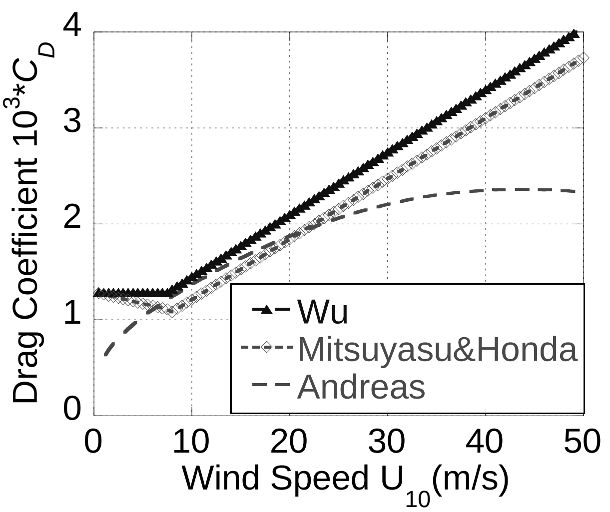

Fig. 1 Proposed sea surface drag coefficients as a function of wind speed

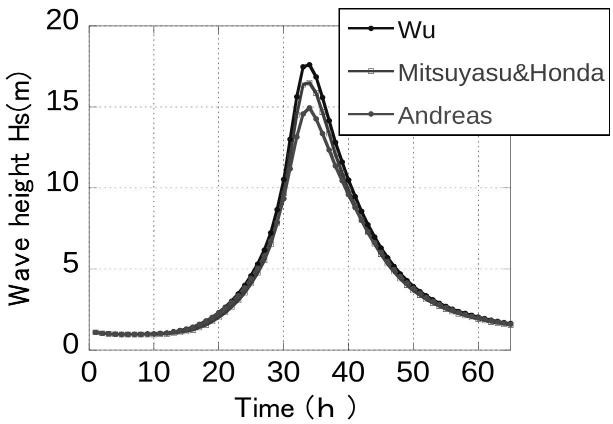

Fig. 2 Comparison of the time series of computed wave height

DATA ASSIMILATION METHOD

In this paper, the piecewise constant values of the sea surface drag coefficient as function of wind speed were assumed as unknown parameters as shown in Fig.3. The range of wind speed is defined from 0 to 50 m/s and the interval of the unknown parameter is fixed as 2m/s. The procedure of the adjoint WAM is almost the same as that of Hersbach (1998). The most suitable parameters are automatically estimated from initial values by minimizing the cost function $J(x)$, expressed by Eq.4, composed of the summation of observation error (the difference between observed wave data and the hindcasted wave data) and background error (a priori condition that the drag coefficient is continuous and smooth between the adjoining pieces of wind speeds).

$$J(x) = \sum_{t=0}^{\mathrm{T}} (H_t(X) - y_t)^T \mathbf{R}_t^{-1} (H_t(X) - y_t) + W \sum_{n=1}^{\mathrm{N}} (x_n - x_{n-1})^T \mathrm{B}_t^{-1} (x_n - x_{n-1}) \quad (4)$$

where H_t is the matrix of the operator that converts the model state X into y_t, X is the vector of model parameters x_n, and y_t is the vectors of observations, $\mathbf{R}_t$ is the covariance matrix of the observation errors, B_t is the covariance matrix of the background errors and W is a weighting coefficient assumed as 10^4. To obtain the optimum value of X, a method of descent which requires the descendent value of the cost function is applied. In the actual computation, it is directly computed with the adjoint model code. For constructing the adjoint code of WAM, we used AMC (Adjoint Model Compiler, Giering and Kaminski, 1998).

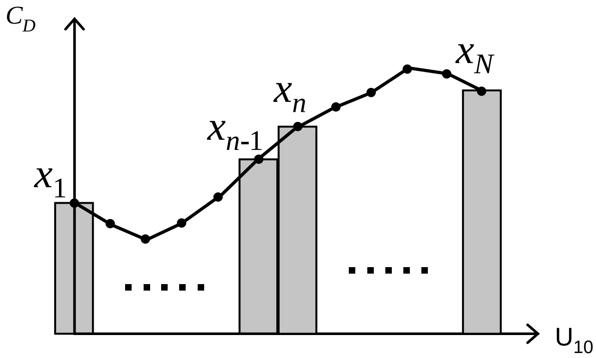

Fig. 3 Sea surface drag coefficient defined as a piecewise constant function of wind speed

COMPUTATION CONDITION

In this study, estimation of the sea surface drag coefficient was carried out with adjoint WAM during the approach of typhoon 0402 (NIDA). Fig.4 shows the track (red plus, 6hr interval) and the central pressure (red circle, 24hr interval) of the typhoon 0402 (RMSC Best Track Data, Japan Meteorological Agency).

For computation of data assimilation during the approach of this tropical cyclone, the objectively analyzed meso-scale grid point wind data (6hr interval, 10km resolution) provided by the Japan meteorological agency and the observed wave data (2hr interval) at Shionomisaki (longitude: 33.4333, latitude: 135.7472, depth: 54.7m) provided by NOWPHAS (the nationwide ocean wave information network for ports and harbors) were used. Time series of observed wave heights and analyzed wind speeds at Shionomisaki are shown in Fig.5. The maximum wind speed at the observation point is lower than 10m/s. The dimension of the computational area is 12.5 degrees in latitude by 25 degrees in longitude, and the grid interval is 0.5 degree as shown in Fig.6.

Before applying the adjoint WAM to this typhoon data, possibility of estimation in wind speed range over 30m/s was examined. Fig.8 compares the time series of wave height computed with 2 different function of drag coefficients, Mitsuyasu and Honda's equation and Case A (beginning to decline from 30m/s shown with red circle in Fig.7). As seen in Fig.8, the wave height computed with case A completely agrees with the wave height computed with the Mitsuyasu and Honda's equation. This result suggests that the sea surface drag coefficient in wind speed over 30m/s does not affect to the wave height estimation at Shionomisaki with this computation condition. Therefore, sea surface drag coefficient in wind speed under 30m/s are assumed as unknown parameter in the data assimilation.

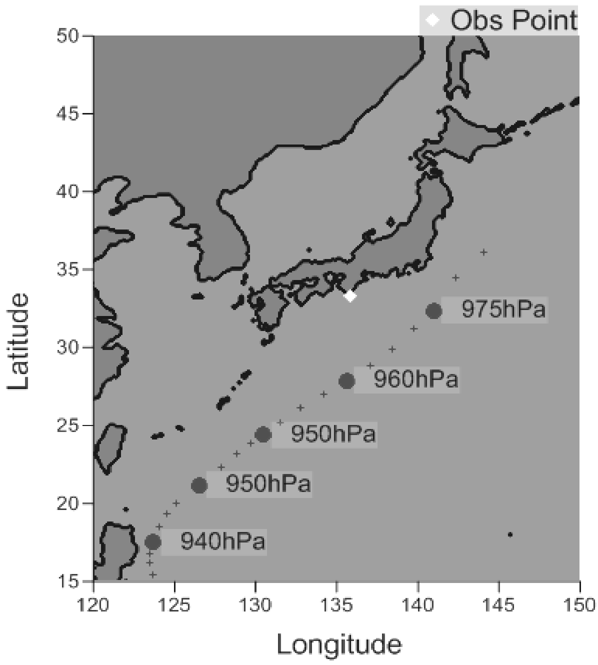

Fig. 4 Track (6h interval) and central pressure (24 h interval) of Typhoon 0402 (RMSC Best Track Data provided by Japan Meteorological Agency, http://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/trackarchives.html)

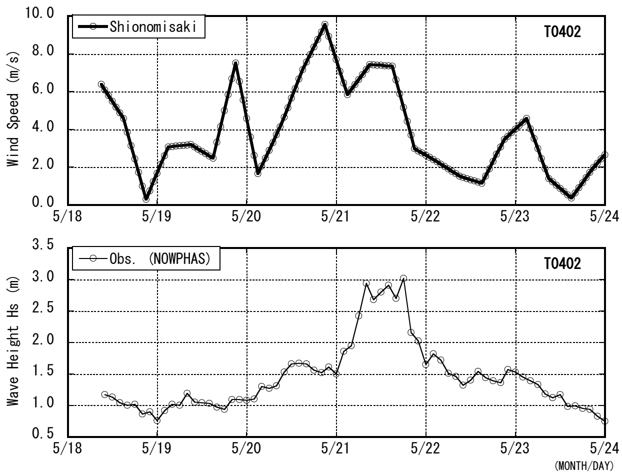

Fig. 5 Time series of observed significant wave height and analyzed wind speed at Shionomisaki

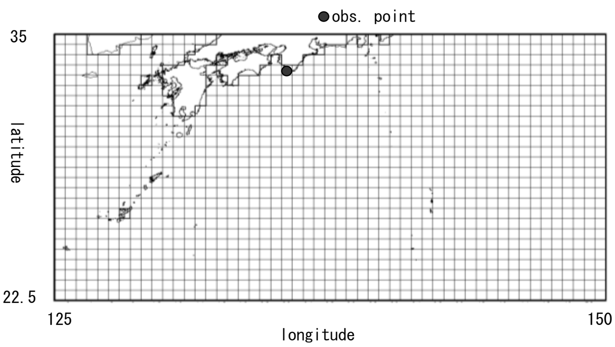

Fig. 6 Dimension of computational area

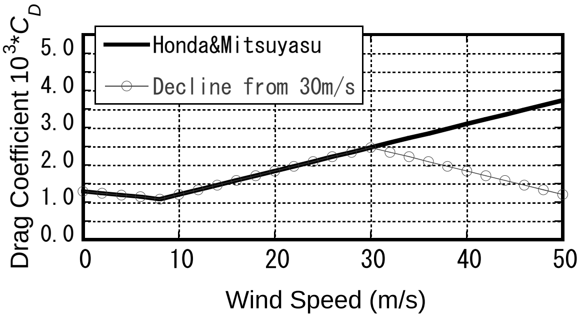

Fig. 7 Assumed sea surface drag coefficient for numerical examination

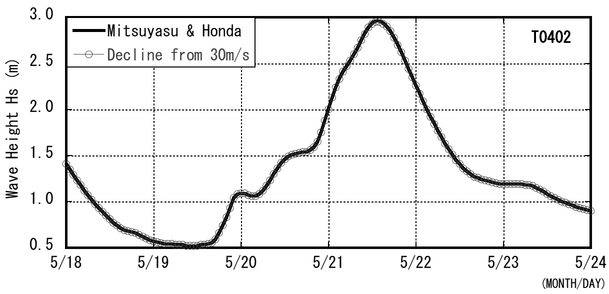

Fig. 8 Comparison of wave heights computed with different drag coefficients

ESTIMATED DRAG COEFFICIENT WITH ADJOINT WAM

By assimilating the time series of observed wave heights shown in Fig.5, sea surface drag coefficient was inversely estimated from 2 different initial parameter assumed as constant value given by $1.09*10^{-3}$(case B) and $5*10^{-3}$ (case C) shown in Fig.9.

The time series of wave height computed with the initial parameter (before data assimilation: solid line) and the deduced parameter (after the data assimilation: pink circle) are compared with the observed wave heights (black circles) shown in Fig.10. Although the wave height computed with the initial parameter "Case B" underestimated the peak of the observed wave height, the wave height computed with the deduced parameter after the data assimilation were corrected to the vicinity of observed data. Similarly for the "case C" which assumed an initial parameter as $5.0*10^{-3}$, the wave heights computed after the data assimilation were corrected to the vicinity of observed data although the peak of the wave height computed before the data assimilation overestimated the observed value.

Fig.11 compares the deduced parameter with the initial parameter. For both cases, sea surface drag coefficients were corrected to the vicinity of Mitsuyasu & Honda's equation. From this fact, it was confirmed that the sea surface drag coefficient can be modified from arbitrary initial value to an appropriate value with adjoint WAM. In addition, despite the fact that the largest wind speed generated at the observation point is 10m/s, sea surface drag coefficient in wind speed over 10m/s were also corrected. Consequently, it was confirmed that the sea surface drag coefficient under stormy condition can be estimated based on the wave data outside the storm.

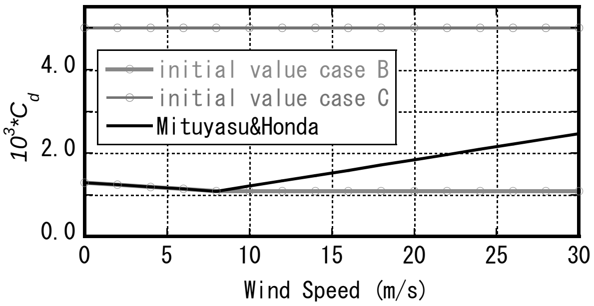

Fig. 9 Arbitrary assumed initial parameters for inverse estimation

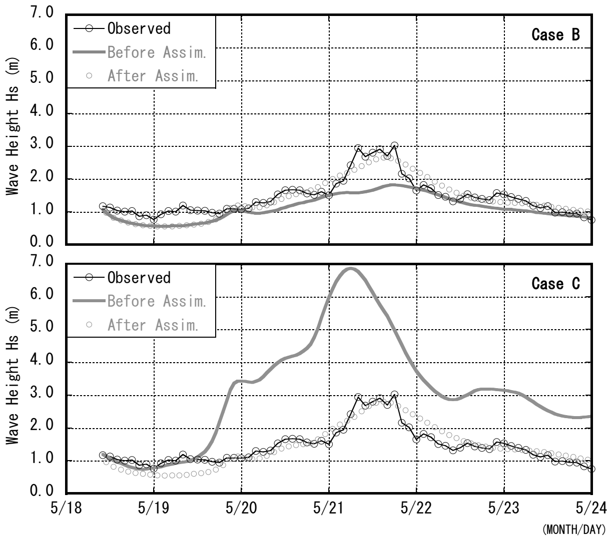

Fig. 10 Comparison of the time series data (observed data, before data assimilation and after data assimilation)

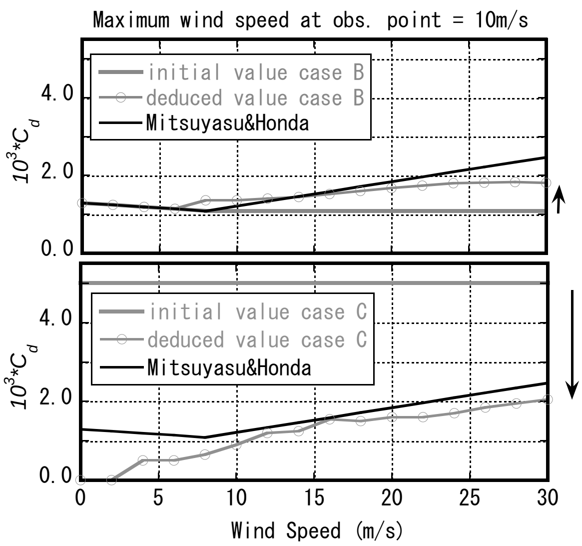

Fig. 11 Deduced sea surface drag coefficients

CONCLUSION

In this study, the ADWAM was utilized as an indirect observation system to deduce the sea surface drag coefficients. Then the piecewise constant values of sea surface drag coefficient as function of wind speed were deduced by assimilating the actual wave observation data. As a result, the sea surface drag coefficient, unknown parameter, was confirmed to be modified from arbitrary initial value to an appropriate value. Also, it was confirmed that the sea surface drag coefficient under stormy condition can be estimated based on the wave data observed outside the storm if the waves propagated from the storm were observed.

FUTURE PLANS

I will apply this data assimilation method to the wave data including the affect of strong wind that exceeds 30m/s. Also, I will raise the reliability of the estimated parameter by accumulating the application examples.

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REFERENCES

Andreas E., L (2004) Spray stress revisited, Journal of physical oceanography, volume 34, pp.1429-1440

Giering, R. and T. Kaminski (1998) Recipes for Adjoint Code Construction, ACM Transactions on Mathematical Software Volume 24 Issue 4, Dec. 1998 pp. 437-474

Hersbach, H. (1998) Application of the adjoint of the WAM model to inverse wave modeling, J. Geophys. Res. Vol. 103, No. C5, pp.10469-10487.

Janssen, P.A.E.M.(1991) Quasi-linear theory of wind – wave generation applied to wave forecasting, J. Phys. Oceanogr., 21, pp.1631-1642.

Mitsuyasu, H. and Honda, T. (1982) : Wind-induced growth of water waves, J. Fluid Mech. , 123, pp.425-442.

Powel, M.D., Vickery, P.J and T.A. Reinhold (2003) Reduced drag coefficient for high wind speeds in tropical cyclones, Nature, 422, pp.279-283

Wu, J (1980). Wind Stress Coefficients over the Sea Surface near Neutral Conditions-A Revisit, J. Phys. Oceanogr., Vol 10, pp.727-740.

Yokota, M., N. Hashimoto, K. Kawaguchi, H. Kawai (2011a) Development of an inverse estimation method of sea surface drag coefficient under strong wind conditions, Proceedings of the 30th International Conference on Coastal Engineering.

Yokota, M., N. Hashimoto, Y. Tanaka (2011b) Inverse estimation of sea surface drag coefficient based on waves observed away from strong wind region, Proceedings of the 21th International Offshore and Polar Engineering Conference, Volome3

WEB REFERENCES

Japan Meteorological Agency, RMSC Best Track Data, http://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/trackarchives.html

The Nationwide Ocean Wave information network for Ports and HArbourS, http://www.mlit.go.jp/kowan/nowphas/index_eng.html