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ON THE STORM SURGE GENERATED IN ARIAKEKAI BAY

By Kinji SHINOHARA

Synopsis: This paper presents the method of evaluating appropriate values of storm surge and the relation between properties of low pressure and the occurrence of abnormal rising of water level as well as the characteristics of storm surge at the various places of Ariakekai Bay, based on the data of storm tide collected at the author's laboratory for the past 10 years.

1. Introduction

Ariakekai Bay is an inland sea with an area of about 1700 km^2 and surrounded by 4 prefectures of Nagasaki, Saga, Fukuoka and Kumamoto in Western Kyushu (Fig. 1). The Bay is shaped almost like an *L* which is bent orthogonally in its center and connected with Tachibana Bay in the open sea through Hayasaki-Strait and also with Yatsushirokai Bay through Misumi-, Hondo- and Yanagi-Strait. The distance along the axis from the innermost part of Ariakekai Bay to the entrance is about 90 km, 17 km in average width and has 50 m water depth in the part along the coasts of Shimabara Peninsula from Hayasaki-Strait, but the interior part is shallow to a great distance from the shore, having about 20 m water depth in average.

The tide along the coasts of Ariakekai Bay is as shown in Table 1 according to 1960 Tide Table. It is seen from the table that the mean sea level of the innermost part (Suminoe) is about 1 m higher than the entrance (Kuchinotsu), spring rise 2 m higher and neap rise 1.3 m higher respectively, which shows gradual increase

Table 1.

Place	Latitude (N)	Longitude (E)	Time Diff. to H. W.*	Rise		Tidal Range		
				Spring	Neap	Mean	Spring	Neap
Kuchinotsu	32° 36′	130° 11′	−10min.	3.4 m	2.6 m	2.08m	2.90m	1.26m
Misumi	37′	27′	−10	4.0	3.0	2.50	3.54	1.46
Shimabara	47′	22′	0	4.4	3.3	2.94	4.06	1.82
Takezaki	57′	13′	0	5.1	3.7	3.16	4.54	1.78
Miike	33° 1′	25′	0	5.0	3.7	3.18	4.56	1.80
Wakatsu	13′	21′	+ 5	5.0	3.7	3.22	4.58	1.86
Suminoe	12′	12′	+20	5.4	3.9	3.44	4.94	1.94

* Compared with Miike as standard

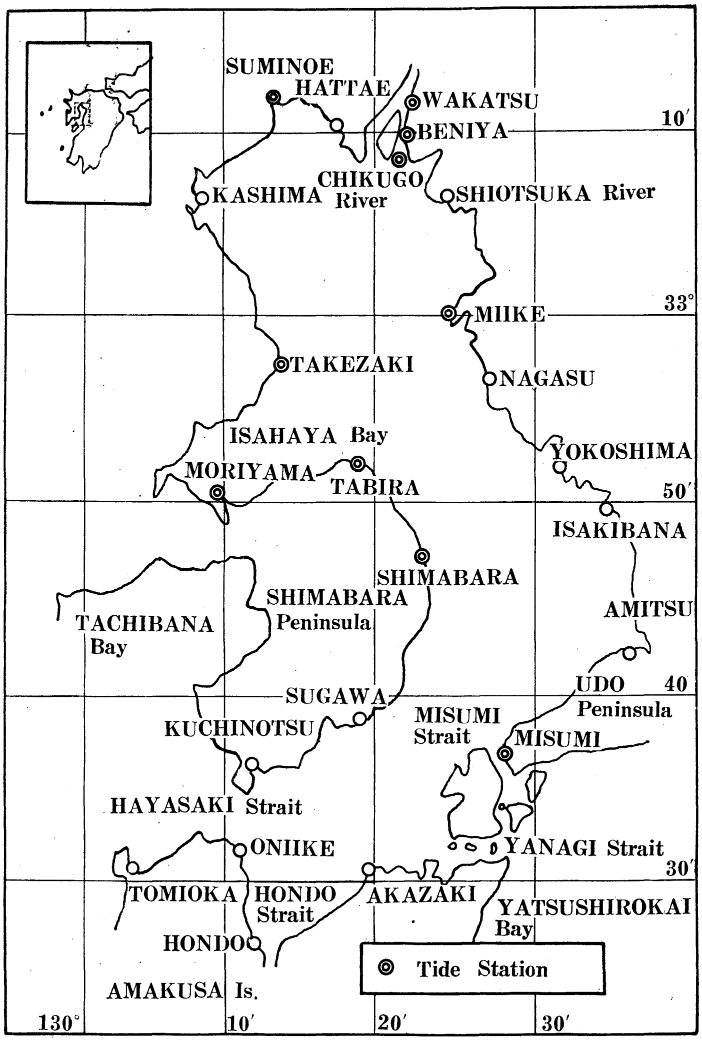

Fig. 1.

in the sea level from the mouth to the interior sea. The time of flood tide at the mouth of the Bay is different about 30 minutes from that of the interior sea. Also the values of the tidal range given in the table, which were evaluated from the existing harmonic constants of tide, show increase from the mouth to the interior sea, the value of the innermost part being higher than that of the entrance by 1.4 m in average, 2 m at spring tide and 0.7 m at neap tide respectively. Since each strait connected to Yatsushirokai Bay has narrow width and shallow depth as known from the chart, the volume of water flowing in and out at the mouth of these straits is not so large. It is therefore considered that the tide at Ariakekai Bay is chiefly subjected to that of the open sea passing through Hayasaki-Strait. The volume of sea water flowing in and out is 6.3 km^3 at spring tide and 2.7 km^3 at neap tide according to the calculation of the Nagasaki Marine Meteorological Observatory.

The records of abnormal rising of water level occurred hitherto along the coast of Ariakekai Bay give 34 times before 1868 and 19 times between 1868 and 1945. The occurrence especially well known after 1868 took place on the 25th of August, 1914 and the 13th of September, 1927. Their maximum storm surges were estimated at 2～2.5 m and 3 m respectively. This report gives the method of evaluating appropriate values of storm surge and the relation between properties of low pressure and the occurrence of abnormal rising of water level as well as the characteristics of water level and storm surge at the various places of Ariakekai Bay, based on the data of storm tide collected at the author's laboratory for the past 10 years.

2. On the data

The tide stations where investigations were made are nine in all as given in Fig. 1 and the tide gauges used are the three kinds of Fuess type, Richard type and Roll type.

The meteorological disturbances that were made an object of these investigations were the occasions of the passage of typhoons or low pressure which seemed to cause abnormal rising of water level. The meteorological disturbances considered here cover the period of 10 years between 1951 and 1960 since the data were collected during corresponding time. Within the range of the author's investigations, the numbers of typhoons which are likely to cause storm tide in Ariakekai Bay are 16 given in Table 2. Three of them that swept across the Bay or crossed over it longitudinally or just passed near it are Nos. 2, 3 and 8, eight of them that passed Kyushu Island obliquely or longitudinally are Nos. 1, 4, 5, 6, 7, 9, 10 and

Table 2.

Typhoon	Date of Occurrence	Name	Lowest press. at Miike (mb.)
No. 1	1951, Oct. 14	Ruth	966.7
No. 2	1951, Nov. 15		1014.9
No. 3	1952, July 14	Freda	1005.0
No. 4	1954, Aug. 18	Grace	970.6
No. 5	1954, Sept. 7	Kathy	998.9
No. 6	1954, Sept. 13	June	964.6
No. 7	1954, Sept. 26	Marie	983.8
No. 8	1955, July 16	Dot	1004.0
No. 9	1955, Sept. 30	Louise	970.6
No. 10	1955, Oct. 4	Marge	1003.9
No. 11	1956, Aug. 17	Babs	978.4
No. 12	1956, Sept. 10	Emma	984.0
No. 13	1956, Oct. 8		1008.2
No. 14	1957, Aug. 21	Agnes	990.6
No. 15	1957, Sept. 7	Bess	987.1
No. 16	1959, Sept. 17	Typhoon No. 14	993.4

15 and five of them headed north on the western side of the Bay are Nos. 11, 12, 13, 14 and 16. In the same table, the values of the lowest pressure at Miike are also given. Showing these typhoons in the figures by classifying them into three parts according to their tracks, the result will be as shown in Figs. 2~4.

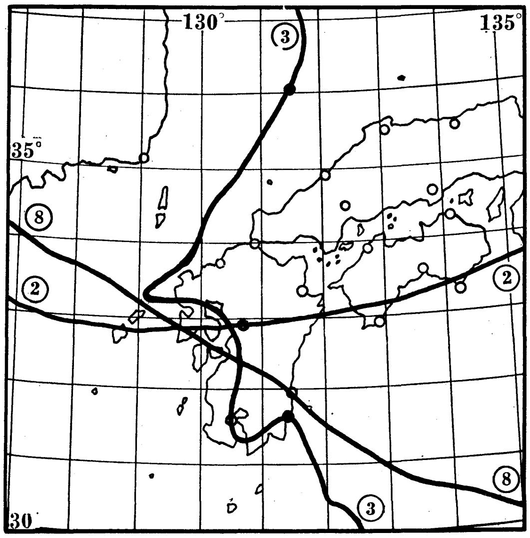

Fig. 2.

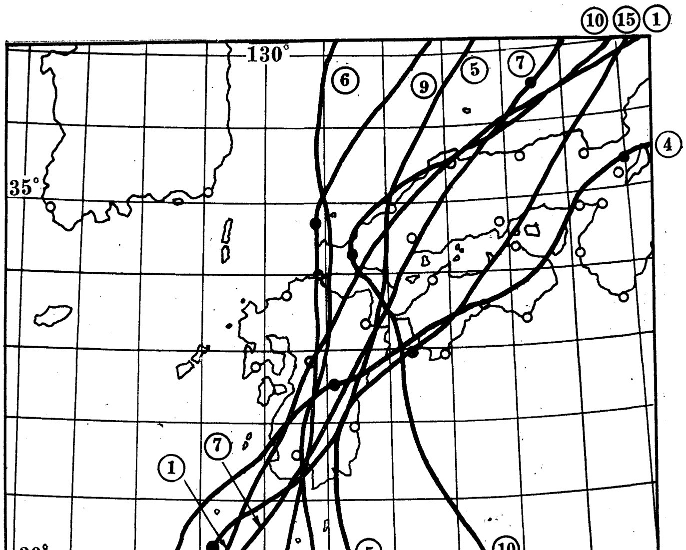

Fig. 3.

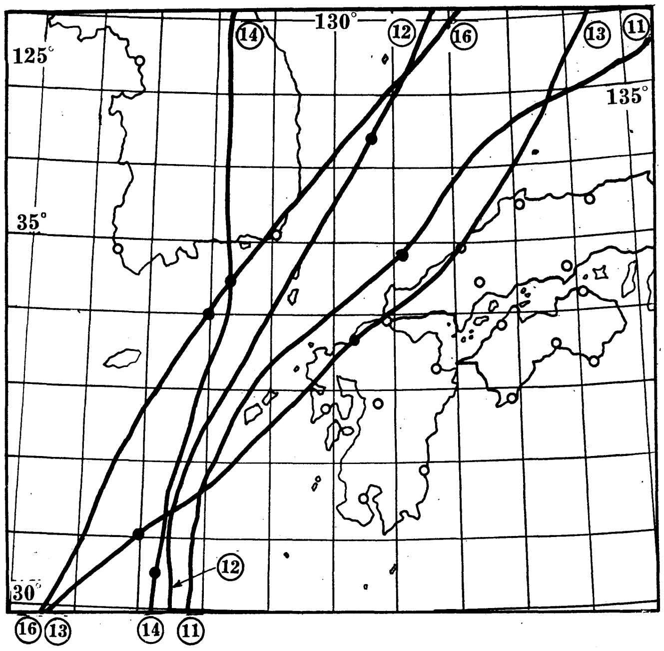

Fig. 4.

What is to be considered in evaluating the storm surge is the method of estimation of water level at normal state or sea water level by astronomical tide in which no meteorological disturbances are assumed to have occurred. The author tentatively weighed the following methods.

(1) A method to use harmonic constants of tide

This method has been found to be inapplicable to the place where constant is unknown and, even when many component tides are used as in the tide table, it gives sometimes the discrepancy of 50 cm at the most as compared with the observed value.

(2) A method to use known observed data

a) Mean value of water levels on the days of almost equal age of the moon, 6 months before and after the day in consideration, provided that the water level in the morning is exchanged for the one in the afternoon.

b) Mean value of water levels of the days before and after such semilunar month as almost equal age of the moon from the day in consideration, that is, the mean value of water level before and after almost half a month of the day.

c) Mean value of water levels before and after 25 hours of the time in consideration.

d) Mean value of water levels about 25 hours before and after the time in consideration, provided that the observed time of flood tide coincides with that of the estimated tide.

Applying the above-mentioned four kinds of estimation method to the known

Table 3. Estimated Max. Storm Surge (cm)

Typhoon	Misumi	Miike	Beniya	Suminoe	Takezaki	Moriyama
No. 2	14(SW)	24 (N)	17	13	—	—
No. 3	19(ENE)	0	—	0	—	—
No. 8	17(SSW)	28 (SE)	—	75?	—	—
No. 1	49(W)	55 (NE)	—	—	—	—
No. 4	40(NNE)	36 (N)	—	14	61	—
No. 5	23(WNW)	32 (W)	46	39(W)	28	—
○No. 6	59(NE)	61 (SW)	120	66	64	—
No. 7	39(NE)	43 (W)	50	48 (NNW)	29	—
No. 9	41(WSW)	41 (W)	?	46(W)	—	—
No. 10	?	19? (NE)	16	34	—	—
No. 15	17(NW)	22 (N)	65	22	—	—
◎No. 11	103(SSW)	151 (SW)	237?	—	—	138
◎No. 12	89(SSW)	124 (SW)	188	208 (SSW)	—	75?
No. 13	19(NW)	25 (NW)	—	—	—	21 (S)
○No. 14	50(SSE)	56 (SE)	67	74	—	55
◎No. 16	58(SSW)	102 (S)	133	—	69	—

(…) Wind direction, ○ Reliable data, ◎ Most reliable data,
— No recording

water level at normal state, method (a) has been found to have less fitness compared to (b)~(d) and is less convenient in calculation or in collection of data. Methods (b)~(d) have almost the same fitness, but method (d) is considered to be most appropriate for the convenience of practical calculation and the scarcity of discrepancy in the time of flood tide. The author therefore adopted method (d).

The result of evaluation made on the storm surge at the time of meteorological disturbances with the foregoing 16 cases are given in Table 3.

3. Characteristics of sea level along Ariakekai Bay

At spring tide between the 24th~25th of October, 1961, Kyushu Branch of Ministry of Construction carried out the simultaneous observation of water level along the coasts of Ariakekai Bay. Graphitizing the simultaneous tide level and the high water level at various places in the Bay with the high water level at Tomioka on the outside of the Bay which is considered to represent the water level of open sea as a standard, the result will be as shown in Fig. 5.

According to the record, at the interior part from Misumi in the Bay, there is little deviation of time at flood tide, except at the mouth of the Chikugo and the Rokkaku rivers (innermost part of the Bay) where time lag is less than 30 minutes. As to the time of ebb tide, deviation is larger than at flood tide with about 1 hour or an hour and a half time lag. For the above-mentioned reasons, the line connecting the water level at flood tide of various parts in the figure may

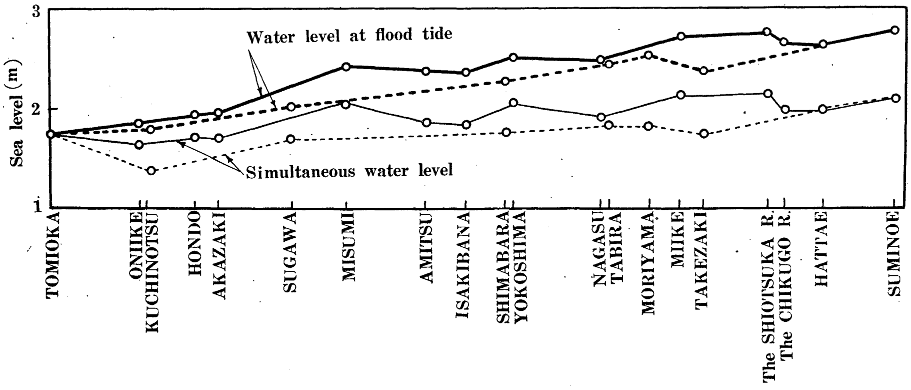

Fig. 5. Sea levels of various places of the ARIAKEKAI Bay
(Full line shows the east side of the Bay, dotted line shows the west side of the Bay)

be regarded as that of simultaneous water level in the part farther to the interior from Misumi. As seen from the figure, the slope of sea surface tending to the mouth is steeper than that tending to the interior part of the Bay with the adjacent parts along Misumi as boundary.

Also, compared to the east coast of Ariakekai Bay the water level at the west coast is lower, which is likely to be related with the convection current in the Bay.

When the slope of sea water surface at storm tide caused by principal typhoons for the past 10 years is compared with that at normal state, there is observed little difference at the part between Misumi and Miike, but at the interior part farther from Miike, the rise of water level is larger than that at normal state. This is considered to be due to the topographical effect, but there may be also some effect from the local rising of water level due to the flood accompanying to typhoons since many of the tide stations in the interior are built on the rivers, as those at Suminoe and Beniya.

4. Anomaly of water level at the storm

(1) Track of typhoon and storm surge

The typhoons that were made objects of investigation will be considered by dividing them into three kinds according to their tracks.

a) When they pass the Bay or its neighbourhood, [Typhoon Nos. 2, 3, 8 (cf. Fig. 2)]

Since low pressure passes the Bay, across or longitudinally or around its circumference, there will naturally be expected considerable anomaly of water level. The storm surge in September 1927 is a representative one in these tracks, whose maximum anomaly of water level is reported to be 3 m. In the case of Nos. 2, 3 and 8 the lowering of pressure all showed slight with little storm surge because of weak wind velocity. The one that has comparatively large storm surge was typhoon No. 8, which was 75 cm at Suminoe. The wind direction was SSE and the maximum wind velocity was 8.5 m/sec.

b) When they pass the east side of the Bay, [Typhoon Nos. 1, 4, 5, 6, 7, 9, 10, 15 (cf. Fig. 3)]

The typhoons that pass the east side of the Bay include those sweeping Kyushu Island longitudinally and those cross diagonally the south eastern part of Kyushu. Among those that passed Kyushu longitudinally Nos. 9 and 6 came closest to Ariakekai Bay. With these typhoons, the lowering of pressure is conspicuous, but storm surge is comparatively small. It is generally believed that storm surge is caused not only by the lowering of pressure but by the effect of piling action of water, blown together by the wind (Built up). The wind causing this effect is that directed from SSE up to *W*, and in the case of a typhoon passing along the east side of the Bay, this kind of wind direction is scare in number, which explains the smallness of storm surge. On the other hand, when this track is taken, the time when the maximum surge occurs is considerably deviated from that of the maximum lowering of pressure.

c) When they pass along the west side of the Bay, [Typhoon Nos. 11, 12, 13, 14, 16 (cf. Fig. 4)]

As it is already known, when a typhoon takes this track, unusually high water level with large surge is likely to occur. The same thing can be said about the 5 typhoons that occurred during the period of investigations made by the author. However, when lowering of pressure is small, even if the track lays close to the Bay, as in the case of No. 13 typhoon, there is hardly any surge. It is understandable why typhoons No. 11 and No. 12 showed large surge from the facts that lowering of pressure was considerably large and that the wind direction was south-

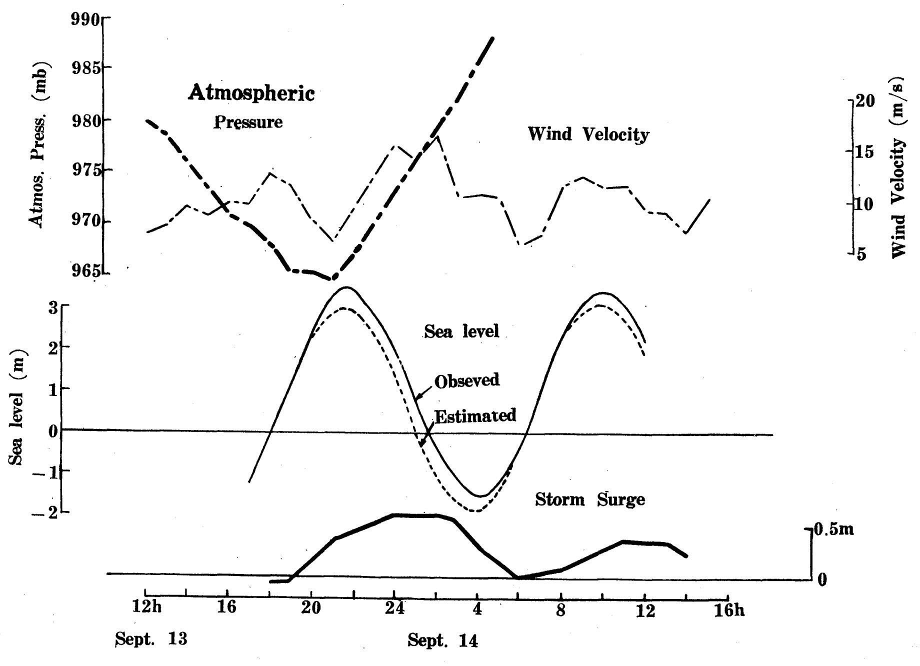

Fig. 6. Data at MIIKE in the Typhoon No. 6

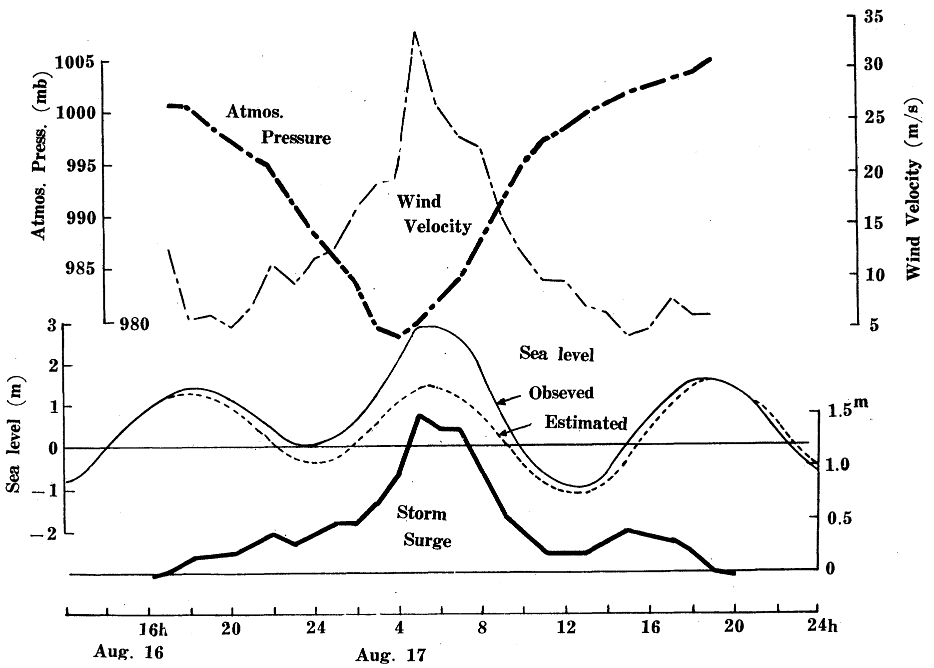

Fig. 7. Data at MIIKE in the Typhoon No. 11

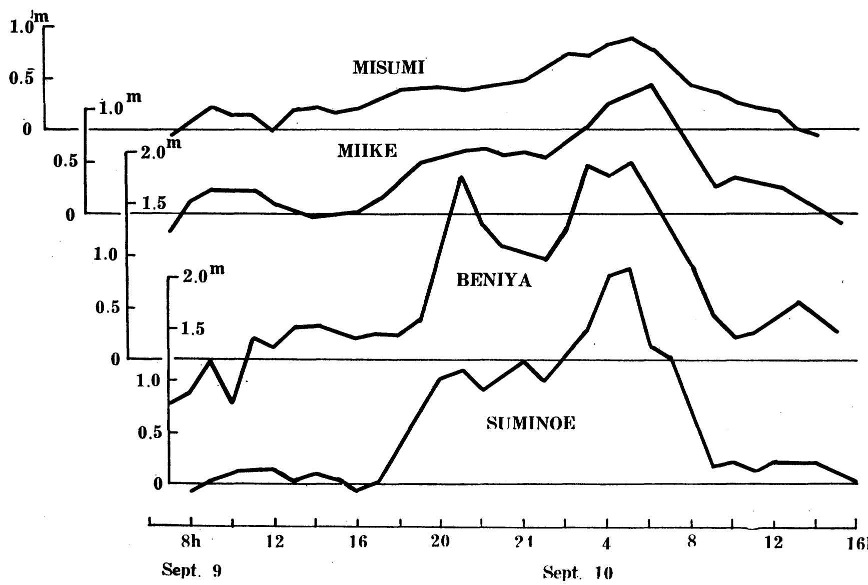

Fig. 8. Storm surges at various tide stations in the Typhoon No. 12

west with velocity of 20～30 m/sec. With this track there is seen clear storm surge curve.

The above-mentioned facts lead to a conclusion that it is when a fairly large typhoon sweeps longitudinally or across Ariakekai Bay or when it passes along the western side of the Bay that a large storm surge occurs. It is also found about the case of a typhoon passing on the western side that there occurs surge larger than that of a typhoon passing on the eastern side, even if lowering amount of pressure were small. This is suggestive of the conditions necessary for large surge to occur in the Bay, that is, beside the lowering amount of pressure, appropriate direction of the wind (SSE～W) and wind velocity.

(2) Characteristics of storm surge

As an example showing the process of time change of surge at a tide station, the records of typhoons Nos. 6 and 11 at Miike will be given in Figs. 6 and 7. No. 6 shows the typhoon progressing east side of the Bay and No. 11 that progressing west side, and a considerable degree of discrepancy is noticed in the relation between the astronomical tidal curve and observed tidal curve of the two.

In Fig. 8 is shown the storm surge curves of typhoon No. 12 at Misumi, Miike, Beniya and Suminoe. While the time change of surge is varied a little according to each tide station, the period during which surge occurred and the time at which the maximum surge occurred are almost the same. The amount of the maximum surge shows increase, the further to the interior of the Bay.

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