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Sea Level Response in the Korea Strait to Typhoons

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A shallow water numerical model is established to investigate the response of coastal water in the Korea Strait to typhoons that pass nearby the Korea Strait. Atmospheric pressure and wind by Fujita's formula (1952) and Miyazaki *et al.* (1961), respectively are used in the model. The model results show an agreement fair with the observation partially, but poor with the amplitude of the sea level variation. In particular, the discrepancy is larger in a typhoon passing through right side than that through left side of the Korea Strait. The model showes that the disagreement between the model and the observation can be caused by numerically unrealistic distributions of armospheric pressure and wind around the strait. In the Korea Strait the isostatic effects in the model were underestimated, whereas the wind fields were overestimated.

INTRODUCTION

According to Hong and Yoon (1992, hereafter referred as HY), and Yi (1974) a sudden variation of sea level in the Korea Strait in summer occurs due to a passage of typhoon. In the observation HY investigated the sudden variation of the sea level for typhoons that enter the East Sea (the Japan Sea) through the Korea Strait (hereafter strait-passing typhoons) as shown in Fig. 1 (See HY's Fig. 3), and also could fairly successfully reproduce the sea level variation in a strait-passing typhoon (Fig. 2; See HY's Fig. 5 and 11). However, HY did not discuss for other paths of typhoons. In this paper We investigate the response of sea level in the Korea Strait to nearby-passing typhoons using sea level data and a shallow water numerical model.

Fig. 3 shows two types of typhoon paths in this study, i.e. the left hand side path (lhs) and the right hand side path (rhs) of the Korea Strait. We investigated the responses of the sea level variations of Korean side, Pusan, and the Japanese side, Izuhara and Hakata to two track's typhoons above during the periods of 1966-1986. The results of numerical experiment are presented for typhoons with two different tracks. This study will complement the results for the strait-passing typhoons obtained by HY and will give a comprehensive understanding of the response of sea level elevation in the Korea Strait to typhoons.

NUMERICAL MODEL

The model is based on shallow water equations in the spherical coordinate (Gill, 1982). The basic equations consist of momentum equations,

$$\frac{\partial U}{\partial t}+\frac{1}{a\cos\phi}\frac{\partial(uU)}{\partial\lambda}+\frac{1}{a\cos\phi}\frac{\partial(uV\cos\phi)}{\partial\phi}-\frac{uV}{a}\tan\phi-fV=-\frac{gH}{a\cos\phi}\frac{\partial(\eta-\eta_0)}{\partial\lambda}+\frac{\tau^{\lambda}}{\rho}-F^{\lambda}+T^{\lambda} \tag{1}$$

$$\frac{\partial V}{\partial t}+\frac{1}{a\cos\phi}\frac{\partial(vU)}{\partial\lambda}+\frac{1}{a\cos\phi}\frac{\partial(vV\cos\phi)}{\partial\phi}+\frac{uU}{a}\tan\phi+fU=-\frac{gH}{a}\frac{\partial(\eta-\eta_0)}{\partial\phi}+\frac{\tau\phi}{\rho}-F^{\phi}+T^{\phi} \tag{2}$$

and continuity equation

$$\frac{\partial\eta}{\partial t}+\frac{1}{a\cos\phi}\frac{\partial U}{\partial\lambda}+\frac{1}{a\cos\phi}\frac{\partial(V\cos\phi)}{\partial\phi}=0 \tag{3}$$

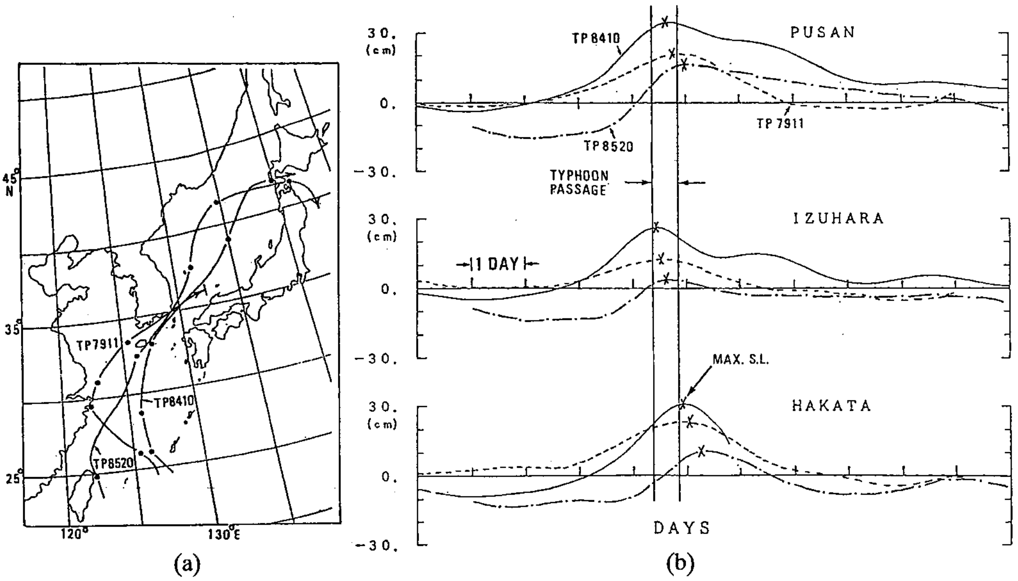


Fig. 1. (a) Tracks and (b) time series of hourly sea levels of the strait-passing typhoons, TP7911, TP8410, and TP8520. The black circles on the tracks represent the positions of typhoons at 0900 local time every day, two parallel solid lines a period of typhoon passing, and cross marks the peaks of sea level (refer to HY's Fig. 3).

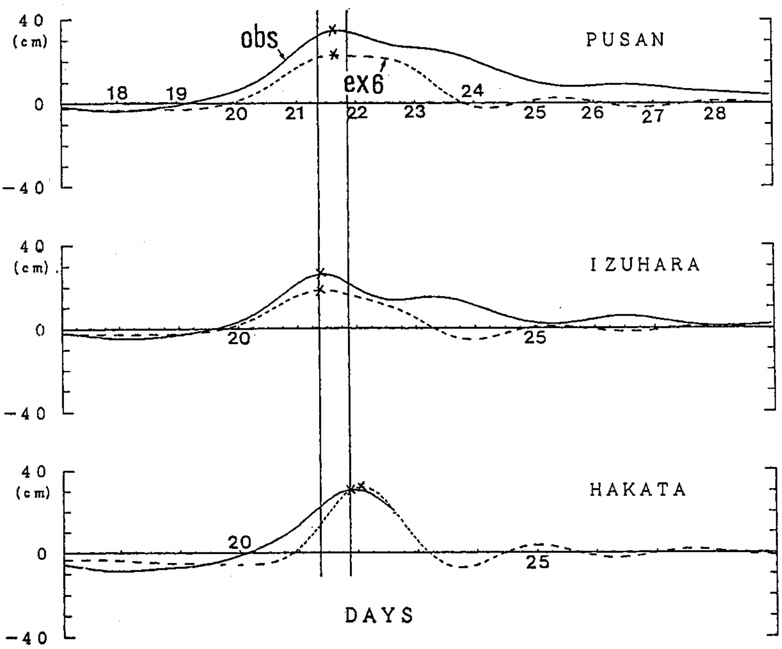
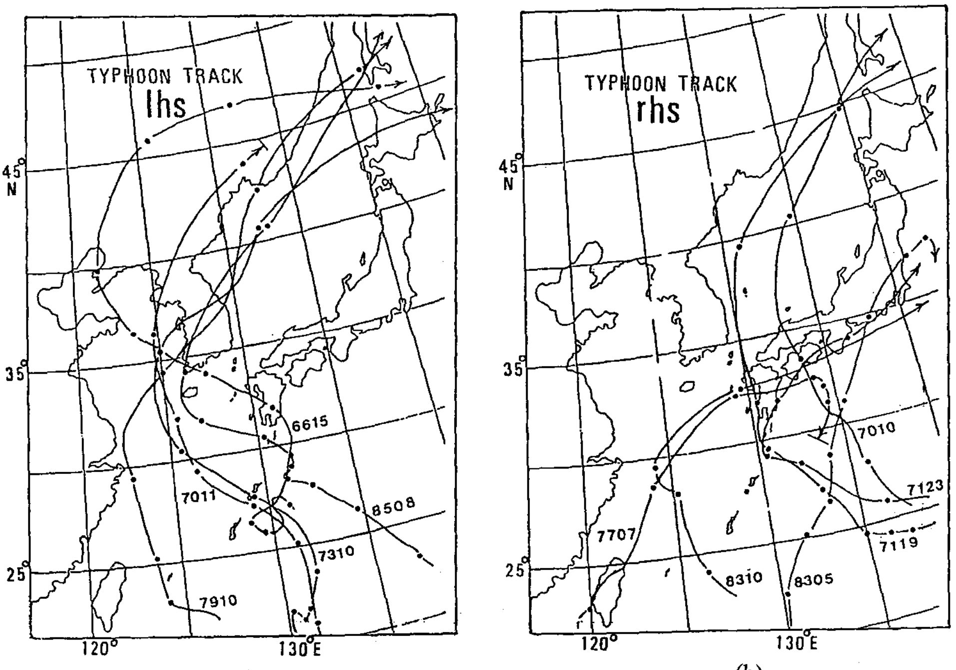


Fig. 2. As in Fig. 1 except a comparison of the model with the observation for TP8410 (refer to HY's Fig. 5 and 11).

where (u, v) are the velocity components in the longitudinal (λ) and latitudinal (ϕ) directions, respectively, η the sea surface elevation, a the earth's radius, $H=h+\eta$ the water depth, h the depth from mean sea level to bottom, ρ the density, f the Coriolis parameter, g the gravitational acceleration,



(a) (b)

Fig. 3. The tracks of typhoons passed to the left (a) and to the right (b) of the Korea Strait during 1966-1986. The numerals assigned to the points on the track indicate the center pressure, day, and time.

η_0 the isostatic elevation given by $\eta_0 = -\delta P/\rho g$. The $(\tau^\lambda, \tau^\phi)$ and (U, V) are (λ, ϕ) components of wind stress and the volume transports, (F^λ, F^ϕ) and the horizontal viscosities (T^λ, T^ϕ) are given by

$$(F^\lambda, F\phi) = \gamma(u,v)\sqrt{u^2+v^2} \tag{4}$$

$$T^\lambda = A_h H\left(\Delta u - \frac{1}{a^2\cos^2\phi}u - \frac{2}{a^2\cos^2\phi}\frac{\partial}{\partial\lambda}(v\sin\phi)\right) \tag{5}$$

$$T^\phi = A_h H\left(\Delta v - \frac{1}{a^2\cos^2\phi}v + \frac{2\sin\phi}{a^2\cos^2\phi}\frac{\partial u}{\partial\lambda}\right) \tag{6}$$

respectively, where γ is a bottom friction coefficient, A_h horizontal eddy viscosity coefficient, operater Δ given by

$$\Delta = \frac{1}{a^2\cos^2\phi}\frac{\partial^2}{\partial\lambda^2} + \frac{1}{a^2\cos^2\phi}\frac{\partial}{\partial\phi}(\cos\phi\frac{\partial}{\partial\phi}). \tag{7}$$

Values of 2.3×10^{-4} and 10^7 cm^2 s^{-1} were used for γ and A_h, respectively. The bottom topography data with resolutions of $1/12^\circ\times1/12^0$ obtained from the Japan Oceanographical Data Center is used. The model ocean covers the East China Sea, the Yellow Sea, and the East Sea (see HY's Fig. 2). Normal velocity components to coastal boundary are set to be zero. In the experiment with an open boundary, a radiation condition (Hearn *et al.*, 1990), as an open boundary condition, is used by

$$u = \frac{\sqrt{gH}}{H}(\eta - \eta_0) \tag{8}$$

which is a normal velocity component to the open boundary. Under this condition, although other waves such as topographic Rossby waves, would not propagate well, gravity waves propagate well outward of the model ocean (Chapman, 1985). The model runs on initial condition with (u, v) and $\eta = 0$. Atmospheric pressures and winds by Fujita's formula (1952) and Miyazaki *et al.* (1961), respectively are used. The detailed description of the model is given by HY.

In the analysis of data we firstly investigated the

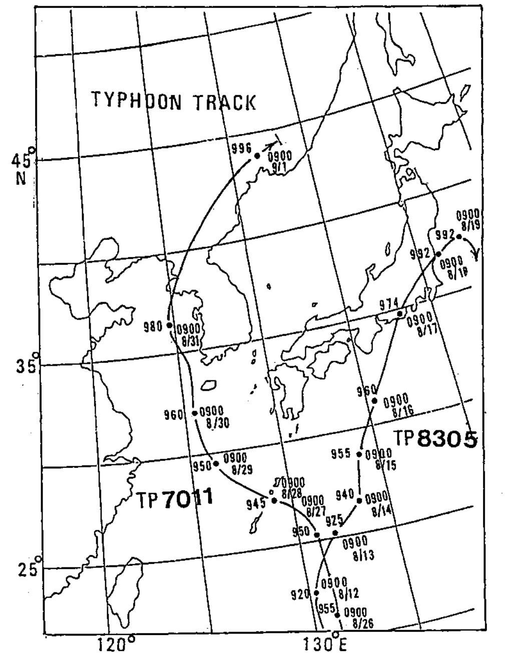


Fig. 4. The tracks of the model typhoons. (a) TP7011 and (b) TP8305.

responses of the sea level variations of Pusan, Izuhrar and Hakata to typhoons except the strait-passing typhoons during the periods of 1966-1986. However, because of variety of the tracks of the typhoons, we could not find common features between the sea level variations and the typhoon tracks, such as obtained by HY for the strait-passing typhoons. Thus we selected TP7011 (lhs) and TP8305 (rhs), as model typhoons (Fig. 4). The symbol, e.g. TP7011 indicates the 11th typhoon in 1970. Advantages to select them were to be able to obtain observed sea level data without a loss in the Korea Strait in passing period of the typhoons. Their tracks seem to be typical of each type as shown in Fig. 4.

RESULTS

The results of the model are compared with the observed sea level variations in Pusan, Izuhara, and Hakata in the Korea Strait.

Fig. 5 shows the time series of sea level variation

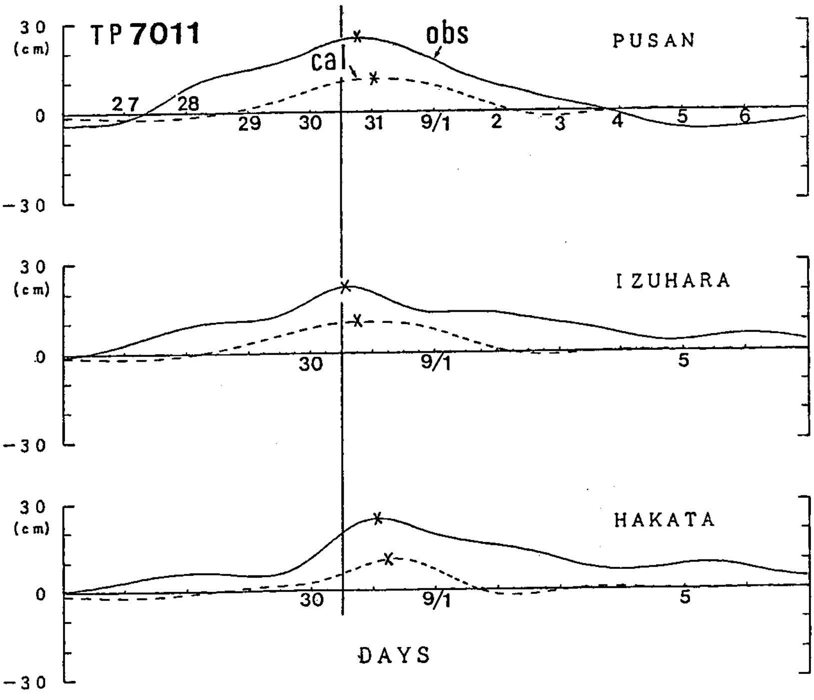


Fig. 5. The time series of sea level variation in the model (broken lines) and the observation (solid lines) at Pusan, Izuhara, and Hakata in TP7911. A vertical line and crosses indicate closely passing time of the typhoon to the Korea Strait, and the time of maximum sea level, respectivly.

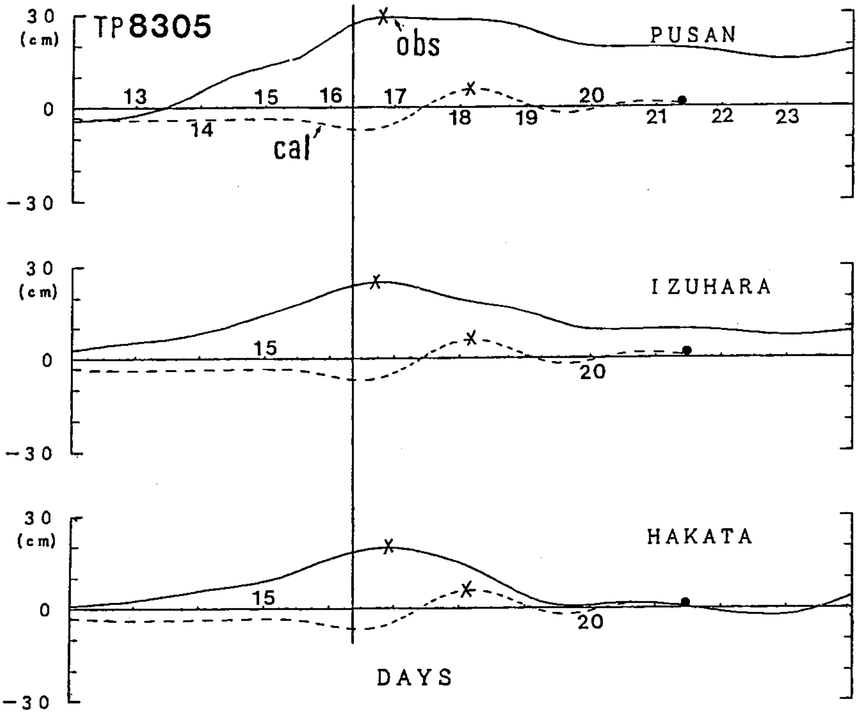


Fig. 6. As in Fig. 5 except for TP8305.

in TP7011 for about ten days. A vertical line indicates the time when the typhoon was the closest to the Korea Strait. The model (dashed line) corresponds well to the observation (solid line) in the time of the maximum sea level (cross mark) and an oscillation appearing after passing of the typhoon to the strait, as shown in HY. However the absolute values of each amplitude are far from coincidence, i. e. the model is much smaller than the observation. The tendency for TP8305 (Fig. 6) is totally worse than for TP7011. The experiments (here not presented) indicate that the discrepancy between the observation and the model tends to be larger in the typhoons passing to the right of the Koreat Strait, such as TP8305. A number of experiments were carried out to find causes of the disagreement. Here we give the case of TP8305, as a typical instance for the analysis because the results of other experiments basically show asimilar tendency to this case.

The result of an experiment using the open boundary condition is given in Fig. 7. The conditions of experiment are the same as Fig. 4 except for having an open boundary. The amplitude of the sea level varation has increased about 10 cm than that with the close boundary. In TP8410, the strait-passing typhoon, the similar result to TP8305 was also given (see Fig. 21 of HY).

Fig. 8 gives a comparison of model elevations (broken lines) with isostatic sea level elevations (black circles). The isostatic elevations were obtained by difference between the calculated atmospheric pressure and the ambient pressure (1010 hpa) (theoretically at infinite radius, however, in practice, the value of the first anticyclonically curved isobar is used) (Hearn *et al.*, 1990). The difference between them is about 10 cm, especially during closely appoaching period to the Korea Strait, i. e. the model elevation by isostatic effect was underestimated during the period. In the experiments, the pressures obtained by Fujita's formula (1952) corresponded well to the observation within the vicinity of typhoon's core (about 100~150 km). As an

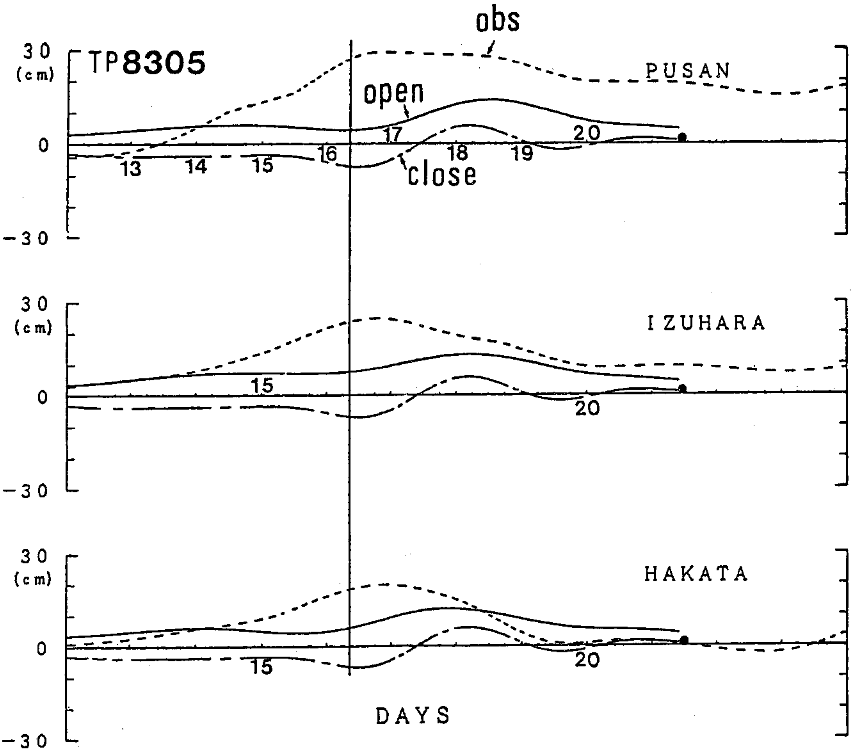


Fig. 7. As in Fig. 6 except for giving an open boundary condition. The curves indicate the result of experiment with open boundary condition (solid lines), with closed boundary condition (broken lines), and the observation (dotted lines).

example, Fig. 9 gives a comparision of atmospheric pressure (Fig. 9a), wind speed (Fig. 9b), and wind vector (Fig. 9c) in the model with a weather chart at 0900 local time August 20, 1984 (refer to HY's Fig. 6). However, since the Korea Strait is about 500 km distant from the center of TP8305, it seems difficult to obtain atmospheric pressure data in the model corresponding to the observation. If we give a good atmospheric pressure distribution and the open boundary condition in the model, the amplitude of the sea level will increase about 20 cm and approach to 70~80% of the observation.

The wind fied of the model also seems to be the cause of the disagreement. The wind components at Hakata are given in Fig, 10, and the model and the observation by open circles and by closed circles, respectively. During the typhoon passing period closed to the Korea Strait (Aug., 13~18) the observed wind speed at east-west direction (upper panel) was almost zero, but the model wind speed was about 5~8 m/s. Especially, the north-south components (lower panel) of the model (about 13~14 m/s) are about 2 times the observation (7~8 m/s except daily variation) during the period. If the northeasterly wind stronger than that of the observation blows continuously for several days untill the typhoon closely approaches to the Korea Strait, the sea levels in the East Sea and the strait will decrease by a lot of mass transport from the East Sea to open ocean. The sea level of the model in the strait is lower than the observed level may be caused by the overestimated wind of the model blown during the typhoon passing period closed to the Korea Strait. Here, to obtain an insight concerned with an effect of wind on decrease of the sea level in the strait, we assumed that the width and the depth in the Korea Strait are 100 km and 100 m, respectively, the surface area of the East Sea is 700

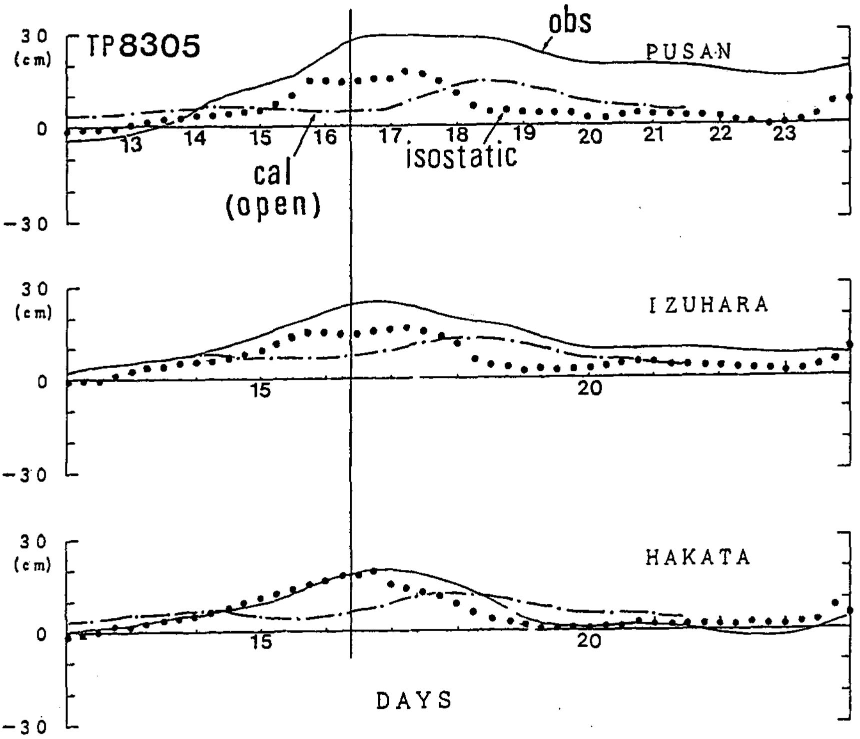


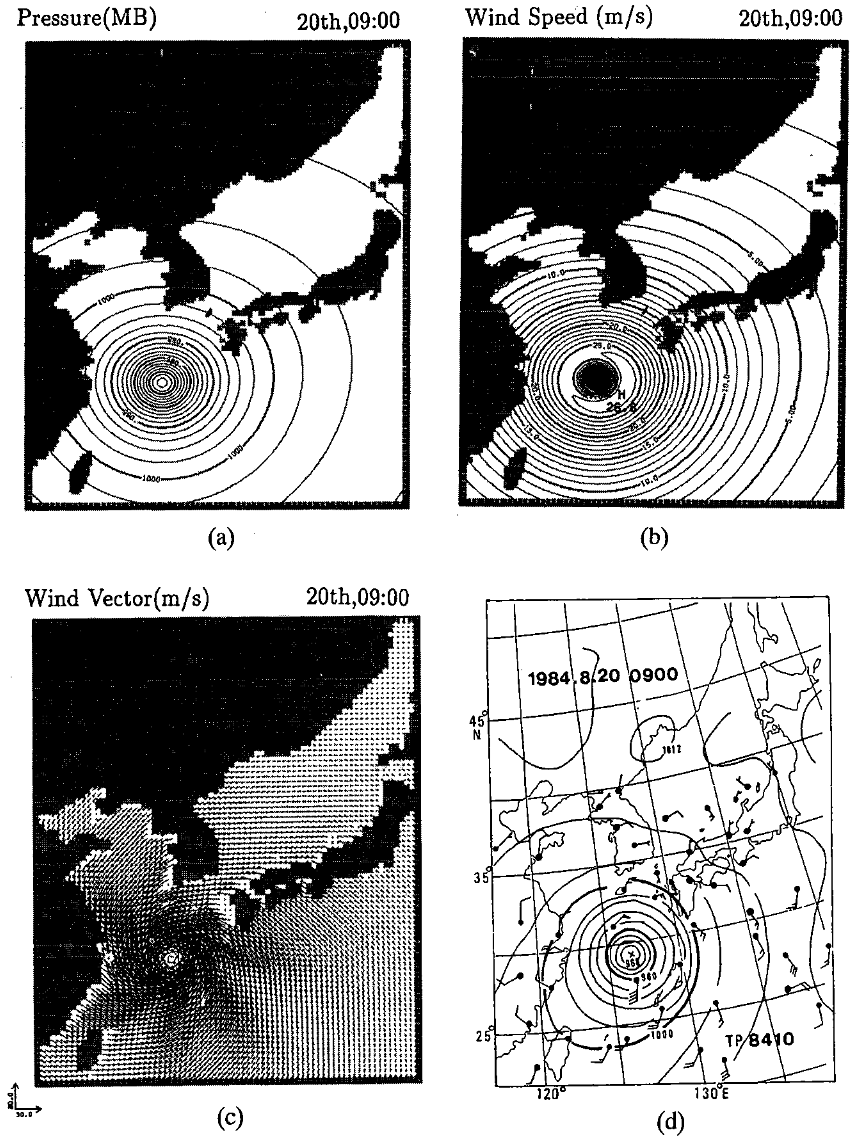
Fig. 8. The isostatic sea level elevations (closed) produced by the atmospheric pressure field of the model, model elevation (broken lines), and the observation (solid lines).

km × 700 km, and the Tsugaru and Soya Straits are closed. If under these assumption a steady current with 10 cm/s by a wind flows out through the strait, The drop of the sea level in the East Sea will be 2.0 × 10^{-4} cm/s, i.e. 17~18 cm/day. Of course, in reality two straits are open. However, since both of them are shallow and narrow, the pressure depression due to friction effect will be probably large. Under this condition the straits may be regarded as close boundaries to some extent.

In TP8410, the strait-passing typhoons, the trend of wind field was also similar to TP8305 as given in Fig. 11. In the amplitude of elevations in TP8410 (see Fig. 11 of HY), however, a good result corresponding to the observation was obtained This may be caused by the track of TP8410, i.e. since the wind direction in the typhoon is reversed after passing through the Korea Strait, the decrease of the sea level by mass transport from the East Sea to open ocean does not continue for a long time. Similarly, we can understand that the correspondence of TP 7011 to the observation (Fig. 5) was better than that of TP8305. The present study indicates that the model results including an open ocean might be greatly influenced by the design of the model typhoon.

CONCLUDING REMARKS

A shallow water numerical model was established to investigate the response of coastal water in the Korea Strait to the typhoons that pass nearby the strait. Although the model results shows fair agreement with observation partially, but the amplitude of the sea level variation shows poor agreement. In particular, the discrepancy is larger in a typhoon passing through right side than that through left side of the Korea Strait. The results of experiments to find a cause of the discrepancy give us an insight to improve the model typhoon. The distributions of atmospheric pressure and wind obtained by Fujita's



(a) (b) (c) (d)

Fig. 9. (a) Pressures (mb), (b) wind speed (m/sec), and (c) wind vectors (m/sec) of TP8410 in the model. (d) Weather map at the same time (refer to HY's Fig. 6).

formula (1952) and Miyazaki *et al.* (1961), respectively, did not correspond to the observation except for the vicintiy of the center of typhoons. In the Korea Strait the isostatic effects in the model were underestimated, whereas the wind field were overestimated. On the other hand most of previous studies investigating the effect of typhoons in a bay (or in a coastal area), e.g. Hearn *et al.* (1990) or Konishi (1989), have obtained good numerical results. Because their objectives were to investigate a response to typhoons passing across a small bay (or coastal region) in which the variation of the typhoon in time and space is small. However, the Korea Strait, the study area in this paper, was too distant (above 500 km) from the track of the model typhoon.

Consequently, we could not obtain a good num-

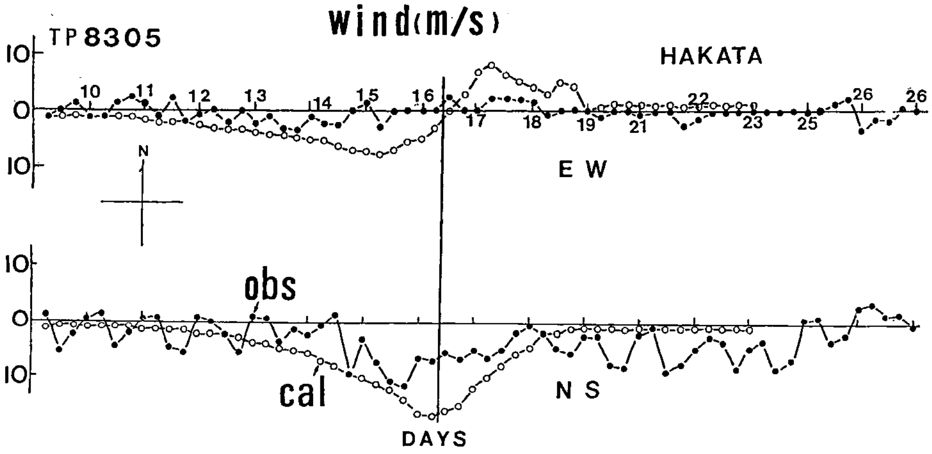


Fig. 10. The wind components of east-west (upper panel) and south-north (lower panel) at Hakata in TP8305. The model is indicated by open circles and the observation by closed circles.

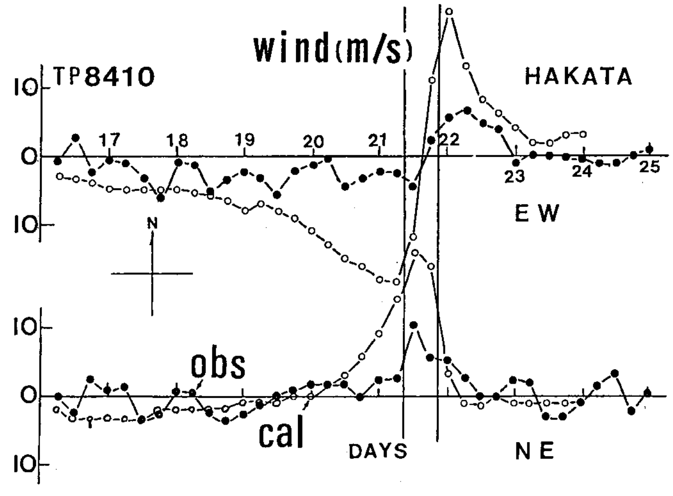


Fig. 11. As in Fig. 10 except for TP8410.

erical solution for typhoons except for the strait-passing typhoons. This indicates that the numerical results seriously depend on track of typhoon, as well as establishment of the model typhoon.

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