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Reanalysis of past major storms in West Kyushu and Study of Wind-induced Currents in Ariake Sea

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Abstract

It is a well-known fact that the reanalysis and accurate numerical simulation of wave climate, coastal currents induced by wind and storm surge simulation require apparently the realistic wind field with consideration of effects of complex land topography. The inland seas and a number of bays in Japan are in the category that needs the accurate wind field for such studies. The reproduction and reanalysis of the wind field, however, had been conducted simply by making spline interpolation of the observed data or by modeling with simple gradient wind typhoon model or by a planetary boundary layer model. Their results showed a deficit in their data qualities. Recently mesoscale meteorological model has been used for hindcast and forecast of atmosphere conditions taking into account of the complex terrain and the reproduction of wind field has been improved in its accuracy.

In this study, the mesoscale atmospheric model was used for the reanalysis of the 47 past storm and severe weather conditions including 42 typhoons focusing on West Kyushu, Japan since 1959. The results of reanalysis had been utilized for a database construction and studies of wind field characteristics in semi-closed Omura Bay. The reanalysis

results were also used to study the characteristics of wind-induced currents in Ariake Sea which is very important in material transport under storm events.

1. Reanalysis of past major storms in West Kyushu

For the accurate simulation of wave climate, coastal circulation and currents and storm surge, reliable estimation of wind fields is required, that can be reproduced by using reliable observed data and/or numerical models. Interpolation of the observed winds is, however, applicable only to a relatively uniform topographic region such as plains. Its application to complex topographic region such as mountainous area and inland seas with a number of islands may cause some problem. In particular, for the long-term simulation or disaster simulation under the severe weather conditions, using observed data is much problematic.

There are many numerical models such as simple gradient wind typhoon model, nonhydrostatic mesoscale model and regional atmospheric model including cumulus physics and in practice, the long-term analysis of meteorological conditions has been generally performed with any gradient wind model, an atmospheric PBL model, a MASCON (Mass Conservation) model or a combined model of three elements. However, those numerical models are limited to apply to complex topographical region that significantly affects on the meteorological processes. In the present study, such complex topographical conditions are taken into account for the simulation of coastal wind distribution by using mesoscale meteorological model, MM5 (Dudhia, 1993; Grell et al., 1995). The past severe meteorological events for about 50 years in West Kyushu in Japan encompassing the Omura Bay and Ariake Sea had been reanalyzed by MM5.

1.1 Model configuration

The initial and surface/lateral boundary conditions were imposed by ECMWF ERA 40 (Uppala et al., 2005) and NCEP Global Reanalysis (Kistler et al., 1999) (both are $2.5^\circ \times 2.5^\circ$ spatial resolution) in this study. The nested computational three domains were set up with 27, 9 and 3km grid intervals and the effective bogussing scheme for typhoon simulation was applied in the first domain. Fig. 1 shows the computational domains and the Omura Bay in Nagasaki.

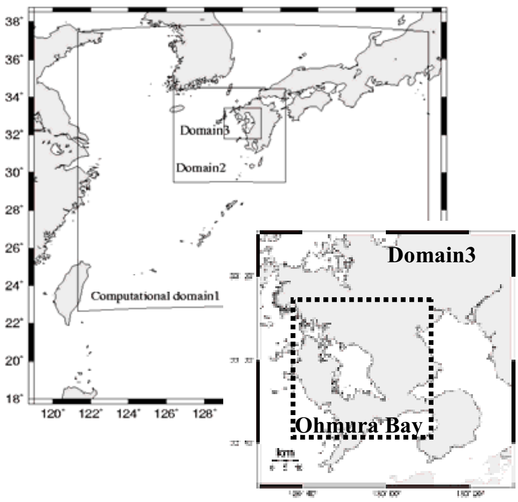


Fig. 1. Computational domains of MM5 and Omura Bay, Nagasaki, Japan.

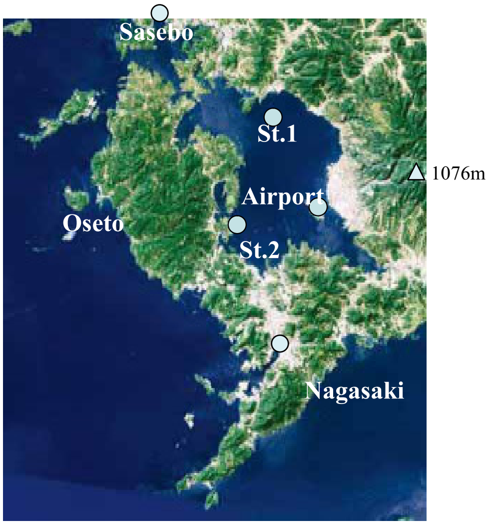


Fig. 2. Four stations (Sasebo, Airport, St.1 and St.2) for wind observation in Omura Bay

1.2 Reanalysis of the severe meteorological events

The criterion of first selection of the past severe meteorological events was based on the list of annual maximum wind field. The storm cases mostly including the typhoons were selected from the list. The criterion of second selection among the results of the first selection was based on the annual maximum wind field in each wind direction together with available weather chart. The criterion of last selection was made for the severe meteorological events, by considering the related disasters that caused damages and casualties in interested area from the second selections. Based on the last selection of severe meteorological events, the storms which made the maximum wind field in Omura, West Kyushu, occurred almost in July to October by typhoons. The moving tracks of the typhoons with the maximum wind field had the northward traces from the East China Sea through the west side of Omura Bay. The typical instances of such storms were the typhoons, 9918, 9119 and 8712.

Table 1 shows the list of storms with the averaged wind speed over 15m/s at the observation stations of both Omura (Nagasaki airport) and Sasebo and with the averaged wind speed over 10m/s at either station of Nagasaki or Sasebo from the final selections. The remarks by LF and atmospheric LP denote the low pressure system accompanied with fronts and atmospheric low-pressure system by Siberian high in wintertime, respectively.

Table 1 List of reanalyzed storms

No.	Simulation period	Observed Max. wind speed(m/s) at Nagasaki and Sasebo (WD)	Remarks
1	2004.08.17 ~ 2004.08.19	10. 5 (SSW), 17.4 (S)	T0415
2	2004.08.27 ~ 2004.08.30	11.8(WNW), 20.5(NNW)	T0416
3	2004.09.04 ~ 2004.09.07	23.3(SW), 23.7(W)	T0418
4	2004.09.25 ~ 2004.09.30	14.1(N), 17.6(N)	T0421
5	2004.10.18 ~ 2004.10.21	13.6 (NNE), 22.8 (NNE)	T0423
6	2003.06.18 ~ 2003.06.19	9(SW), 17(S)	T0306
7	2003.08.07 ~ 2003.08.08	9.2(N), 14.4(NNE)	T0310
8	2003.09.10 ~ 2003.09.13	10.5(SSW), 17.2(SSE)	T0314
9	2002.08.29 ~ 2002.09.01	5(NNE), 17(SE)	T0215
10	2001.06.18 ~ 2001.06.25	Omura 20(SW)	LF
11	1999.04.09 ~ 1999.04.11		LF
12	1999.06.24 ~ 1999.06.29	Omura 19(SSW)	LF
13	1999.09.21 ~ 1999.09.25	15.1(N), 11.6(W)	T9918
14	1998.09.28 ~ 1998.09.30	Omura 15(SSE)	T9809
15	1998.10.15 ~ 1998.10.18	8.8(N), 10.4(ENE)	T9810
16	1997.07.31 ~ 1997.08.09	Omura 15(SSW)	T9711
17	1997.09.13 ~ 1997.09.17	12.1(NNE), 11.6(ENE)	T9719
18	1997.11.24 ~ 1997.11.26	Omura 22.0(SSE)	Atmospheric LP
19	1996.06.17 ~ 1996.06.18	Omura 18(SW)	Atmospheric LP
20	1996.08.11 ~ 1996.08.15	15(WNW), 11.1(NNW)	T9612
21	1994.08.13 ~ 1994.08.14	5(NE), 11.0(E)	T9414
22	1993.09.01 ~ 1993.09.05	13.4(NNE), 11.0(N)	T9313
23	1992.08.06 ~ 1992.08.09	13.9(N), 12.1(NNW)	T9210
24	1991.07.28 ~ 1991.07.29	12(SSW), 8(SE)	T9109
25	1991.09.13 ~ 1991.09.14	15(W), 13(N)	T9117
26	1991.09.25 ~ 1991.09.28	25.6(N), 17.6(ENE)	T9119
27	1990.09.11 ~ 1990.09.20	11.8(N), 10.8(NNE)	T9019
28	1989.07.24 ~ 1989.07.29	7.3(NE), 15.8(E)	T8911

29	1987.08.26 ~ 1987.08.30	12(SSW), 12(E)	T8712
30	1985.08.30 ~ 1985.08.31	16(W), 12(W)	T8513
31	1982.08.26 ~ 1982.08.27	13(WNW), 11(W)	T8213
32	1982.09.23 ~ 1982.09.25	7.0(WNW), 11(NE)	T8219
33	1981.07.30 ~ 1981.07.31	9(NNE), 10(NNE)	T8110
34	1979.10.18 ~ 1979.10.19	10.1(N), 12.1(NE)	T7920
35	1976.09.11 ~ 1976.09.13	12.8(WNW), 13.2(NE)	T7617
36	1971.08.29 ~ 1971.08.30	9(N), 13(NE)	T7123
37	1970.08.13 ~ 1970.08.15	17(W), 14(ENE)	T7009
38	1968.07.28 ~ 1968.07.30	12(SW), 11(W)	T6804
39	1968.09.24 ~ 1968.09.27	16.3(NNE), 23.2(NE)	T6816
40	1966.09.23 ~ 1966.09.25	14.3(NNE), 21.7(NNE)	T6626
41	1965.09.10 ~ 1965.09.18	13.7(NNE), 13(N)	T6524
42	1964.08.23 ~ 1964.08.24	14(NNE), 13(NNE)	T6415
43	1964.09.24 ~ 1964.09.25	11(NNE), 11(NNW)	T6424
44	1963.08.09 ~ 1963.08.10	11(WSW), 13(NNE)	T6309
45	1961.09.15 ~ 1961.09.17	14.5(NNW), 15.7(N)	T6118
46	1959.07.15 ~ 1959.07.18	19.1(SW), 19(S)	T5905
47	1959.09.26 ~ 1959.09.27	15.2(NNE), 19.6(NNE)	T5915

Table 2. Available meteorological variables from the database constructed by the reanalyzed data (15 min temporal resolution)

	3D DATA (23 sigma levels)	2D DATA
1	wind velocity – U, V (m/s)	ground temperature (K) 2m above the ground surface
2	vertical velocity – W (m/s)	accumulated convective precipitation (cm)
3	temperature (C)	accumulated non-convective precipitation (cm)
4	water vapor mixing ratio (kg/kg)	surface sensible heat flux (W/m2)
5	cloud water mixing ratio (kg/kg)	surface latent heat flux (W/m2)
6	rain water mixing ratio (kg/kg)	friction velocity (m/s)
7	geopotential height (m)	sea level pressure (Pa)
8	pressure (Pa)	10m surface wind (m/s) → U10, V10
9	vorticity - vertical component (1/s)	
10	potential vorticity (1/s)	
11	divergence – horizontal component (1/s)	

Table 3. Locations of the four stations of wind observation

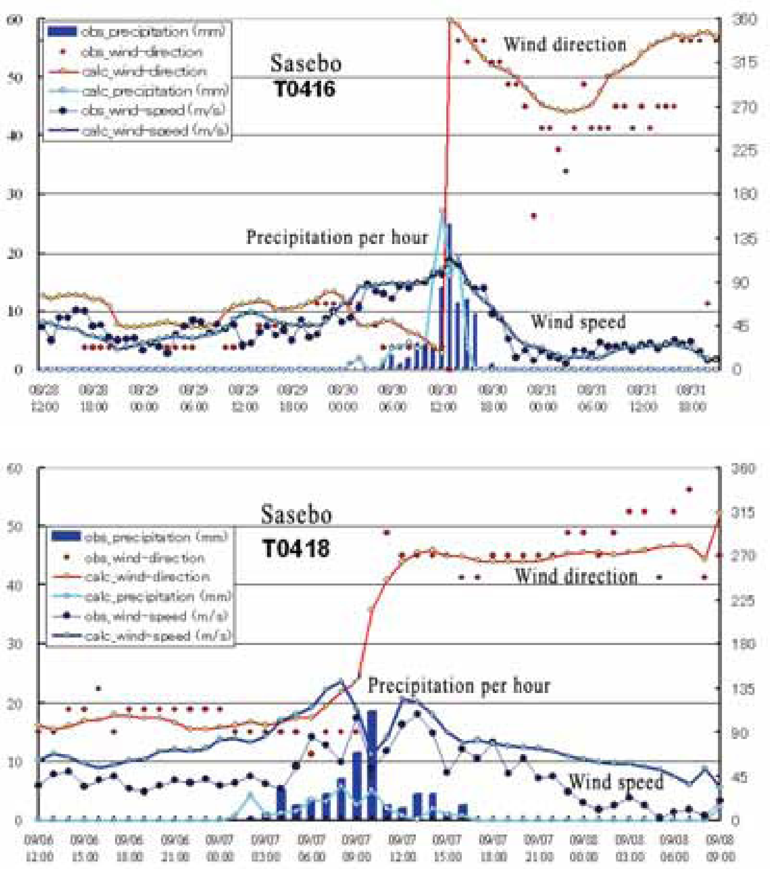
Station	location
Nagasaki Airport	32:55:00 N, 129:54:08 E
Sasebo	33:09:05 N, 129:43:06 E
Station 1	33:00:00 N, 129:52:00 E
Station 2	32:55:00 N, 129:52:00 E

1.2.1 Regional inventory of storm events in West Kyushu

Inventory of reanalysis results of the storms listed in Table 1 was made with 2D and 3D meteorological variables shown in Table 2. The data from the computational domains with 27, 9 and 3km are all available with 15 min temporal resolution over the simulation periods. These data are available upon a request with a read-in Fortran code. The four station points shown in Fig. 2 are available with additional time-series data of wind field.

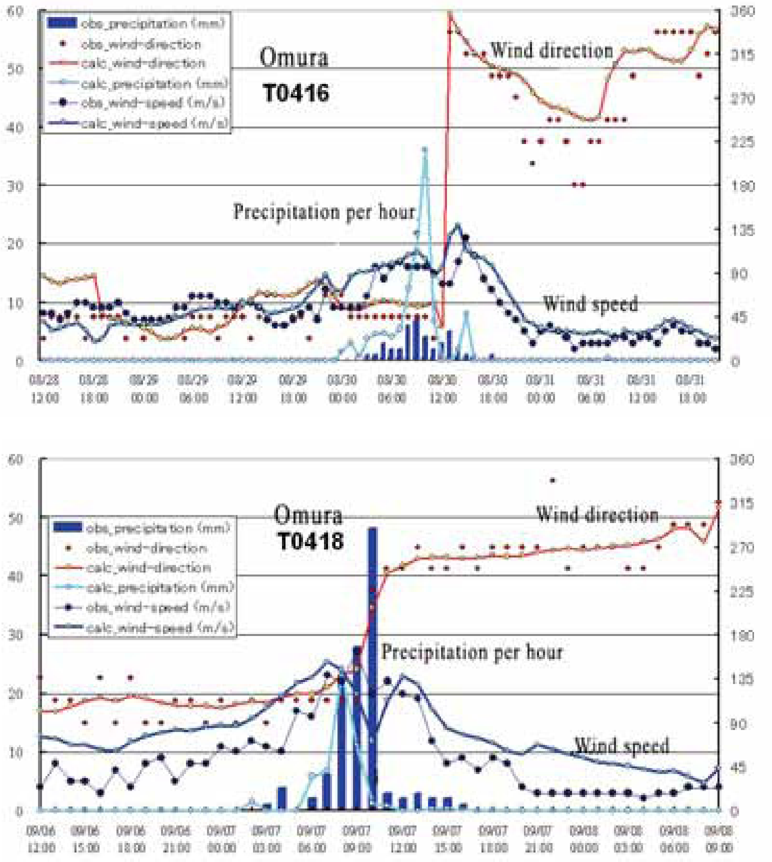
1.2.2 Results of reanalyzed storms

From the results of reanalyzed storms, the typhoons, 0416 and 0418 were presented here for comparison to observed data. The conventional wind direction (North is zero degree and increase in clockwise direction), wind speed (m/s) and hourly precipitations at Nagasaki, Sasebo and Omura (Nagasaki airport) were shown in Fig. 3. The solid circles indicate observed wind speed, wind direction and the bars indicate the observed precipitation and the solid lines with circles are the simulation results by MM5.



(a) At Sasebo

Fig. 3. The comparison of the wind speed, wind direction and hourly precipitatio from the simulated and observed data in case of typhoons, 0416 and 0418.

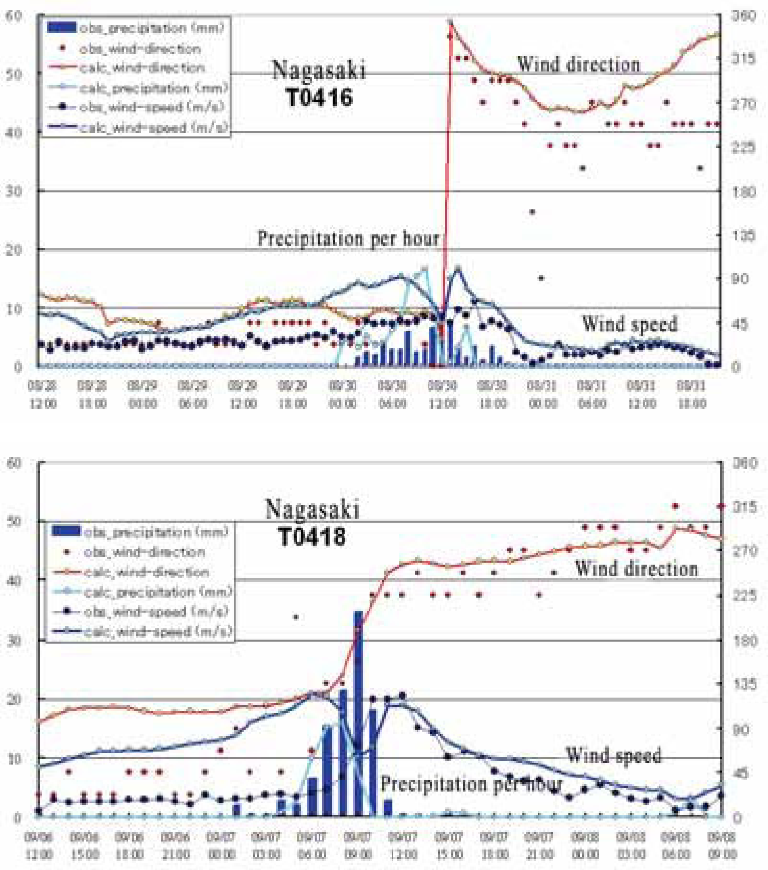


(b) At Omura Bay (Nagasaki airport)

Fig. 3. Continued

The simulated wind direction and wind speed at Omura (Nagasaki airport) and Sasebo showed good accordance with observed data. The variation of wind direction of the Typhoon, 0416 was reproduced accurately through the passage of typhoon. The simulated peak wind speed of typhoon 0416 showed good agreement with the observed one as well. However the results of peak wind speed of typhoon 0418 at the beginning of simulation (east wind) showed some discrepancy with the observation, although the phase of occurrence time was coincided well. In particular, the wind mainly in NNE direction at Nagasaki had unignorable differences both in wind direction and speed and the observed wind direction was biased toward north.

Based on the all reanalyzed results, the discrepancies in wind direction were found in rather constant manner that seemed to be from the local topographical characteristics of observed points which could not be even considered by the computational resolution (1 km) of present MM5. The differences of hourly precipitations in some storm results were mainly due to the inappropriate surface boundary condition in MM5 which contains constant values for sea surface temperature (SST) during the simulation. In other words, the information of SST contained in ECMWF ERA 40 and



(c) At Nagasaki

Fig. 3. Continued

NCEP Global Reanalysis is remained in constant values. The typhoon is known to be very sensitive to SST which is one of the main factors of typhoon generation, growth and dissipation. This is called positive and negative feedbacks in the local air-sea interaction process in case of tropical storms. Therefore, the precipitation reproduced by embedded MM5 physics can be fairly improved by appropriate and accurate surface boundary conditions with high-resolution realistic SST data in space and time (Yamaguchi et al., 2005). Also the local air-sea interaction under typhoon can be considered by fully coupling the atmospheric and oceanic circulation models which is not in the scope of this study.

1.2.2.1 The characteristics of wind field in Omura Bay

From the observations

The Omura Bay as shown in Fig. 2 is a semi-closed bay in West Kyushu surrounded by mountains and topographical obstacles such that their effects on wind field are appreciable. To investigate the topographical influences on wind field, statistical analysis of the observed wind field at four stations of Nagasaki airport, Sasebo, Nagasaki and Oseto were conducted to get the following results below.

1) The topographical influence at Nagasaki airport is not so significant. Strong winds in NNW-N and SE-SSE directions are dominant due to the surrounding mountainous topography. Its frequency of occurrence is higher than the other points. This is probably due to the location of Nagasaki airport constructed inside the bay where wind attenuation is smaller than in the land.

2) The strong wind direction at Oseto is almost in north, because the west and east winds are screened by the topographical obstacles of Matsuyama and Nagauradake, respectively.

3) Wind direction at Nagasaki is predominant in SW due to the topographical screening on the east side.

4) Wind speed at Sasebo is lower than that at Nagasaki airport, but the wind direction is similar to Nagasaki airport. The topographical influence in Sasebo seem to be not significant compared to those at Oseto and Nagasaki.

From the reanalysis

From the reanalyzed results by MM5, the cases of averaged wind speed over 15m/s in Omura Bay by typhoon and seasonal winds (mainly due to winter monsoon) were selected. The occurrence of the maximum wind for the simulation period was investigated and three of results were presented in Fig. 4, that showed the following characteristics.

1) Wind speed over the bay in any directions is estimated larger than that in vicinity area, because the topographical effects are significant in the vicinity of the bay.

2) Wind in southeast and northwest directions are generally estimated high in the bay that is due to the less effects of surrounding topography.

3) Northeasterly wind, the maximum wind is calculated at east of St.1, through east part of the bay whereas the maximum wind is simulated in St.2 through Nagasaki airport area in easterly wind.

4) Wind field in south and west direction shows rather constant distribution and the maximum value of wind speed is less than 20m/s. But the general wind in south direction is somewhat estimated higher.

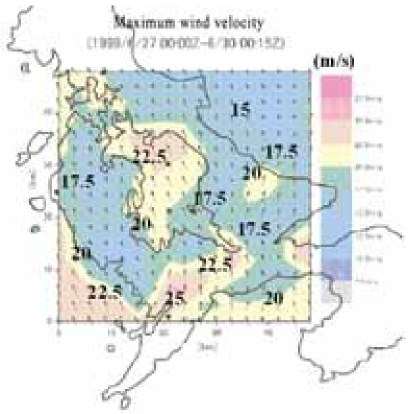
5) Maximum wind in north or northwest direction is estimated in southeast part (Nagasaki airport) of the bay while that in southeast direction is calculated in northwest area of the bay at St.1.

Extreme wind analysis from the reanalysis data

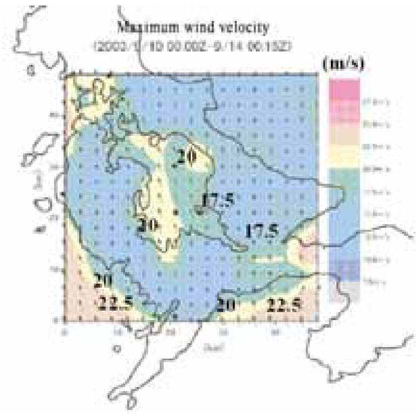
To evaluate the extreme wind in 30 years return period at two points, St.1 and Nagasaki airport, the extreme statistical analysis of wind had been performed with the annual maximum winds of the reanalysis database. The results of probable wind in 30 years return period in every direction were evaluated and presented in Fig. 5.

1) In the comparison of probable wind field in 30 years return period at Nagasaki airport and St.1, the probable wind in north through northwest direction, west-southwest through southwest direction and east direction at Nagasaki airport shows higher values than that at St.1

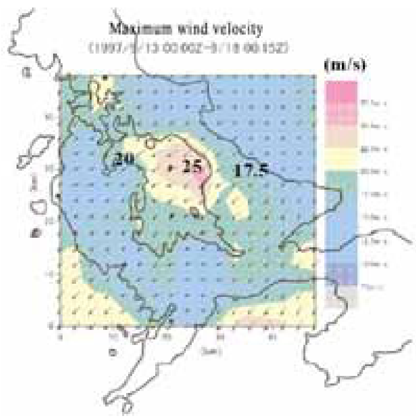
2) In south-southwest through east-southeast direction and northeast direction, the probable wind field at St.1 is higher than those at Nagasaki airport.



(a) Wind field in case of atmospheric low-pressure with fronts

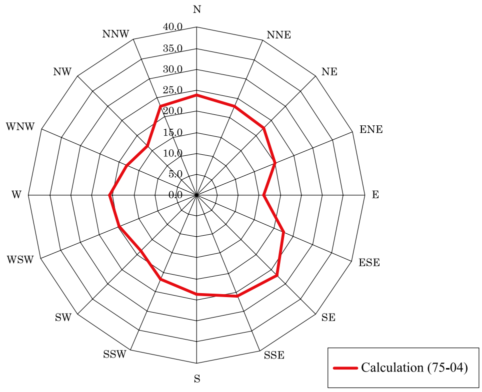


(b) Wind field in case of Typhoon 0314

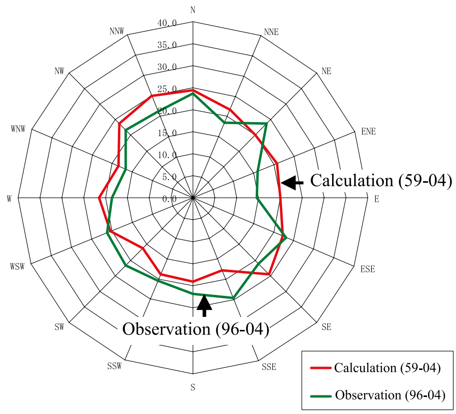


(c) Wind field in case of Typhoon 9719

Fig. 4. The maximum wind speed and direction during the simulation period in Omura Bay



(a) St.1

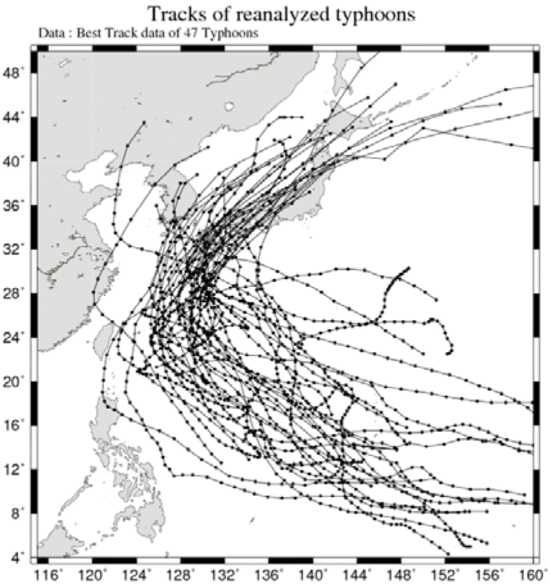


(b) Nagasaki airport

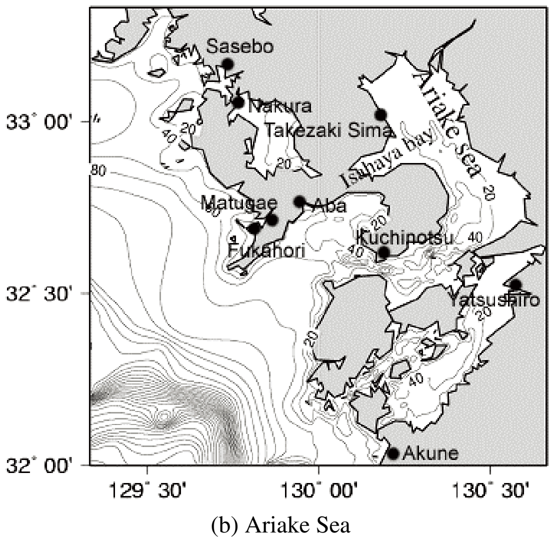
Fig. 5. Probable wind in 30 years return period at St.1 and Nagasaki airport estimated by extreme statistic analysis of reanalysis database

2. Wind-induced residual currents in Ariake Sea

Since there have been significant changes in water circulation and consequent environmental and economical problems in fishery after the construction of Isahaya dyke in Ariake Sea, a number of related studies have been carried out in various kind of aspects to investigate such changes and problems (Arakai et al., 2001; Hiramatsu et al., 2005; Ohtsuka 2005). Although the tide and tidal currents system in Ariake Sea well studied with regards to the Isahaya dike construction (Kim, 2005), the wind-induced residual currents in Ariake Sea has not been studied well. The wind-induced currents as well as the tidal currents are very important forcing that determines the transport of sediments and tracers in water body. Even in the severe storm conditions, the wind-induced currents will directly derive the consequential results in material transports. The dynamic equilibrium state of beach and sediment under a long-term external forcing such as tidally-induced residual currents is also very valunerable to a short-term extreme events such as



(a) Typhoon tracks



(b) Ariake Sea

Fig. 6. The tracks of typhoons reanalyzed by MM5 and employed as same events for water circulation by POM (a). Computational domain 3 of Ariake Sea and Isahaya Bay with water depth contours. ・indicates tidal stations (b).

tropical storms. Therefore the reanalyzsis data of the past major storm conditions would be very helpful to study and understand the long-term water circulation under the storm conditions in the Ariake Sea. Reanalysis data can be used for further study on long-term material transports caused by wind-driven currents.

Additional numerical simulations in addition to the reanalysis of wind field by MM5 (see Table 1) were performed to study the water circulation induced by winds. The primitive equation ocean model, POM (Mellor, 2004), was used for this study with a tide simulation code incorporated in. The computational domain was same as the smallest domain of 3km grid size in MM5 computation as shown in Fig. 6(b). Eleven vertical sigma levels were used to resolve the water depth. The simulation periods of water circulation of each storm events were identical to those of MM5 simulations. Typhoon tracks selected for storm events in this study is shown in Fig. 6(a). The reanalyzed wind and atmospheric pressure were used for the meteorological forcing that derived the circulation in Ariake Sea. The temperature and salinity of Ariake Sea were assumed to be homogeneous in vertical and horizontal spaces. Thus homogeneous barotropic simulations were conducted. The real-time based water level variations by tide were imposed at the open boundary with free surface boundary conditions.

2.1 Model results

First, the results of tidal circulation were represented in terms of tidal residual currents and validated with the previous studies (Figs. 7 and 8). The incorporated tide model computed the major 8 diurnal and semi-diurnal constituents (M_2, S_2, K_1, O_1, N_2, K_2, P_1, and Q1) separately and then they were composed for real-time simulation for the simulation periods. Four computational trials of the tidal residual currents were conducted, which are persistent currents induced by tide and very important for the long-term transport of sediment, tracers and any materials. The reanalyzed depth-averaged tidal residual current velocities shown in Fig. 9 depict good agreements in the flow pattern of tidal residual current with the previous numerical study (Fig. 7) and observation (Fig. 8) even though there exist some differences in the magnitude. From the observation, we just have the information of the current patterns without their magnitude and from the previous study, the current velocities are a bit larger than the results of this study. The relatively large clockwise circulation in the northeast sheltered area of the bay (Fig. 7 right and Fig. 8) was clearly reproduced in the simulation.

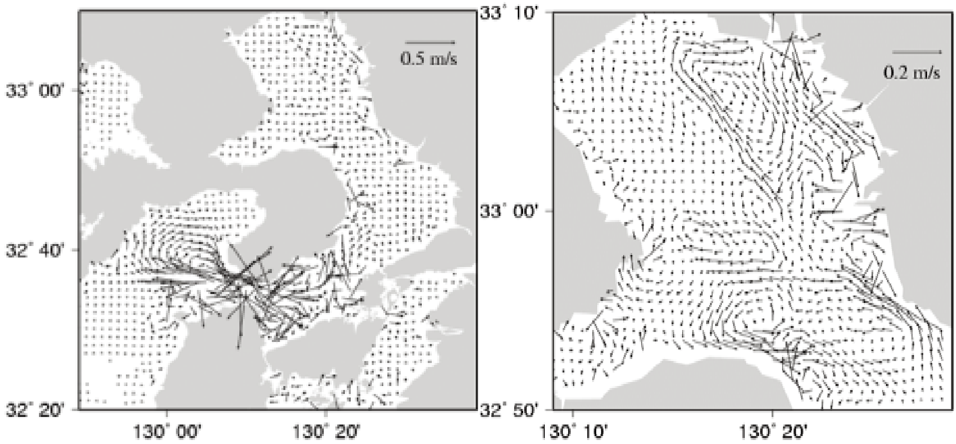


Fig. 7. Depth-averaged tidal residual current vectors (left: Ariake Sea, right: inner Ariake Sea; by Kim, 2005).

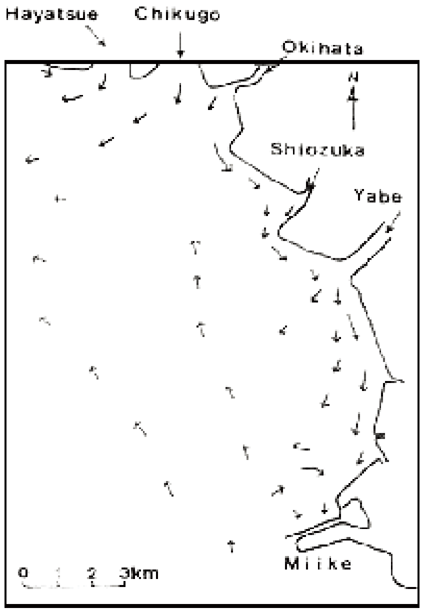


Fig. 8. Mean surface current pattern inferred from the drifter track observations made in July 1992. Cited from "A report on tidal analysis in Ariake Sea fishing grounds" by Sanyo Techno Marine Inc. (1993).

Next, the wind-induced residual current velocities which was defined as the residual currents induced by winds for the periods of target storms were evaluated as following procedures.

1) Simulations with real-time tidal water level open boundary conditions were first performed for all listed storm events.

2) Simulations with the tidal boundary conditions were conducted with the external meteorological forcing such as momentum flux by reanalyzed wind and atmospheric pressure.

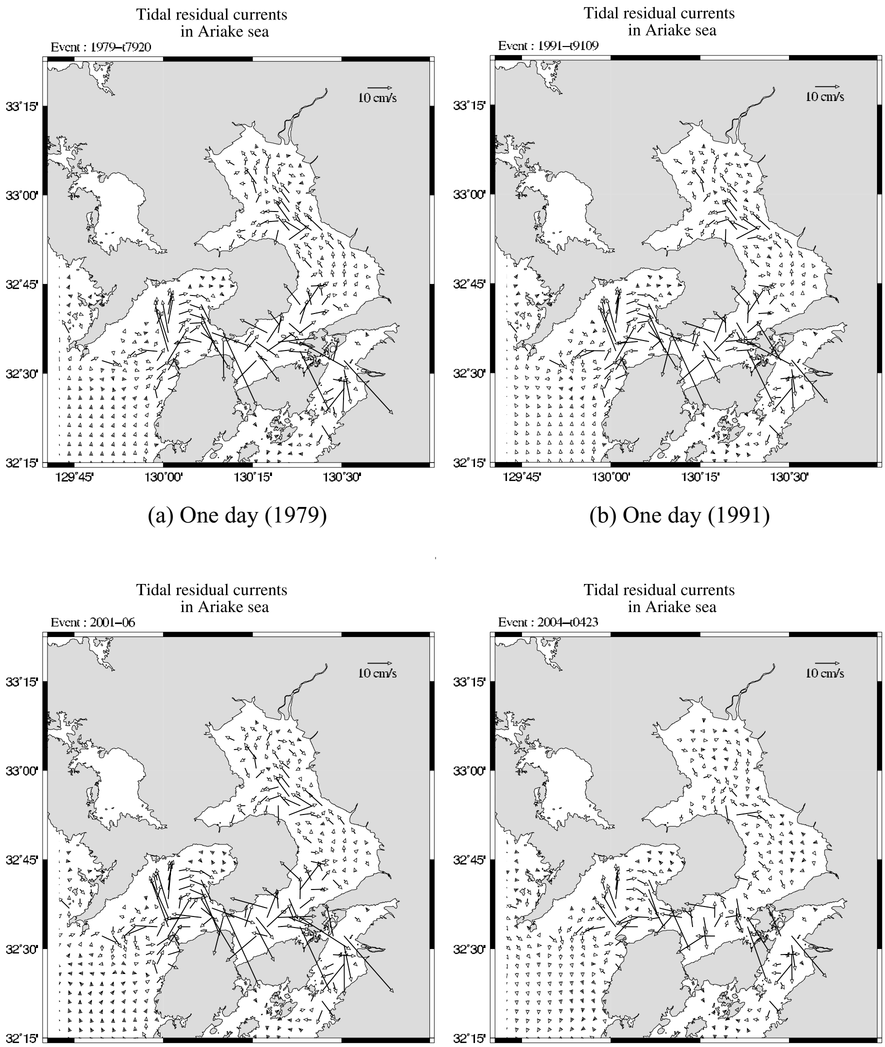
3) Wind-induced currents were calculated by subtracting the tidal residual currents from the second simulation results.

Four examples of the calculated wind-induced currents from the all reanalyzed data were presented in Fig. 10 for the same storm events of tidal residual current simulations shown in Fig. 9. It was interesting to note that the wind-induced currents showed their flow patterns depending on the track of typhoons. The strong southeastward wind-induced currents along the Ariake Sea channel were found when the typhoon passed through the south of Ariake Sea whereas the northwestward currents were revealed when the typhoon passed through the north of Ariake Sea. The small embedded upper right images show the track of typhoons. The magnitudes of almost all wind-induced currents were much larger than those of tidal residual currents implying that the wind-induced currents play crucial roles in the material transport in typhoon and storm conditions. In contrast to the currents situations inside Ariake Sea under the storm events, the wind-induced currents in the mouth, Kuchinotsu (Fig. 6) showed that the strong tidal residual currents are prevailing determining the circulation in the narrow channel.

From these simulation results, one can deduce the interesting consequence that when a typhoon passes through the south of Ariake Sea in the peak of flood tide, the highly feasible energy focusing by currents and wind waves in south of the Sea can be expected, while when a typhoon passes through the north of Ariake Sea in flood tide, the energy could reach to the north of the Sea. These energy focusing could end up with physical storm surge events in the coastal area.

The noticeable thing when a typhoon passes through the north of Ariake Sea in the peak of ebb tide, is that there might be reproduced a strong velocity shear between the southward ebb tidal currents and the strong northward wind-induced currents synoptically, which could induce the considerable turbulent mixing process in the south of Ariake Sea.

Fig. 11 shows the total water discharge by wind-induced residual currents with the typhoon tracks. As the Ariake Sea has large tidal flats in its inner parts (Fig. 6), the water discharge rate in most tidal flats in Ariake Sea is relatively small compared to that in rather deep water region in the south of the Sea.

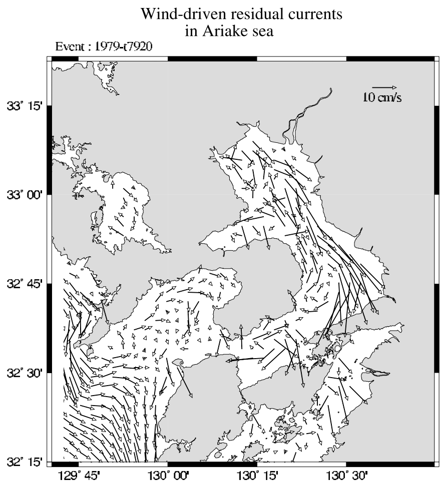


(a) One day (1979) (b) One day (1991)

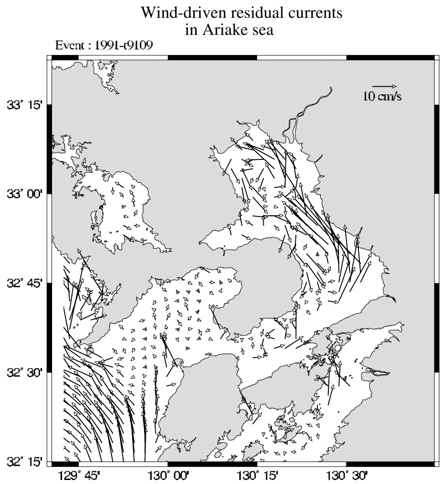
(c) Seven days (2001) (d) Three days (2004)

Fig. 9. Simulated depth-averaged tidal residual currents velocities for different storm events. The simulation periods for the storm events are shown in sub-captions (see Table 1).

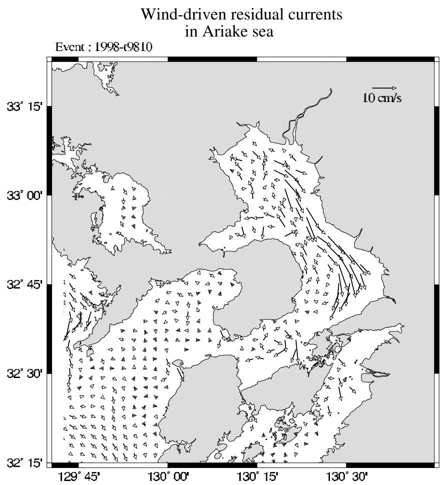
Fig. 12 shows the long-term depth-averaged wind-induced residual currents in Ariake Sea and its vicinity which was derived from the reanalized water circulations of 47 storms in the sea. The overall current velocities remained weak less than 5 cm/s and the rather strong current in the vicinity became smaller in velocities. A clear counter-clockwise circulation was reproduced in the inner shallower area of the sea, that was linked to the northward residual currents in the central part of the sea off Kumamoto. However, clockwise tidal residual circulation in the northeast sheltered area of the sea was not reproduced in the case of wind-driven residual currets.



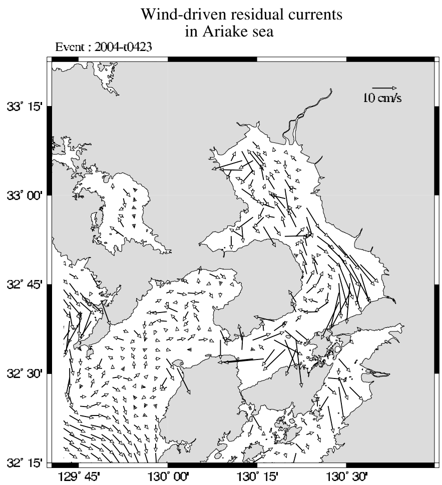
(a) T7920



(b) T9109

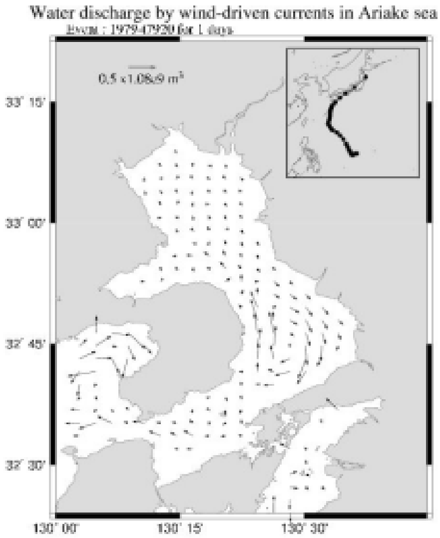


(b) T9810

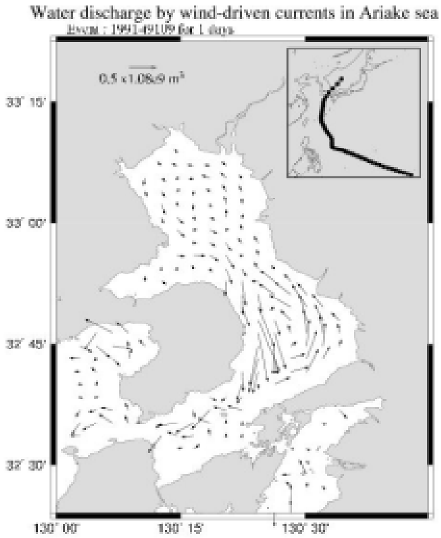


(b) T0423

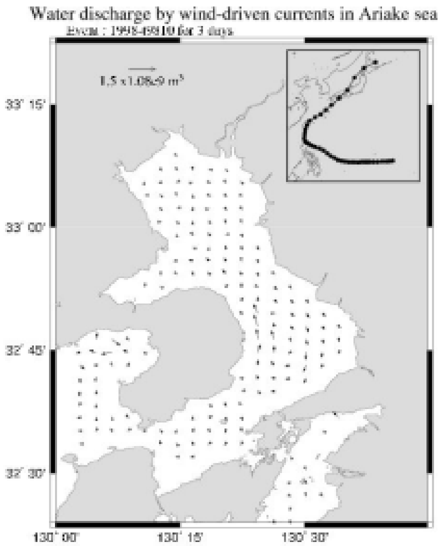
Fig. 10. Simulated depth-averaged wind-induced residual current velocities computed by using reanalyzed atmospheric data.



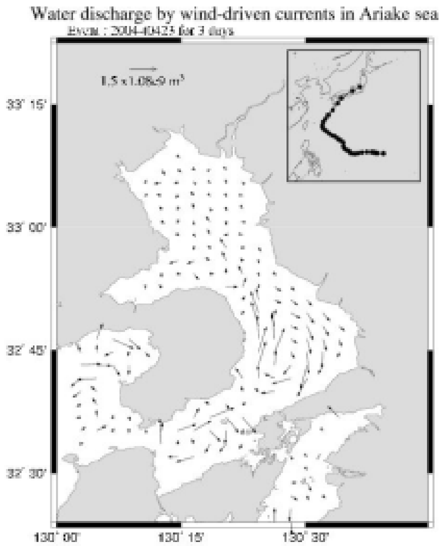
(a) T7920 (1 day)



(b) T9109 (1 day)



(c) T9810 (3 days)



(d) T0423 (3 days)

Fig. 11. Total water discharge for simulation periods by depth-averaged wind-induced residual currents. The upper-right embedded chart shows the track of typhoon.

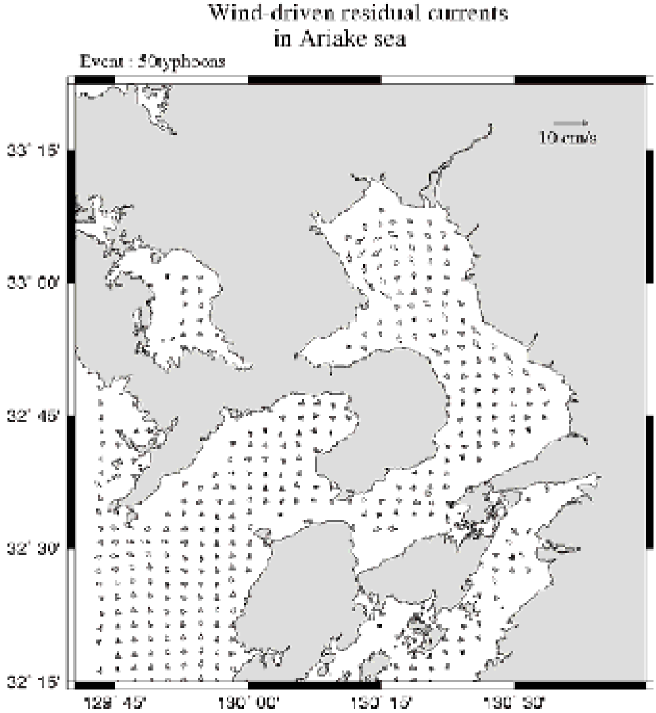


Fig. 12. Wind-induced residual current reproduced by 47 past major storms in Ariake Sea.

3. Summary and conclusions

Mesoscale meteorological model, MM5 was used for the reanalysis of the 47 past major storms since 1959 including 42 typhoons that caused disasters in West Kyushu, Japan to consider the topographical influences on wind fields. The inventory of reanalysis results of the 47 storm events was constructed as a database including the 2D and 3D meteorological variables and now is available upon request with read-in FORTRAN code.

From the reanalysis results, the results of Typhoon 0416 and 0418 were presented and validated with the wind observations at Nagasaki, Sasebo and Omura (Nagasaki airport) stations. The screening effects by mountains and topographical obstacles at specific wind direction in the observed wind field were made clear and reproduced well in reanalysis results. Statistical analysis of extreme wind in 30 years return period in Omura Bay was also performed with the inventory of reanalysis data.

Study on wind-induced currents in Ariake Sea was carried out by using the primitive ocean model, POM, with the external forcing such as wind and atmospheric pressure from the reanalysis inventory. Tidal water level variations in time were imposed as an open boundary condition in POM simulations. The results of these simulations can be summarized below.

1) The simulated tidal residual currents agreed well with previous numerical study by Kim, (2005) and field observation by Sanyo Techno Marine Inc. (1993). The clockwise circulation in northeast sheltered area of the sea is well reproduced in the simulation results.

2) Wind-induced currents in the Ariake Sea depend on the track of typhoons that pass through the north or south of the sea. From these wind-induced currents, the potential storm surge events in coastal area of the sea are deduced in combination with the tidal currents under storm conditions.
3) A clear counter-clockwise circulation was reproduced in the inner shallower area of the sea that was linked to the northward residual currents in the central part of the sea off Kumamoto. However, clockwise tidal residual circulation in the northeast sheltered area was not reproced in the case of wind-driven residual currets.

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