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Atmosphere–Ocean–Wave Coupled Model Performing 4DDA with a Tropical Cyclone Bogussing Scheme to Calculate Storm Surges in an Inner Bay

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Typhoon MELOR struck Ise Bay in Japan on October 2009, creating one of the largest storm tides on record—-a storm tide of 2.6 m—-observed at Mikawa Port. Correct evaluation of sea surface winds must be done to produce highly accurate calculation of the storm surge generated by that typhoon. An atmosphere–ocean–wave coupled model performing four-dimensional data assimilation with the tropical cyclone bogussing scheme (4DDABS) was developed for accurate reproduction of the sea surface winds and the storm surge related to the typhoon. Its validity and utility were verified by comparing the observed results with those computed according to the typhoon tracks, wind speeds, and storm tides. Comparisons revealed that the calculated results obtained using the coupled model with the 4DDABS show good agreement with the observed data of the storm surge generated by typhoon MELOR (2009).

Keywords: Storm surge; Typhoon; Numerical simulation; Four-dimensional data assimilation; Tropical cyclone bogussing scheme.

1. Introduction

Typhoon MELOR struck Ise Bay in Japan on October 2009, creating one of the largest storm tides ever recorded. That storm tide of 2.6 m was observed at Mikawa Port, located at the eastern inner part of Ise Bay. The storm surge disaster set 100 or more containers adrift in the container yard.

Such storm surge disasters in inner bays are worried to increase and intensify because of global warming.[1,2] Therefore, countermeasures against the storm surges become more important. An elucidation of the spatial distribution of the maximum tidal level due to the storm surge is needed to enable the effective countermeasure against the storm surge. This is because risk management for the storm surges such as safety assessment of coastal structures, damage reductions, production of hazard maps, land-use control, disaster education and so on, is performed based on the information of the spatial distribution of the maximum tidal level.

Since a field observation of the storm surge is very dangerous and difficult, spatial resolution of the observational data is not clear enough to elucidate the spatial distribution of the maximum tidal level. On the other hand, a numerical simulation enables us to obtain detailed data of the storm surge although it may include a computational error. Therefore, the development of a numerical model that can reproduce accurately storm surges in inner bays is strongly required to elucidate the spatial distribution of the maximum tidal level and thereby enable the effective countermeasures against storm surges.

Correct evaluation of sea surface winds affected by complicated coastlines and landforms surrounding inner bays must be done to produce highly accurate calculations of storm surges in inner bays. Conventional simulations for storm surges have used parametric typhoon models such as those presented by Schloemer[3] and others, or meteorological models with a tropical cyclone bogussing scheme[4] to calculate sea surface winds. However, the former parametric typhoon models are inadequate for physical evaluation of the roughness effects of complicated coastlines and landforms and three-dimensional effects of the meteorological field on the sea surface winds. For the latter meteorological models, the track and structure of the typhoon can not be reproduced correctly as time progresses because the tropical cyclone bogussing scheme is applied only to the initial field of the meteorological models and cannot control the track. Therefore, it is impossible to calculate sea surface winds accurately using those models.

For this study, a meteorological model MM5[5] performing four-dimensional data assimilation with the tropical cyclone bogussing scheme (4DDABS) was constructed to resolve the problem described above. An atmosphere–ocean–wave coupled model using a coastal ocean current model CCM[6] and a wave model SWAN,[7] together with MM5 performing the 4DDABS, was developed to regenerate the storm surge caused by Typhoon MELOR (2009) in Ise Bay. The calculated results obtained using the coupled model performing the 4DDABS are compared with the observed data. Then they are compared with the calculated results of the storm surge using the conventional parametric typhoon model and the MM5 with the usual tropical cyclone bogussing scheme.

2. Model Descriptions

2.1. *Four-dimensional data assimilation with tropical cyclone bogussing scheme*

In the initial field of the meteorological model, correct reproductions of the steep distribution of the strong winds and the atmospheric pressure generated by the typhoon are extremely important to perform highly accurate typhoon calculations. Analytical data such as NCEP global analyses (1-degree resolution) have been used as the initial field of the meteorological model. However, the steep distribution of the strong winds and the atmospheric pressure are not reproduced in the analytical data because of the coarse resolution of the data. Tropical cyclone bogussing schemes were presented to mitigate this problem. A bogus vortex that correctly reproduces the steep distribution of the strong winds and the atmospheric pressure is added to the initial field by the bogussing schemes.

The tropical cyclone bogussing scheme used for this study is the scheme presented by Ohsawa *et al.*,[8,9] constructed as follows. (1) Based on the central pressure, size, and the environmental pressure, the radial surface pressure distribution is defined using the formula reported by Fujita.[10] (2) The radial distribution of D-values is defined by analytical functions. (3) From the D-values, the wind field at each level is obtained from the gradient wind equation. (4) To compensate for the wind field asymmetries associated with steering, the geopotentials are recomputed from the asymmetric wind field using the nonlinear reverse balance law.

As described previously, the tropical cyclone bogussing scheme suffers from its inability to control the typhoon track as time progresses because the bogussing scheme is applied only to the initial field of the meteorological model. Therefore, we performed 4DDABS, which adds the bogus vortex not only to the initial field, but also to the analytical data for the four-dimensional data assimilation. The 4DDABS methodology is the following.

(1) Analytical data for one-hour interval are estimated using the interpolating NCEP global analyses (6 hr time resolution).
(2) The bogus vortexes are added to all analytical data using the aforementioned tropical cyclone bogussing scheme.
(3) Four-dimensional data assimilation is performed based on the nudging method. The values of the difference between the analytical data including the bogus vortexes and the calculated values of the meteorological model add to the time-dependent equations related to the wind speed, air temperature, and mixing ratio as external force terms in each time step.

2.2. *Atmosphere–ocean–wave coupled model*

The atmosphere–ocean–wave coupled model performing the 4DDABS to calculate the storm surge is constructed using the MM5 meteorological model, the CCM ocean model, and the wave model SWAN. Figure 1 portrays a calculation diagram of the coupled model performing the 4DDABS.

In fact, MM5 is a non-hydrostatic, fully compressible primitive equation model designed to simulate complex mesoscale meteorological phenomena of approximately a few to several hundred kilometers. It can therefore physically evaluate the roughness effects of the complicated coastline and landform, the

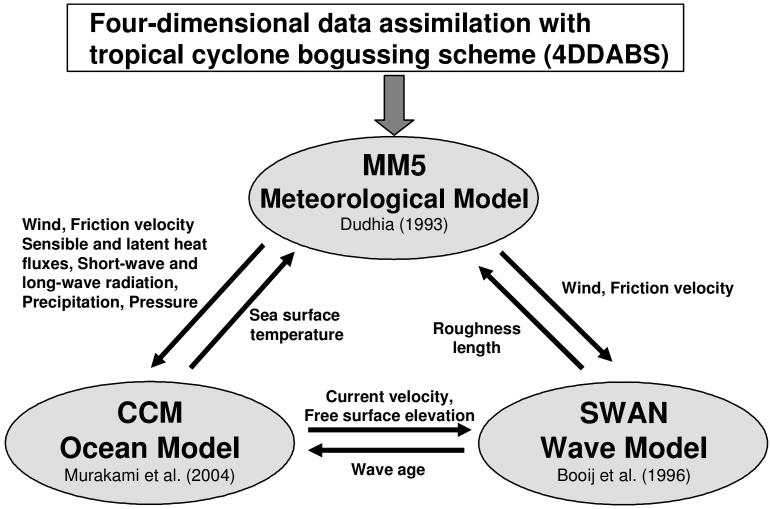

Figure 1 Schematic diagram of the atmosphere–ocean–wave coupled models used for the 4DDABS.

three-dimensional effects of the meteorological field on the sea surface winds, and so on. The 4DDABS described above is performed in MM5 of the coupled model.

The Coastal ocean Current Model (CCM) is characterized by adoption of a multi-sigma coordinate system developed by Murakami *et al.*,[3] although it is a primitive ocean model. The multi-sigma coordinate system supports the accurate calculation of inflow rates of seawater from offshore, which greatly influences the storm surges occurring in the inner bays.[11]

A sophisticated third-generation time-dependent spectral wave model designed for the near-shore to offshore zone, SWAN, can effectively simulate wave generation and propagation attributable to local winds.

3. Calculation Methods

3.1. *Simulation using the coupled model performing the 4DDABS*

A simulation is performed to reproduce the storm surge caused by Typhoon MELOR (2009) in Ise Bay. The inner bay area is surrounded by a complicated coastline and landforms, as presented in Figure 2. The calculation using the coupled model with the 4DDABS is made based on the configuration presented in Table 1; it is designated as Case 1.

3.2. *Simulation using the parametric typhoon model*

A calculation of sea surface winds using the conventional parametric typhoon model instead of MM5 is performed to demonstrate that the conventional model is

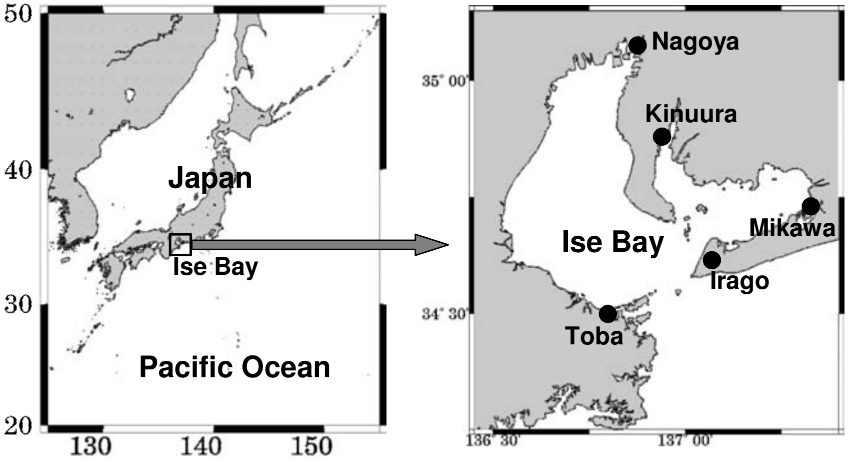

Figure 2 Ise Bay and locations of observation stations.

insufficient to evaluate the sea surface winds. The parametric typhoon model used for this study is Fujii and Mitsuta's model,[15] which consists of a gradient wind equation, Schloemer's pressure distribution,[1] and Blaton's formula.[16] The storm surge is calculated by inputting the distributions of the sea surface winds and the atmospheric pressure, as obtained from the parametric typhoon model, into CCM; it is designated as Case 2.

3.3. *Simulation using the coupled model without the 4DDABS*

Furthermore, the third calculation is performed using the coupled model without the 4DDABS. In this calculation, the 4DDABS is not used, but the usual tropical cyclone bogussing scheme, which is applied only to the initial field of the MM5, is used to demonstrate that the typhoon track cannot be reproduced correctly as time progresses. It is designated as Case 3.

4. Results and Discussion

For comparison, Figure 3 depicts the typhoon tracks generated using observed and calculated data for Cases 1, 2, and 3. The calculated value of Case 2 is identical to the observed one because the parametric typhoon model uses the observed typhoon track as the input data. Results show that the usual tropical cyclone bogussing scheme of Case 3 suffers from a large computational error and cannot control the typhoon track. In contrast, the calculated value of Case 1 agrees well with the observed one. These results demonstrate that the use of 4DDABS is indispensable to reproduce the typhoon track with high accuracy.

Table 1 Model configuration used in Case 1.

Coupled model	Period	0:00 a.m. 7 Oct. through 0:00 p.m. 8 Oct. in 2009
4DDABS	Input data	Best track data (Japan Meteorological Agency)
	Data for 4DDA	NCEP global analyses
	Time resolution	1 hour
	Nudging coefficient	1.0×10^{-4}
Meteorological model (MM5)	Calculation domain (two-way nesting)	Region 1: 23.4–39.3°N, 127.3–142.5°E Region 2: 33.9–35.3°N, 135.9–137.7°E
	Horizontal resolution	Region 1: 9 km Region 2: 3 km
	Number of horizontal grids	Region 1: 199 × 160 Region 2: 52 × 52
	Vertical levels	Region 1: 24 Region 2: 24
	Time step	Region 1: 30 s Region 2: 10 s
	Physical parameterizations	Planetary boundary layer: Blackadar scheme[12] Cloud Physics: Reisner graupel scheme[13]
	Initial and boundary conditions	NCEP global analyses
Ocean model (CCM)	Calculation domain (one-way nesting)	Region 1: 30.0–35.4°N, 130.7–138.9°E Region 2: 34.2–35.1°N, 136.5–137.3°E
	Horizontal resolution	Region 1: 2.6 km Region 2: 0.8 km
	Number of horizontal grids	Region 1: 199 × 160 Region 2: 52 × 52
	Number of regions in multi-sigma	Region 1: 7 Region 2: 7
	Total number of layers	Region 1: 40 Region 2: 40
	Time step	Region 1: 10 s Region 2: 5 s
	Initial and boundary conditions	Observed data (Sekine, 1996)[14]
Wave model (SWAN)	Calculation domain	34.2–35.1°N, 136.5–137.3°E
	Horizontal resolution	0.8 km
	Number of horizontal grids	99 × 97
	Time step	150 s

Figure 4 presents distributions of the wind velocity vectors of Cases 1, 2, and 3 at 8:30 p.m. on October 7. As portrayed in Figure 4(b), the wind velocity vectors calculated using the parametric typhoon model of Case 2 are distributed uniformly around concentric circles. This distribution shows that the roughness effects of the complex land topography were not reflected in the wind velocities of Case 2. The meteorological model MM5 can evaluate roughness effects of the complicated coastline and landforms and the three-dimensional effects of the axis-asymmetrical meteorological field of the typhoon on the sea surface winds. Consequently, the

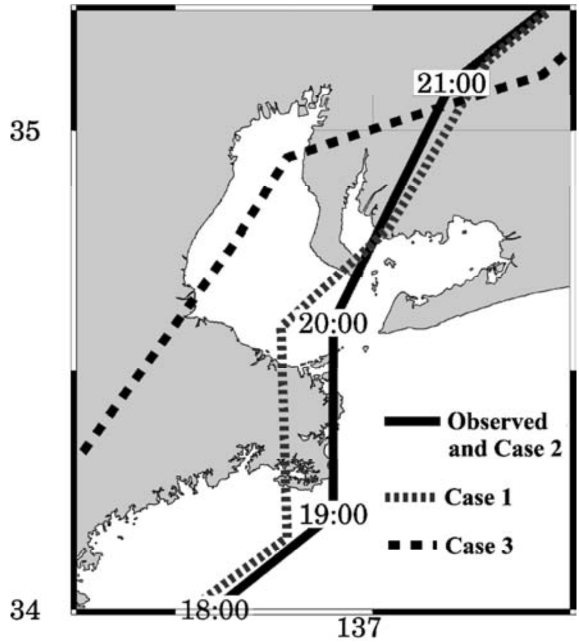

Figure 3 Calculated and observed typhoon tracks for Cases 1, 2 and 3: The calculated value of Case 2 is identical to the observed one because the parametric typhoon model uses the observed typhoon track as the input data.

wind velocity vectors of Cases 1 (Figure 4(a)) and 3 (Figure 4(c)) are not distributed uniformly around concentric circles as they are in the distribution of Case 2. Furthermore, they have spatial variations such as differences of wind speeds between the land area and the sea area and between the eastern part and the western part of Ise Bay. Nevertheless, a definite difference exists between the distributions of the wind velocity vectors of Cases 1 and 3 because of the difference of the typhoon tracks of Cases 1 and 3, as depicted in Figure 3. In particular, the wind velocities heading toward Mikawa (Figure 2), where the storm surge disaster occurred, of Case 1 are stronger than those of Case 3.

Figure 5 presents comparisons of time histories of the wind velocity at Irago (Figure 2) between the calculated values and the observed ones. The accuracy of Case 2 is low because the parametric typhoon model cannot evaluate the roughness effects of complicated coastlines and landforms and three-dimensional effects of the meteorological field on the sea surface winds as shown in Figure 4(b). Similarly, the usual tropical cyclone bogussing scheme of Case 3 was unable to calculate the sea surface winds with high accuracy because the model was unable to control the typhoon track, as shown in Figure (3). In contrast, the calculation method of Case 1 can evaluate the roughness effects of complicated coastlines and control the typhoon track because of the use of the meteorological model

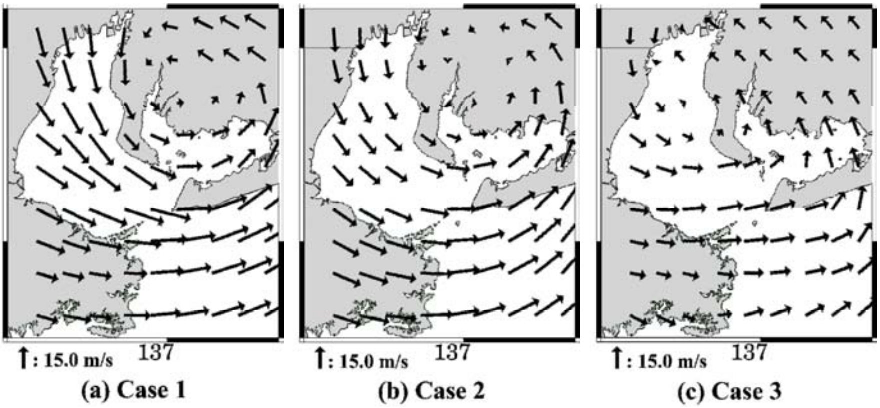

Figure 4 Distributions of the wind velocity vectors of Cases 1, 2, and 3 at 8:30 p.m. on October 7: The vectors show the wind velocities and directions.

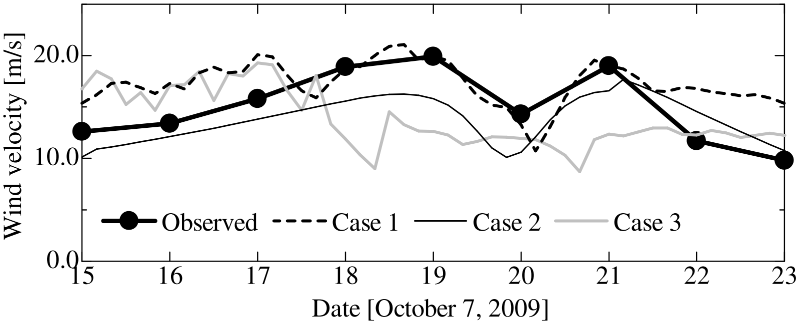

Figure 5 Time histories of the wind velocity at Irago (Figure 2): calculated values and the observed one.

MM5 performing the 4DDABS. Consequently, the calculated values of Case 1 agree well with the observed ones. This result implies that the distribution of the wind velocity vectors of Case 1 presented in Figure 4 is much more realistic than those of Cases 2 and 3.

Figure 6 depicts the spatial distributions of storm tides of Cases 1, 2, and 3 at 9:30 p.m. on October 7. Results showed definite differences among the distributions of the storm tides of Cases 1, 2, and 3. In particular, the storm tides of Case 1 are higher than those of Cases 2 and 3 around Mikawa (Figure 2). These differences arise because of the differences of the distribution of the wind velocity vectors portrayed in Figure 4.

Figure 7 depicts data for storm tides at Mikawa, Kinuura, Nagoya, and Toba (Figure 2), showing the calculated values and observed ones for comparison. The results show that the calculated storm tides of Case 1 agree well with the observed

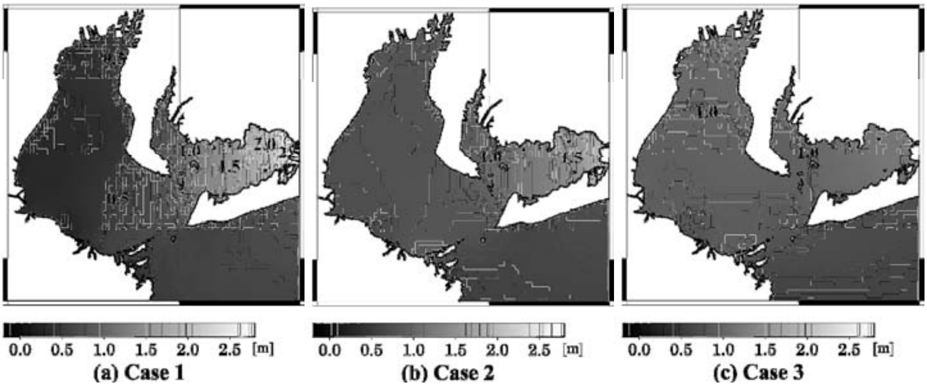

Figure 6 Distributions of the storm tides of Cases 1, 2, and 3 at 9:30 p.m. on October 7: The color tone and the contour lines show storm tides.

ones at all locations in Ise Bay. Moreover, the accuracy of the storm tides calculated by Case 1 far exceeds those of Cases 2 and 3 at all locations. Particularly, the computational error of Case 1 for the peak of the storm tide is only 0.05 m in Mikawa (Figure 7(a)) where the storm tide of 2.6 m was observed and where the storm surge disaster occurred. In contrast, the calculation using the conventional parametric typhoon model of Case 2 includes a computational error engendering underestimation by 0.8 m. The calculation using the usual bogussing scheme of Case 3 suffers from a computational error engendering underestimation of 1.1 m. These results demonstrate that the most effective method to calculate the storm surge accurately in the inner bay is the use of the atmosphere–ocean–wave coupled model performing the 4DDABS.

5. Conclusions

For this study, we developed the atmosphere–ocean–wave coupled model performing the 4DDABS and reproduced the storm surge attributable to typhoon MELOR (2009) in Ise Bay. Results demonstrated that the use of the coupled model performing the 4DDABS enables us to perform highly accurate calculation of the storm surge in the inner bay, as influenced by the complicated coastline and landform. Primary results obtained in this study are summarized as follows.

- We constructed the meteorological model MM5 performing 4DDABS for accurate evaluation of the sea surface winds under typhoons. The atmosphere–ocean–wave coupled model using the coastal ocean current model CCM and the wave model SWAN together with MM5 performing the 4DDABS was developed to calculate the storm surge in inner bays.
- The storm surge caused by Typhoon MELOR (2009) in Ise Bay, Japan was

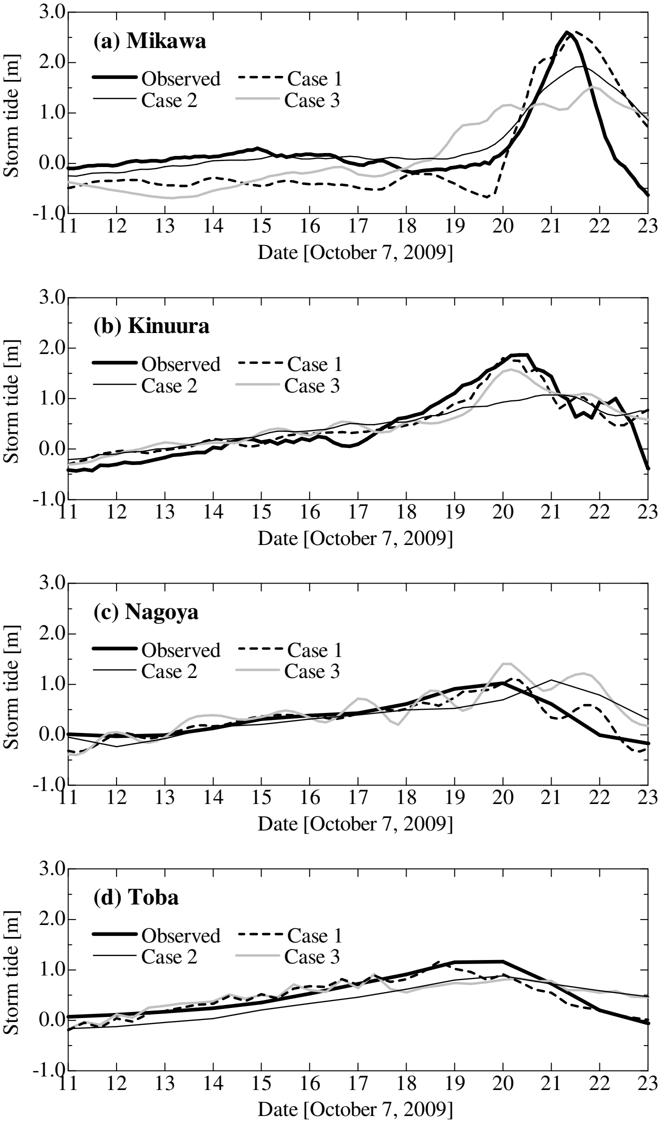

Figure 7 Time histories of the storm tides at Mikawa, Kinuura, Nagoya, and Toba (Figure 2): calculated values vs. observed ones.

reproduced using the coupled model performing 4DDABS. Comparisons of the storm tides between the calculated values and observed ones were performed at four observation stations located in Ise Bay. Results show that the model can calculate the storm tides accurately at all locations.

- For comparison, we performed the calculations of the storm surge using the conventional parametric typhoon model and the MM5 with usual tropical cyclone bogussing scheme. Results showed that these conventional models cannot accurately calculate the storm surge in the inner bay. This reason is because the former parametric typhoon model cannot evaluate the roughness effects of complicated coastlines and landforms and the latter usual tropical cyclone bogussing scheme cannot control the typhoon track.

The coastal zone management is very important in not only advanced countries but also developing countries.[17,18] Especially, the risk management for the storm surges is an urgent issue in countries such as Japan and Taiwan where large cities are located in the coastal zones.[2]

In this study, it was demonstrated that the most effective method to calculate accurately the storm surge in the inner bay was the use of the coupled model performing the 4DDABS. Therefore, our model is helpful for the risk management of the storm surges such as the safety assessment of coastal structures, the damage reductions, the production of hazard maps and the land-use control.

Disaster education to local people, both adults and children, is necessary to perform effectively the risk management planned by official organizations, etc.[19,20] However, our model cannot be applied directly to the disaster education because it would be difficult for the local people to understand and interpret the numerical results correctly, also having to take into account computational errors. Therefore, our model will contribute to the disaster education by developing methods which incorporate the numerical results in Web GIS technology, disaster archives, etc.[21] In addition, it is predicted that the vulnerability of coastal cities in Asia is increased by the impact of climate change.[22] Hence, our model needs to be progressed so that it can evaluate storm surges influenced by the impact of climate change. The risk management for the storm surges due to the impact of climate change will be performed by applying the numerical results to an index for vulnerability of coastal cities such as the Climate Disaster Resilience Index.[22] These are our tasks for future study.

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