THE IMPACT OF ROUGHNESS CHANGES BY SEA STATE UNDER TYPHOON FIELD.

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1. INTRODUCTION

It is necessary to estimate accurately the amount of exchange of momentum, heat, etc. in sea surface, for evaluating not only ocean waves but also other atmospheric and oceanographic phenomena properly. Especially, very rough sea condition as under a strong wind field by typhoon, where high ocean waves of over 10m exist and so many sea sprays blow, air-sea interaction seems to be influenced by sea state (ocean waves). However this problem about the flux dependency on sea state has not been solved satisfactorily, without being completed by theory and the observation result, even though this knowledge may give the important basis about the coupling mechanism between the ocean and the atmosphere. Even if only the momentum or energy exchange is considered, there are various views and the present perspective is almost chaotic.

Since various numerical models – weather models, ocean model, and wave models – have progressed recently, researches, which consider the various interactions with an integrated model, have been carried out (Bao et al., 2000; Perrie et al., 2002; Zhao et al., 2006 etc). However, the fundamental mechanism how much influences of the flux change by the sea state (ocean wave) will occur is seldom investigated. It seems to be desirable to consider the wave development based on the interaction of the atmosphere and the sea since the source of development is the energy input from a wind.

Therefore, although there is the uncertainty about the wave dependability on flux now, it will be significant to investigate the impact on typhoon and wave intensity as a joint system with a weather-wave coupled model.

A change of drag coefficients makes the change of typhoon intensity due to frictional convection changes, this arises the change of wind field, and waves. And thus, we examined the sensitivity of ocean wave and typhoon condition as a coupled system, with the concern of variability by several formula of drag coefficient.

Although the decisive conclusion about the wave dependency on drag coefficients and its impact are not yet to obtained, the possibility in the present condition and its prospect, are reported.

In the following section, the outline of calculation is explained, the results of the sensitivity experiment by the model are provided in section 3, and discussion is in section 4. We end with our summary and future subjects in section 5.

2. NUMERICAL METHODS

2.1 Outline of the models

In our calculation is carried out by a weather-wave coupled model: the Non-Hydrostatic Model (NHM) of the Meteorological Research Institute / Numerical Prediction Division of JMA (Saito et al., 2001) as a weather model and the third generation wave model MRI-III (Ueno and Kohno, 2004) as a wave model.

Since the NHM is fully compressible model, the high resolution within 10km interval can be selected, and thus, we define the horizontal grid scale as 5km in our calculation, and there are 50 layers in vertical.

The grid resolution of the MRI-III is also se t as 5km in a Cartesian coordinate system. The wave spectrum consists of 900 components; 25 in frequency and 36 in direction. The frequency of spectral components are divided logarithmically from the minimum of f_{min} = 0.0375Hz to the maximum of f_{max} = 0.3000Hz.

The original NHM estimate the surface flux value with the scheme of Kondo (1975), and roughness length z_0 and the drag coefficient C_d are used implicitly, the sensitivity by the change of z_0 is very weak. Therefore, we modified to use the calculated value of z_0 directly in flux calculation.

The coupling scheme is the same way of two-way interaction by Janssen and Veturbo (1996) as is often used in a weather-wave coupled model. The physical parameters are exchanged every 20 minutes.

2.2 The drag coefficient formulae compared

Since there are so many formulae of drag coefficient (Jones and Toba, 2001) and it is impossible to check all of them, we selected several typical formulae used in our calculation.

The NHM default uses the drag coefficient Cd calculated by Kondo (1975). This is formulated by the wind velocity dependency only and is expressed using the 10m-height wind velocity U_{10} as follows:

$$Cd \times 10^3 = \begin{cases} 1.08U_{10}^{-0.15}, U_{10} \le 2.2 \\ 0.771 + 0.0858U_{10}, 2.2 < U_{10} \le 5.0 \\ 0.867 + 0.0667U_{10}, 5.0 < U_{10} \le 8.0 \\ 1.200 + 0.025U_{10}, 8.0 < U_{10} \le 25.0 \\ 0.073U_{10}, 25.0 < U_{10} \end{cases} \quad (1)$$

This formula shows linear increase of the drag coefficient in high wind (25.0 m/s) range and gives almost same value of classical Charnock constant (Charnock, 1955).

On the other hand, when wave dependency is taken into consideration in drag coefficient, the formula based on the wave induced stress by Janssen (1989) is mainly used in numerical simulations.

Janssen (1989) estimated energy dissipation by the additional stress by waves, and derived a formula.

$$\frac{gz_0}{u_*^2} = 0.010\left(1 - \frac{\tau_w}{\tau}\right)^{-1/2} \quad (2)$$

where, g indicates the gravitational acceleration, u_* shows a friction velocity. The total stress τ and the wave induced stress τ_w are calculated from a friction velocity and a energy input function S_{in} for waves as,

$$\tau = \rho_a u_*^2, \quad \tau_w = \rho_w g \int \frac{S_{in}}{C_p} df d\omega \quad (3)$$

where ρ_a and ρ_w indicate air and water density, C_p is the phase speed of waves. The wave induced stress is calculated from an energy input function of a wave model. In MRI-III, the energy input function is expressed as,

$$S_{in} = 0.32 \frac{\cos^3(\theta_W - \theta)}{|\cos(\theta_W - \theta)|} \left(\frac{u_*}{C_p}\right)^2 \cdot F(f, \theta) \quad (4)$$

where θ_w and θ indicate wind direction and direction of wave spectrum $F(f, \theta)$.

Since this method results in improvement of the estimation accuracy of the surface wind, besides it, the upper atmospheric pressure field was also improved (e.g. Janssen et al., 2002), this method is widely used: For example, the WAM model is coupled with the ECMWF weather models by this method.

In addition, the wave boundary layer model of Hara et al. (2004), which treats the energy dissipation in high frequency range in detail, has been proposed as extended scheme of this method recently, though we did not compare it this time.

Our knowledge is far from satisfactory level and so many formulae are proposed and discussed, because of plenty of problems such as observation errors, the difference of the measurement method etc, The mostly accepted formula should be that of Smith et al. (1992) based on the wave age dependency.

$$\frac{gz_0}{u_*^2} = 0.48\left(\frac{u_*}{c_p}\right) \quad (5)$$

However, there is still an inconsistency in wide-range formulation from the ocean to a laboratory tank, and this formula is mainly adaptable for windsea only. This may be a serious problem especially in case of a typhoon field where large swell often exists.

Recently Taylor and Yelland (2001) proposed a new formula based on the wave steepness instead of wave age.

$$\frac{z_0}{H_w} = 1200\left(\frac{H_w}{L_w}\right)^{4.5} \quad (6)$$

This formula seems to be easy to estimate the drag coefficient when sell is predominant, as well as windsea, of course we need further investigation.

Therefore, we checked the performance by three characteristic type of formula: (1) wave induced stress (hereafter refers as I), (b) wave age (hereafter refers as II), and (c) wave steepness (hereafter refers as III). The results are compared with the control run by the Kondo (1975) formula and one another.

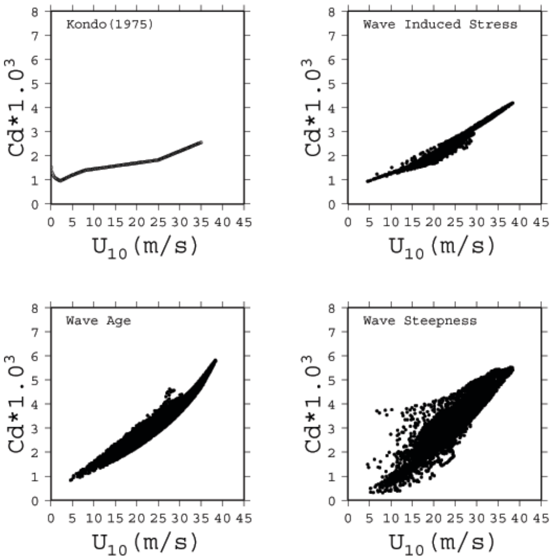

Fig. 1. The drag coefficient tendency calculated by the selected formulae.

In order to grasp the basic characteristics, the drag coefficients which calculated with the selected formulae are shown in Fig.1. We did not consider the interaction in this value and simply calculated the drag coefficient from wind speed and wave parameters.

There is a qualitative difference among the formulae, although the increasing tendency for drag coefficient accompanied by strong wind speed is commonly detected in all formulae. The formula of Kondo, used in the standard NHM, determines drag coefficients uniquely by velocity. Drag coefficients calculated by other three formulae tend to scatter in same wind speed due to the wave dependency. In the formula by wave induced stress, drag coefficients tend to scatter in middle wind speed range, by the resonance effect which wave induced stress and turbulent stress become comparable, but are determined almost uniquely in high wind speed. In case of wave age dependency, drag coefficients have a quadratic tendency to wind speed, and values become large in strong wind. In case of wave steepness dependency, a large spreading is detected in drag coefficients and the wind dependency seems to be rather weak, and drag coefficients tend to be saturated in strong wind conversely.

Although it is difficult to verify the validity of values since there is almost no measurement under a strong wind, the general tendency is almost same among them. However, since there is a new report that the observed drag coefficients become rather small in typhoon central field (Powell et al., 2003), the further verification is required.

3. CALCULATION RESULTS

Since our main concern is an impact of the roughness change by wave condition to wind-wave coupled system, we compare the drag coefficient firstly. Fig. 2 shows the horizontal distribution of drag coefficients at 05UTC on 20 Oct. by every calculation. This result comes from a coupled system, and thus, all of drag coefficients, surface winds, and wave condition changed under interactions. The time of drag coefficients plotted in Fig. 2 is 30 hours later from the calculation start, and these values should keep a balance.

According to Fig. 2 the drag coefficients calculated with wave dependency are larger than

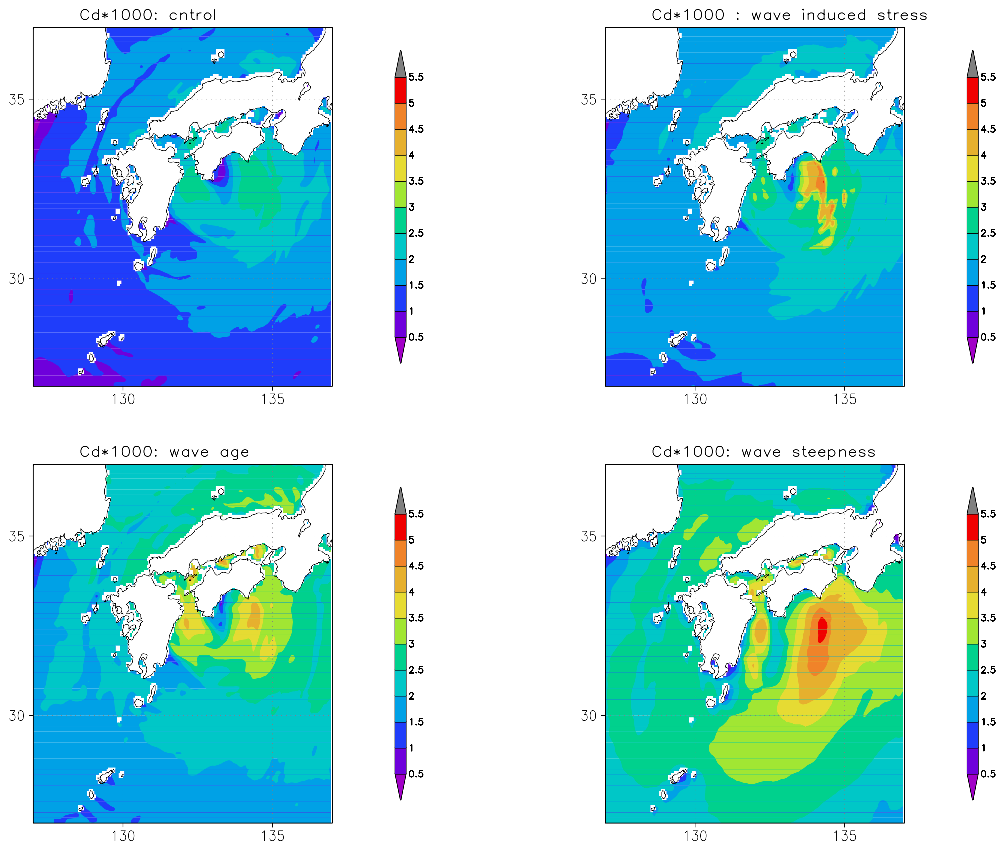

Fig. 2. The horizontal distribution of drag coefficients.

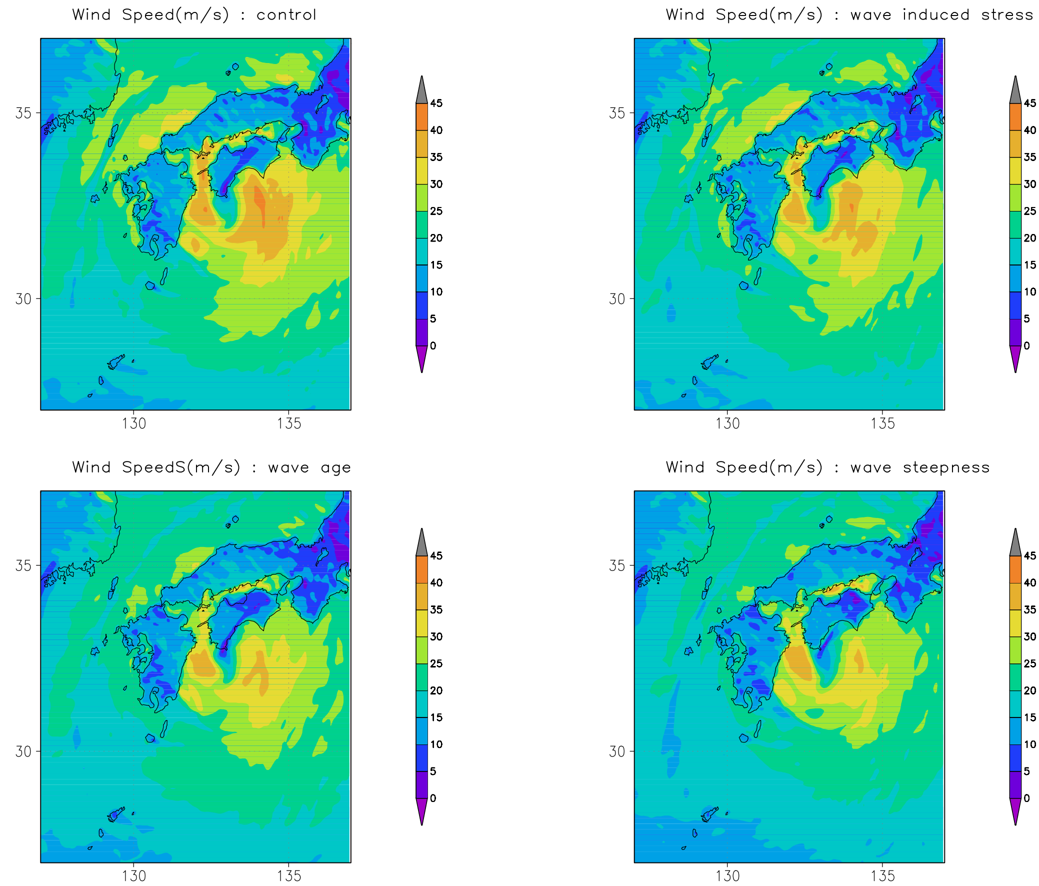

Fig. 3. The horizontal distribution of surface wind.

those by control run generally. Especially The calculation III shows large values in wide area and large values extended the rear part of typhoon, which may come from high swell. This tendency is slightly detected in cal. I, the large drag coefficient area locate at the right-hand side of typhoon centers, and elongate along the typhoon path. However, the area of high value of the drag coefficients in cal. I is not so widely spreading and only concentrated in the right-hand side of typhoon, the drag coefficients around typhoon are comparable to those in control run.

On the contrary, the drag coefficients by cal. II show similar distribution to the control run, though the value is large. The drag coefficients become decrease quickly in rear part of typhoon, since wind speed weakens after typhoon passes and wave age becomes old. Therefore the wave age dependency seems similar to the wind dependency in quality, except its values.

In order to check the influence of drag coefficients on surface wind, (sea) surface wind speeds at same time are shown in Fig. 3. It is acceptable that the wind speed in II and III are weaker than others, since the drag coefficients shown in Fig. 2 show very large values and thus surface wind should be weakened. In the case of cal. I, the wind speed is not so weak and almost same as the control run. Since the drag coefficients around typhoon in I is not so large, and wind speed is almost same as the control run. This means that the frictional convergence in lower layer should be maintained and the typhoon intensity should be kept, and thus, wind speed in central part does not weaken, even though wind is dissipated by large drag.

It is difficult to imagine the wind speed distribution since some parts are covered by lands, The wind speed in the control run tends to have a concentric circle shape. On the contrary, the wind speed becomes rather asymmetrical distribution when wave dependency is considered. The point of maximum wind is also different in calculations: It locates forward right in control run and cal. I but it

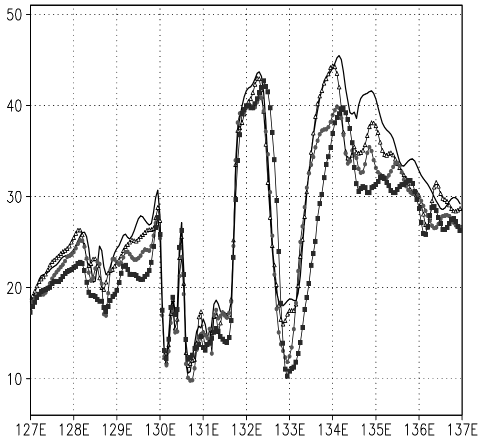

Fig. 4. Wind speed along the latitude 32.5N. The thick line shows control run, and line with triangles, circles, and blocks indicate the calculation of I, II and III respectively.

changes to rear right rear in cal. II. To tell the truth, the point of maximum wind is rather left-hand side in cal. II and III. This tendency is comes from the large dissipation in right-hand side by the large drag coefficients, and detected all calculation with wave dependency.

In order to check this character, wind speed along the latitude 32.5N around typhoon center is plotted in Fig. 4. The weak wind in western part (about 130E to 131.7E) is by land (Kyusyu Island) effect, but other area shows a typical wind profile around typhoon.

The typhoon center locates around 133E where wind speed is weak, and maximum winds locate about 132.3E and 134E.

It is notable that a large difference occurs in the wind speed of right-hand side of the typhoon between calculations by formula, although there is little difference in left-hand side.

Generally speaking, the right-hand side of typhoon is known as a ‘dangerous semicircle’, where strong wind blows and high waves generate. Therefore, the accuracy of wind in this area is crucial for correct estimation of ocean waves and disaster

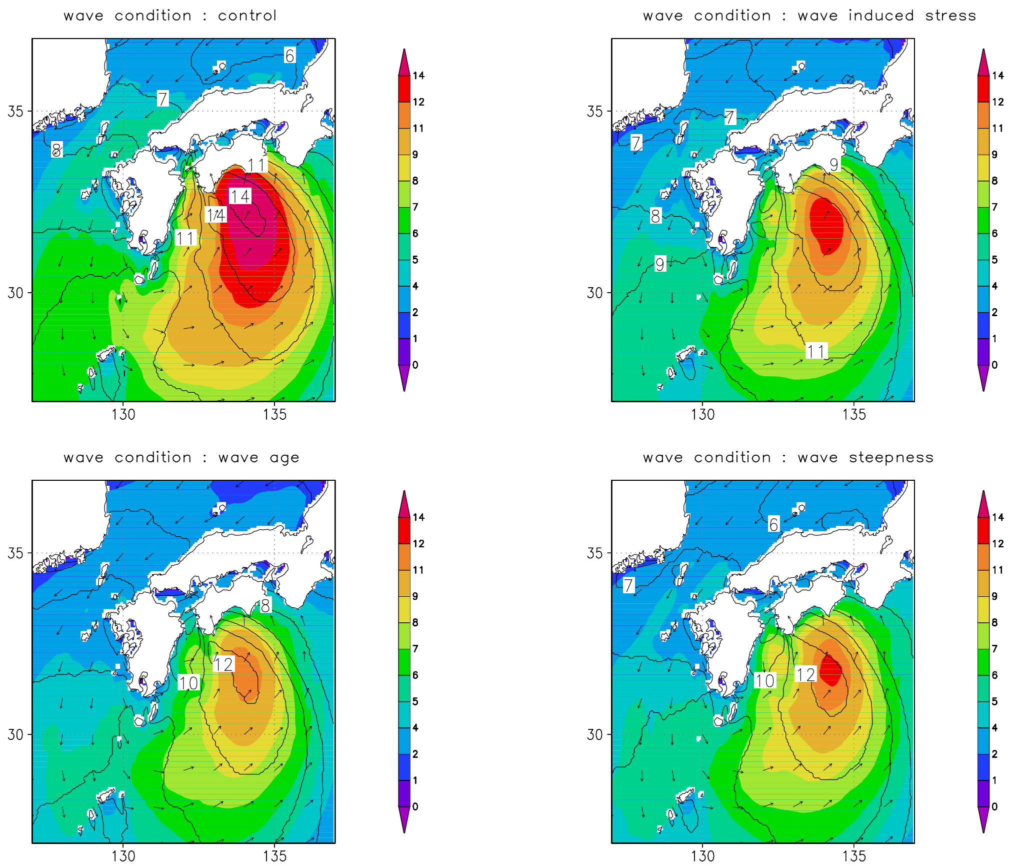

Fig. 5. The wave condition 05UTC on 20 October. The wave heights are shaded and contours show the wave period. The arrows show predominant wave directions.

prevention. This result indicates that there is still an uncertainty in deciding the wind field. Of course, there may be some problem in formulae of drag coefficient used in calculation, and thus, further researches should be necessary.

Since the drag coefficients with wave dependency tend to have large values, wind speeds become weaker than that of control run in general. The maximum wind speed of cal. I is not as weak as that of control run, but the difference is apparent in outer rain-band region (around 134.5E).The point of maximum winds of cal. II and III changes to left-hand side, since the wind in right-hand side become weak. It is also notable that the point of maximum wind in right-hand side shifted to outer side. This may lead to a change of a radius of strong wind and typhoon size, and may influence on wind field.

The wave condition is shown in Fig. 5. Though the surface wind fields are different between calculations as shown in Fig. 4, the general feature of wave fields is not so different, except in quantity. The wave heights calculated with wave dependency are also lower than the control run result, which is consistent with the tendency of weak wind speed in three calculations. The wave periods also show the same tendency in all calculation.

The point of maximum wave height is slightly different: the maximum in the control run locates the most northern point and the nearest to the Shikoku Island, but other peak phases seem to be delayed. This reason may come from the propagation speed of waves since higher waves in control run move faster toward north. It is interesting that the maximum wave height of cal. III is higher than cal. II though wind speed of III is weaker. Since the wave heights (and related parameters) interact with wind fields, and such inconsistency may happen temporary.

The calculated wave heights are compared with observation. There is a wave recorder at Murotomisaki, which locates in the south edge of Skikoku Island. The high waves by the right-hand side of Ty Tokage hit there and maximum wave height of 13.6m is observed at 05UTC on 20 Oct., which is quite a high value observed in the coast of Japan. This may partly because that the water depth around Murotomisaki is deep and the wave energy did not been decreased by bottom friction.

The observed wave heights and calculation results are drawn in Fig.6. The result show that wave heights by control run tends to be overestimated, though others are underestimated. It is difficult to decide the most proper simulation since the observed value is just the middle point between the control run and cal. I. The wave heights by cal. II and III show strong underestimation, but even this tendency may be modified if we tune up the coefficients. Therefore, we here only show the result, and do not judge.

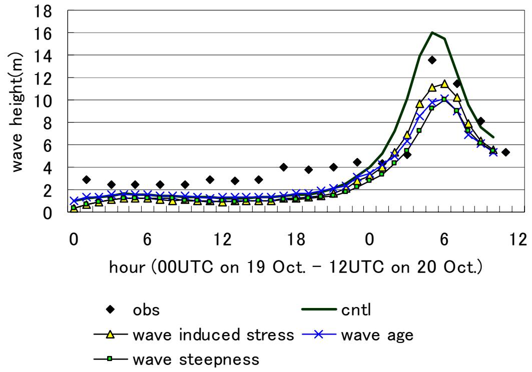

Fig. 6. The sequence of wave height. The diamonds show the observation and lines show the calculated wave heights.

4. DISCUSSION

Though we could not judge the most preferred formula, nor clear the interaction mechanism between winds and waves, the general tendency in our results is considered.

The drag coefficients become large in all calculations when the wave dependency is considered. The increase of drag coefficient may lead to two effects: one is that the wind speed is weakened by the large drag and the other is that wind becomes large by the intensification of typhoon since frictional convergence in lower level is promoted. All of our results supported the former mechanism.

The time scale of the former mechanism is much shorter than that of the latter, and wind should be directly weakened by the increased drag.

As for ocean waves, a large drag coefficient (that is large friction velocity) means large energy input from wind and we can expect a big development of wave. However, our results showed that, weakening of wind is quickly occurred before the wave development by large friction velocity and the calculated waves are rather lower than that of control run. This reason is that the wind is more changeable than ocean wave and is easily weakened. These results imply that the impact of roughness change by wave on wind seems to occur in short time.

Since the wave heights in the control run were overestimated, the decrease of wave height in other calculation may be not necessarily wrong. Especially, the case we simulated was about the developed typhoon which was gradually weakening, this may also lead to the result that the retarding effect on wind speed is remarkable.

Finally, we comment on the typhoon intensity. The time sequence of typhoon central pressures is plotted in Fig. 7. There is almost no difference between the control run and the cal. I, though other calculation showed large decay of the typhoon. The maximum difference of pressure is about 7hPa, and this value is not negligible. This large value seems to be sensitive to the value of drag coefficients, not the qualitative difference in formulation.

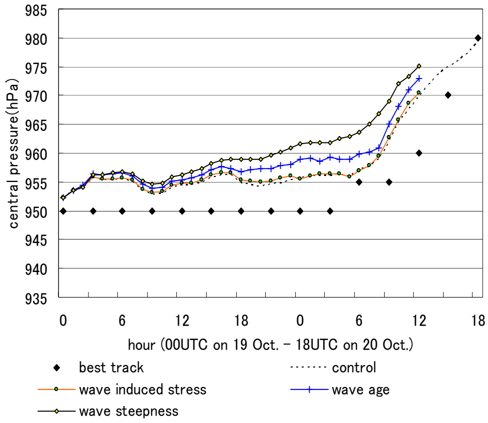

Fig. 7. Time sequence of central pressure from 00UTC on 19 Oct. to 18UTC on 20 Oct.

5. SUMMARY

We examined the impact of roughness dependency on waves to wave and atmospheric fields, by a wave-weather coupled model. Since our knowledge about this topic is far from satisfactory level, we just compare the results by some characteristic formulae for roughness length. Though there are still uncertain matters, we summarize our results:

1) The drag coefficients generally become large when the wave dependency is considered. The values of drag coefficient have a large scatter between formulae.
2) The weakening of wind speed by the increasing drag coefficient is systematically seen in all calculations. The surface wind field in a typhoon changed by the formula of drag coefficients, especially asymmetry in wind field is intensified.
3) The waves become low by decreasing wind speeds according with the increasing drag coefficients. The qualitative difference in wave field is not apparent in our calculation, though the wind field changes significantly.
4) According to our results, the change of roughness leads to the wind speed at first, since a wind easily changes than a wave or a typhoon system.
5) The difference of the central pressure of a typhoon between calculations arises as large as 7hPa and not negligible.

Although it is regrettable, our results are not yet confirmed, and further researches about this topic including a fundamental mechanism are necessary. In addition, there is a report that mentions that the drag coefficients in the strong wind region in typhoons become small conversely (Moon et al., 2004), and thus we are to consider the coupling mechanism further to clear this problem.

This is an important problem which is deeply related to the input of energy and development of waves, and thus, we want to advance investigation, although there are so many difficult problems to be solved.

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