COMPARATIVE STUDY OF STORM SURGES IN A BAY INDUCED BY TYPHOONS WITH QUICK INVERSION IN WIND DIRECTION

Shin-ichi Aoki [1] and Tomokazu Inui [1]

Three events of storm surge which yielded different tidal departures in the head of Mikawa Bay, Japan are compared and discussed from the viewpoint of response to the wind forcing. The mechanism of sudden sea level rise is investigated based on the data of wind, sea level and velocity obtained in the period of three different Typhoons which passed near the bay. The magnitude of preceding east wind which gives rise to the sea level in Ise Bay and quick inversion in wind direction from east to west are key factors to the development of large tidal departure in the head of Mikawa Bay. The propagation of surge waves as a free long wave is confirmed through the velocity profile data and also tested using a 2D simple numerical model.

Keywords: storm surge; typhoon; wind effect, wind direction

INTRODUCTION

In the recent decade, risk of storm surge disaster seems to be higher because of the global climate change and of aging deterioration of coastal and harbor structures. In October 2009, typhoon No. 0918 landed central Japan in the early morning. It brought about a storm surge in Ise and Mikawa Bays resulting in a very large sea level rise (the maximum tidal departure = 2.6 m) in Mikawa Port. The departure was the same as the record by the so-called Isewan Typhoon (Typhoon Vera) in 1959, which caused historical disaster by the storm surge (Risk Management Solutions Inc., 2009). Although the disasters by the typhoon No. 0918 were fortunately not as destructive as the Typhoon Vera, more than one hundred houses were inundated because of the flood and a number of cars and containers in the port were damaged. Following this typhoon, in 2011 and 2012, two strong typhoons, No. 1115 and No. 1217 having similar wind speed to No.0918 passed over/near Mikawa Bay and also yielded storm surges to the head of the bay. The tidal departures induced by these typhoons, however, were less than half of No.0918.

In this study, storm surges caused by the three typhoons No. 0918, No. 1115 and No. 1217 were compared with each other and the mechanism of the development of high tide in 2009 was discussed. The data of tide, current, wind and atmospheric pressure observed around the bay were used, some of which were obtained in the head of Mikawa Bay by the authors. Numerical simulations were also used to elucidate the occurrence of the storm surge.

TYPHOONS AND OBSERVATIONS

Figure 1 illustrates trajectories of three typhoons, No. 0918, No. 1115 and No. 1217 in the year of 2009, 2011 and 2012, respectively. Atmospheric pressure at the centre of typhoon and the time (JST) of passage are also indicated in the figure. Figure 2 shows locations of measurement stations in which the authors measured bottom pressure and current profile at Stn. A in all the typhoon events. Figure 3 shows variations of atmospheric pressure of three typhoons observed at Stn. P, where time=0 in the horizontal axis indicates the time when the tidal departure at Stn. A reached the maximum. The atmospheric pressures showed the lowest peaks about one hour before the tidal departures at Stn. A reached the maximum.

In Mikawa Bay, which is extending east and west, the wind blowing over the bay undergoes quick inversion in its direction as a typhoon passes over the bay from south to north. Figures 4 shows time histories of wind speed and wind direction (16-point compass) at Stn. W1, where the anemometer was located 25m above the quay. The time axis is the same as Fig.3. The notable features are (i) in 2009, strong east wind was observed before the departure showed the maximum, (ii) quick inversion of wind direction from east to west was observed at the time the departure showed the maximum in all the typhoon events. The turnover period was the minimum in 2009. Figure 5 shows the wind data at Stn. W2 located inland at the west end of Mikawa Bay. Although the wind speed at Stn. W2 shows smaller value than W1, the above properties (i) and (ii) are also recognized. Comparing the wind data of the three typhoons, there was a significant difference in the speed and duration of the preceding east wind although the wind speed and duration of the west wind that may cause wind-driven surge at the east

[1] Dept. of Civil Engineering, Division of Global Architecture, Graduate School of Engineering, Osaka University, 2-1 Yamadaoka, Suita, Osaka 565-0871, Japan

end of the bay shows little difference. The decrease in wind speed in the data of 2012 just before the departure reached the maximum is because the wind station was located near the center of the typhoon. In addition, the inversion of wind direction in 2009 was quicker than other two typhoons.

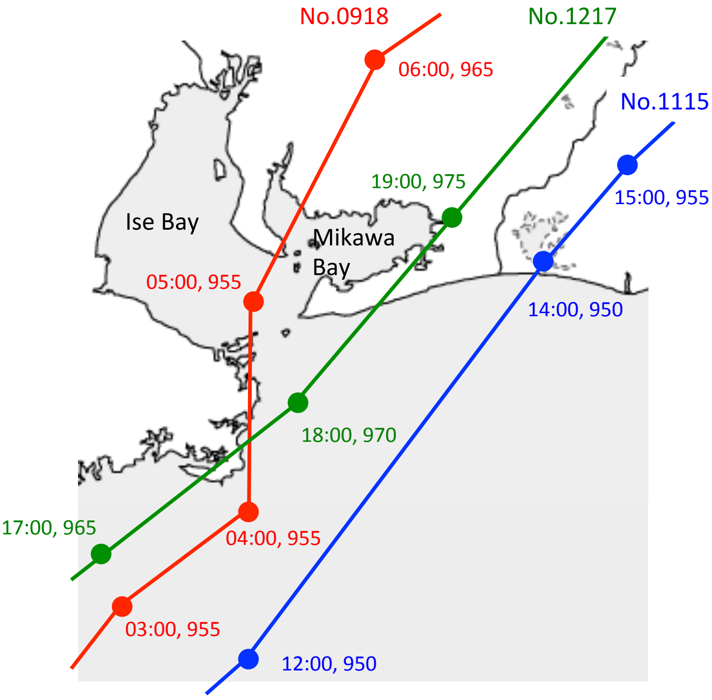

Figure 1. Paths of three typhoons compared (Red: 2009, Blue: 2011, Green: 2012).

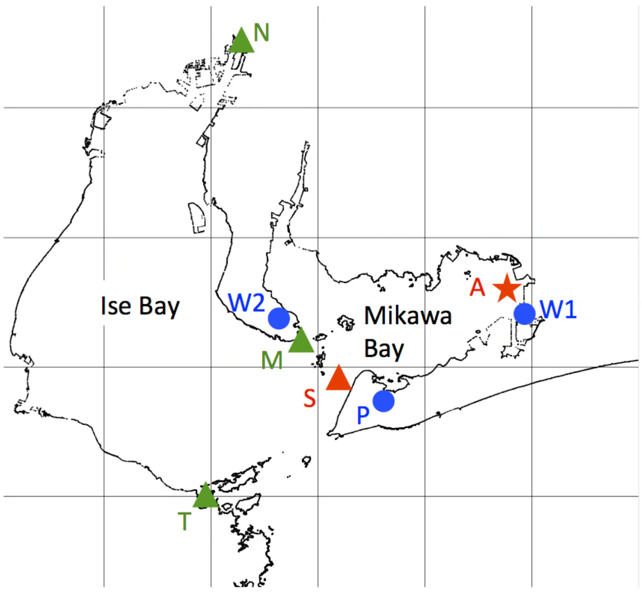

Figure 2. Locations of measurement stations (P: atmospheric pressure, W1, W2: wind, N, M, T: tide, S: tide and current, A: tide and current profile).

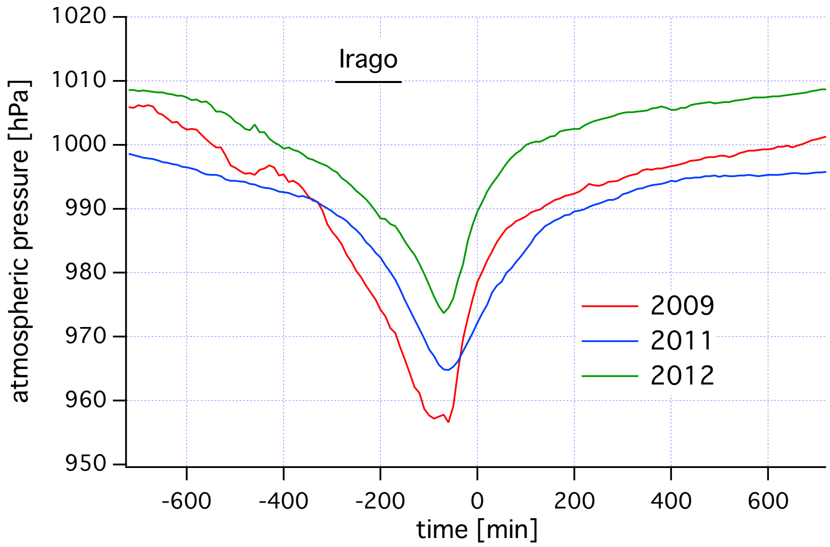

Figure 3. Variation of atmospheric pressure in the storm surge period when the tidal departure at Stn. A shows the maximum at time = 0.

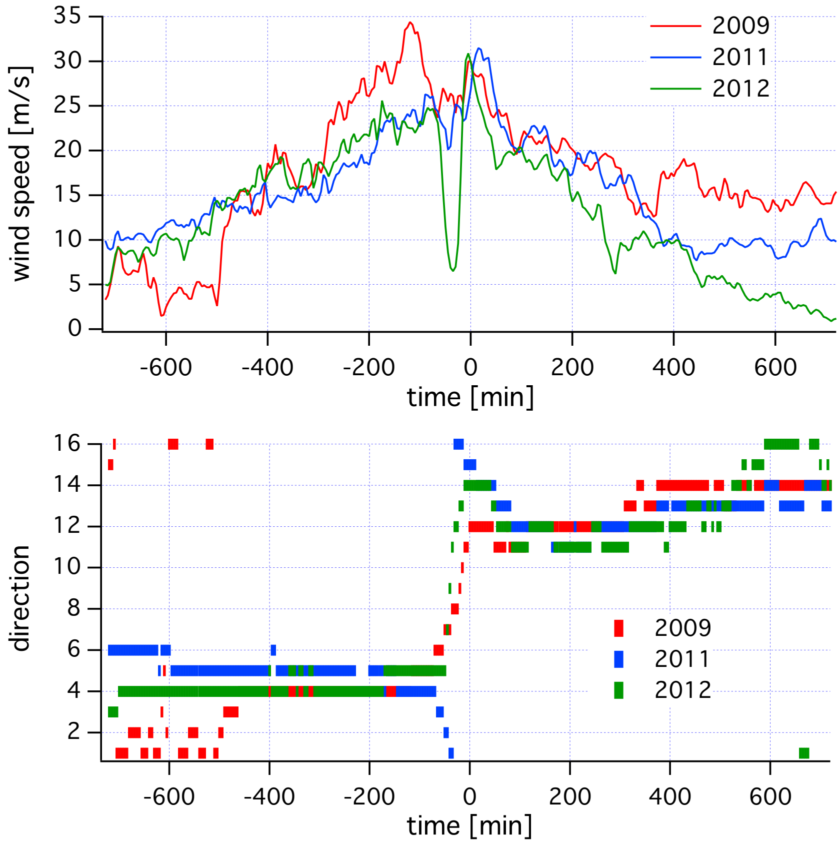

Figure 4. Variation of wind speed and direction at Stn. W1 in the storm surge period when the tidal departure at Stn. A shows the maximum at time = 0.

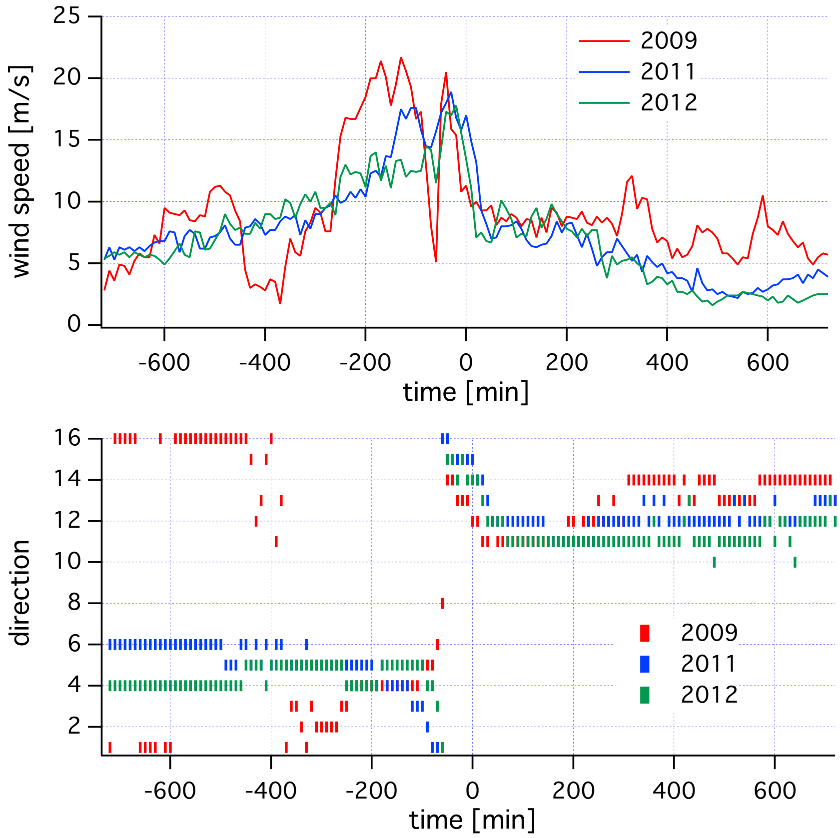

Figure 5. Variation of wind speed and direction at Stn. W2 in the storm surge period when the tidal departure at Stn. A shows the maximum at time = 0.

STORM SURGE

As mentioned above, we carried out the measurements of bottom pressure (water level) and current profile at Stn. A using ADCP (Nortek, Aquadopp) in the periods of the three typhoon events. The time interval of measurement was 10 min. and the vertical resolution of velocity measurement was 0.5m in 2009 and 1m in 2011 and 2012. The water depth at Stn. A was 7m – 8m.

Figure 6 shows water surface elevations at Stn. A, converted from bottom pressures in which no correction was made on atmospheric pressure. Same as the figures of atmospheric pressure and wind, time = 0 indicates the time at which the tidal departure at Stn. A shows the maximum. Comparing the three cases, the sea level for 2009 increased quickly and showed larger peak than other two years. Figure 7 shows the tide record at Stn. M located in the west side of the bay. The sea level in 2009 did not increase very much compared to that at Stn. A.

Figure 8 compares the tidal departures for three years. The departures were obtained by eliminating tidal components with the period larger than 10 hours. Although the maximum departure of 2009 was much larger than other two typhoons, waveforms of the oscillation of three surges look very similar, in which the second peaks of oscillation occurred about four hours after the first peak.

Figure 9 shows tidal departures at the stations N (Nagoya) and T (Toba), located in Ise Bay. The data were obtained every hour. The maximum departures at these stations occurred before the time the tidal departure at Stn. A showed the maximum (time = 0). The precedent sea level rise in Ise Bay was larger in 2009 than other two years. This is due to the preceding strong east wind seen in Figs. 4 and 5.

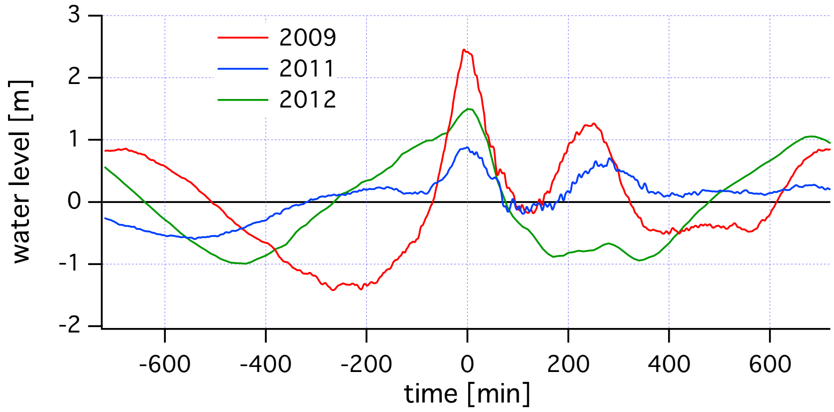

Figure 6. Water surface elevation measured at Stn. A in the storm surge period when the tidal departure at Stn. A shows the maximum at time = 0.

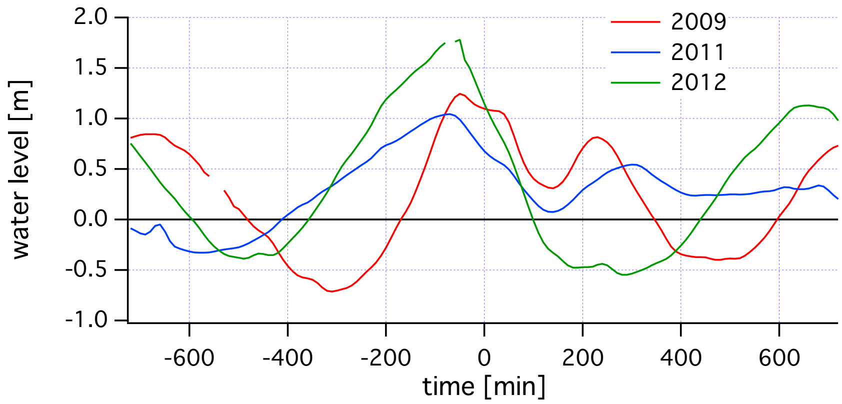

Figure 7. Tidal record at Stn. M in the storm surge period when the tidal departure at Stn. A shows the maximum at time = 0.

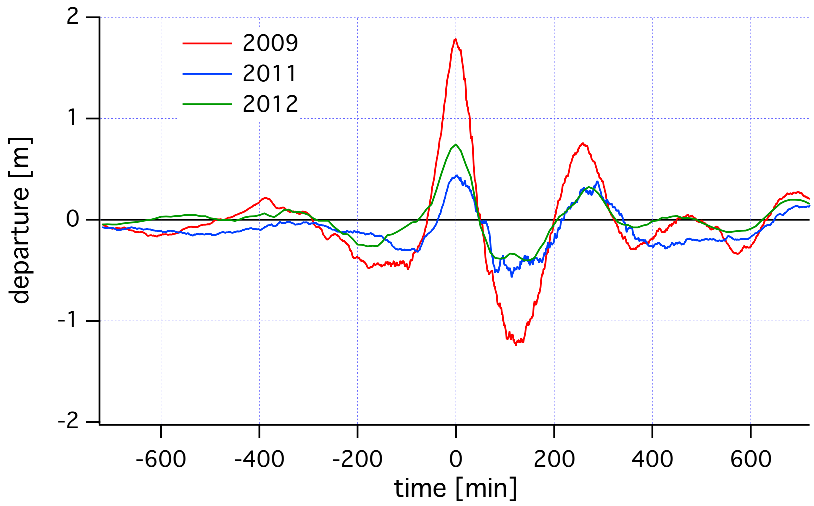

Figure 8. Tidal departure at Stn. A in the storm surge period when the tidal departure at Stn. A shows the maximum at time = 0.

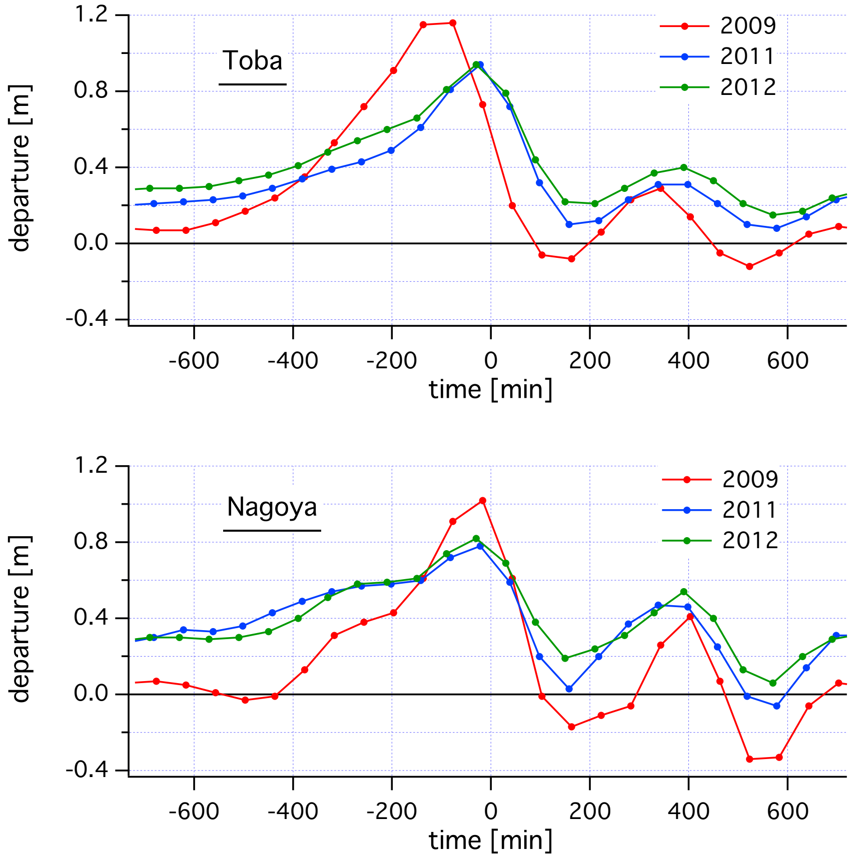

Figure 9. Tidal departure at Stns. N and T in the storm surge period when the tidal departure at Stn. A shows the maximum at time = 0.

MECHANISM OF OCCURRENCE OF HIGH STORM SURGE IN MIKAWA BAY

In this section, we investigate what happened in the storm surge period and what caused such a high storm surge only in 2009. In the following, we discuss it by using the current data at Stn. A and Stn. S, and also by employing a simple numerical model.

(1) Currents induced by storm surges

Figure 10 shows the time series of EW velocities at the surface (6.5m above the bottom) and at the bottom (1.5m above the bottom) of Stn. A. We notice that the EW velocities became zero at the tidal departure showed the maximum (at time = 0). Also, as clearly seen in the bottom velocities, current direction changed east to west at about time = 0. Especially in the case of 2009, the surface velocity varied in phase with the bottom velocity, which indicates that a free long wave propagating from west was reflected in the head of the bay at time = 0. To confirm this, vertical profiles of EW velocity are plotted in Fig. 11, in which velocities at 30 min. before and 30 min. after the peak were compared. It can be confirmed that the current inverted at time = 0, which is very clear in the case of 2009.

Figure 12 shows the water surface elevation and velocities measured at Stn. S located at the entrance of Mikawa Bay. In the period between 4:00 A.M. – 6:00 A.M., when wind direction inverted from east to west, the current in the direction of north-east, i.e. the current flowing into Mikawa Bay, was clearly observed both at the surface and the bottom.

Based on the fact shown above, the maximum departure occurred at the moment when the bottom velocity changed its direction from east to west. Considering that the current profile at this moment showed vertically uniform and in phase from the bottom to the surface, the sudden rise of sea levels at the head of the bay may be related to the free wave propagation and reflection, triggered by the inversion of the wind direction.

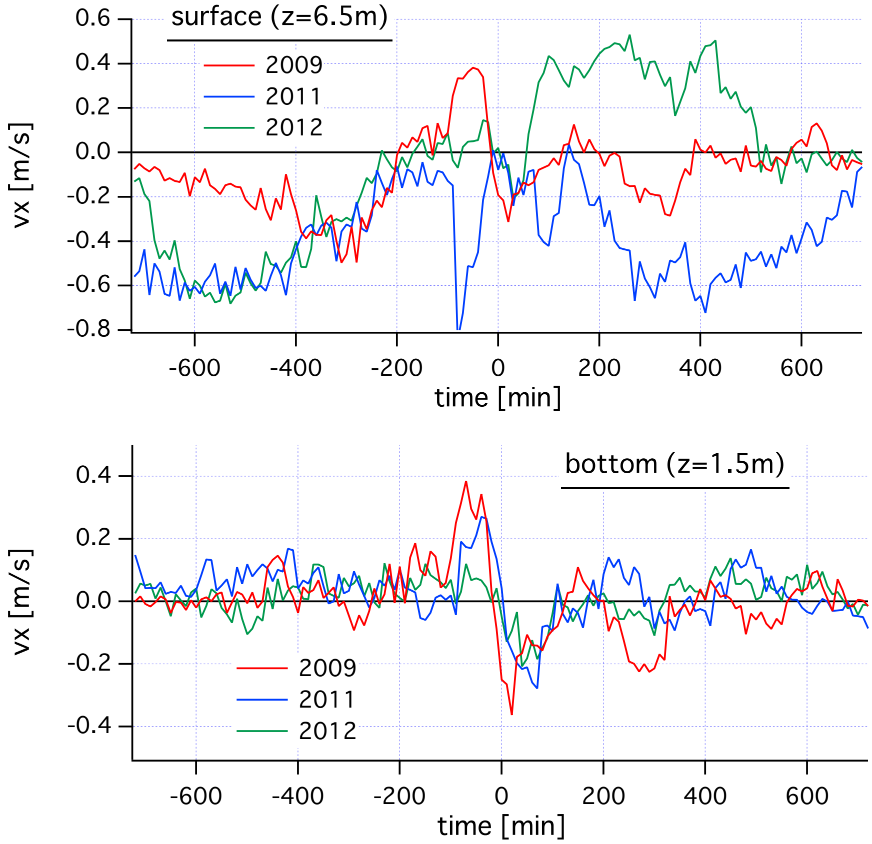

Figure 10. Surface and bottom current velocities in EW direction at Stn. A in the storm surge period when the tidal departure at Stn. A shows the maximum at time = 0.

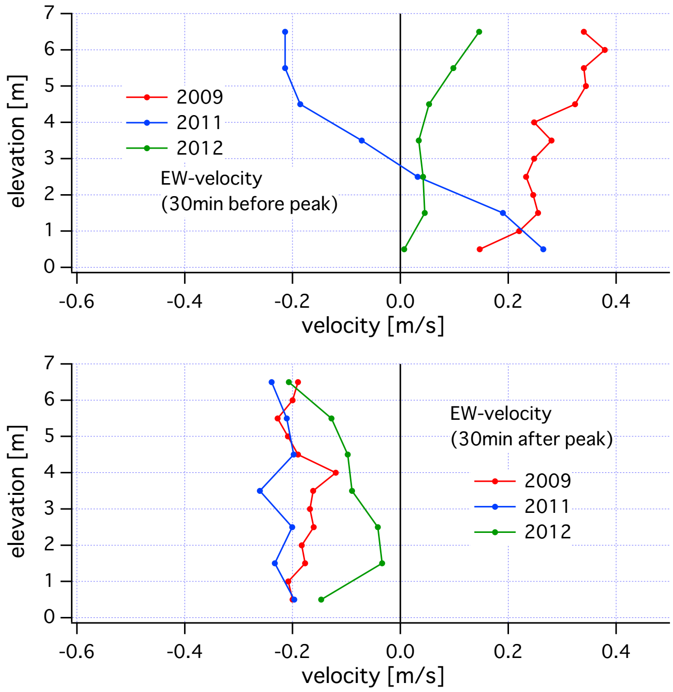

Figure 11. Vertical current profiles at Stn. A at the time 30 minute before and after the time when the tidal departure at Stn. A shows the maximum.

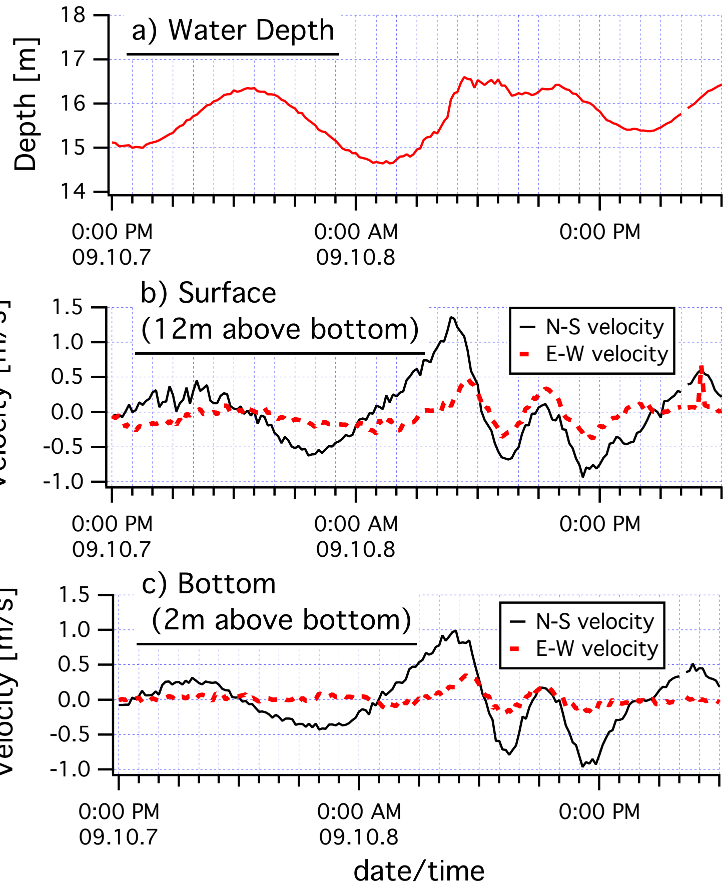

Figure 12. Variations of water depth and current velocities at Stn. S.

(2) Numerical simulation

In order to investigate the effect of the duration that the wind direction inverted from east to west, a simple numerical model was developed. As shown in Fig. 13, Mikawa Bay is modelled as a 2D flume with constant depth. The governing equations and boundary conditions are as follows. The values of the eddy viscosities, K_x and K_z, and the drag coefficient C_D are 10m^2/s, 0.001m^2/s and 0.002, respectively. The equations were solved by the implicit finite difference method with grid numbers of 50 and 20 in x and z directions, respectively. The time step was two minutes.

$$\frac{\partial u}{\partial t} = -g\frac{\partial \eta}{\partial x} + K_x\frac{\partial^2 u}{\partial x^2} + K_z\frac{\partial^2 u}{\partial z^2} \qquad (1)$$

$$\frac{\partial \eta}{\partial t} = -\frac{\partial}{\partial x}\int_{-h}^{0} u\,dz \qquad (2)$$

$$\tau_s = \rho K_z\frac{\partial u}{\partial z} \qquad at \qquad z = 0 \qquad (3)$$

$$u = 0 \qquad at \qquad z = -h,\ x = l \qquad (4)$$

$$\frac{\partial u}{\partial x} = 0 \qquad at \qquad x = 0 \qquad (5)$$

In the simulation, the east wind of U = +20m/s was first blown until the surface elevation reached the steady state. Then the wind direction was changed linearly to U = -20m/s (west wind) in different durations: 30, 90 and 180 minutes. Figure 14 shows time series of water surface elevation at the east end of the flume which correspond to the head of the bay. The results showed that short turnover period tends to cause large oscillation i.e. large surface elevation

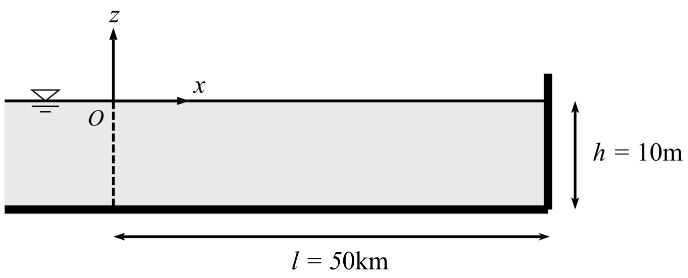

Figure 13. Condition of numerical simulation.

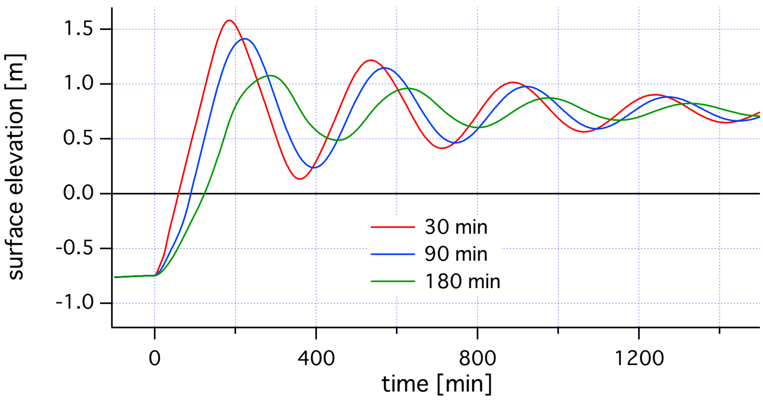

Figure 14. Comparison of surface elevations.

CONCLUSIONS

In this paper, we discussed the development mechanism of high storm surge in Mikawa Bay by comparing the recent three events of storm surges caused by typhoons. Major findings are as follows.

(1) Storm surges in Mikawa Bay occur under the west wind after typhoons passed over the bay. The magnitude of the storm surge, however, are influenced by the wind speed and duration of preceding east wind which gives rise to the sea level in Ise Bay.

(2) Quick inversion in wind direction induces the inflow of water mass from Ise Bay to Mikawa Bay as a free long wave which gives large sea level rise when the wave reflects in the head of the bay.

ACKNOWLEDGMENTS

The authors would like to thank Chubu Regional Development Bureau of MLIT, Aichi prefectural government, and TST Corporation for providing the field data used in this paper. The assistances of the former colleagues and students of Toyohashi University of Technology are appreciated.

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