The Storm Surges in the Seto Inland Sea Caused by Typhoon Chaba (0416) in Japan

by

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ABSTRACT

Typhoon Chaba in 2004 made landfall on the southeastern Kyushu and went through Chugoku (western part of Japan's Main Island) on 30 August, causing large storm surges in the Seto Inland Sea (SIS). The high tide records were broken at tide stations in Takamatsu and Uno Ports. We analyzed the tidal data and simulated this case with a numerical storm surge model.

The results revealed that the wind set-up basically played a key role in causing the large storm surges. However, the maximum storm surge (MSS) in Takamatsu did not occur when the typhoon was the nearest to the city, but about 2 hours later. Since the time of MSS approximately corresponds to the high spring tide time, the record breaking storm tide was observed there.

KEYWORDS: Storm Surge, Typhoon Chaba, timing of warning

1. INTRODUCTION

Storm surges generated by typhoons have often brought large disasters in the coast of Japan. Especially, in the case of Typhoon (TY) Vera, which caused 5,098 dead or missing in 1959, most of the casualties were brought by the storm surges. The countermeasures to storm surges have developed progressively after this disaster. However, serious storm surges still occurred. In 1991, large storm surges were generated in the western part of the Seto Inland Sea (SIS; shown in Fig.1) by TY Mireille[1, 2]. However, severe disaster did not occur since the maximum storm surge (MSS) occurred just in low tide. In 1999, the storm surges by TY Bart led to serious disasters; 13 people were directly killed by storm surges in Yatsushiro Sea, and Yamaguchi-Ube airport in the Suoh-Nada (western part of the SIS) was unavailable by inundation[3, 4]. The tracks of these two





The whole area of the Seto Inland Sea from the Suoh-Nada to the Osaka Bay is an inland sea. The points of tide stations are also shown.

typhoons are almost the same and both of them generated large storm surges in Yatsushiro Sea. Recently, intense typhoons have frequently hit Japan since 2000, and serious disasters sometimes happened. In 2004, as many as ten named tropical cyclones made landfall on Japan, which is quite extraordinary since usual number is two or three. Several tropical cyclones brought disasters due to storm surges. Especially,

TY Chaba generated large storm surges in the SIS, and the coincidence of MSS with the peak time of high tide caused the highest storm tide records at Takamatsu and Uno (central part of the SIS). More than 8,300 houses are inundated above the floor level only in Kagawa Prefecture, and total damages were quite

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enormous as 16,799 houses inundated above the floor level.

Although large storm surges sometimes occurred in the SIS due to typhoon passages as mentioned above, most cases happened in the Suoh-Nada (western part of the SIS) or the Osaka-Bay (eastern part of the SIS), and they rarely occurred in the central part of the SIS. TY Chaba is applicable to the latter case. This case is also characterized by the fact that the MSS occurred a few hours later than the time when the typhoon was nearest. Therefore we have investigated the mechanism of this storm surge with a concern to the effects of sea topography and the sequence of typhoon position, mainly based on a numerical model.

TY Chaba and storm surges in the SIS are described in section 2, and the results are provided in section 3. Section 4 focuses on the factors that may mainly contribute to storm surges, and the conclusion is summarized in section 5

2. TY CHABA(0416) AND STORM SURGES IN THE SIS

2.1 TY Chaba (0416)

A tropical depression (TD) was formed in the sea around the Caroline Islands at 06UTC (all times are expressed in UTC hereafter) on 18 August 2004. It moved slowly westward and developed into a Tropical Storm Chaba at 12UTC on 19 August. Chaba continued to move westward and was upgraded into a Typhoon at 18UTC on 21 August. Then it turned toward the northwest at the southwestern edge of sub-tropical high on 23 August. The typhoon continuously intensified during this period and developed to the strongest level as central pressure of 910hPa and the maximum wind speed of 56m/s at 18UTC on 23 August.

The typhoon kept its intensity till 18UTC on 26 August, moving to northwest and gradually weakened. The typhoon moved to west again in the sea east of the Nansei Inlands and turned to the north-northeast in the sea south of Kyushu.

The typhoon made landfall at Kushikino at about 00UTC on 30 August, with central pressure 950hPa, the maximum wind speed 41m/s, and the radius of storm wind extended to

230km east (Fig. 2). The typhoon passed through Kyushu and moved northward in the Suoh-Nada, and made landfall again at around Hohfu. As the TY Chaba approaching, Chugoku, Shikoku, northern and central part of Kinki were gradually covered by storm winds. The typhoon passed Tottori at about 12UTC with slightly



Fig. 2 Best track of TY Chaba (0416)

The circles on the path indicate the positions of the typhoon every 3 hours. Days and hours (UTC) are plotted to the upper left and central pressures (hPa) to the lower right of each point.

weakened intensity (central pressure 960hPa and the maximum wind speed of 31m/s), and became to move faster in the Sea of Japan. The typhoon made landfall again at Hakodate at 03UTC on 31 August, and transformed into an extratropical cyclone in the east of Hokkaido at 06UTC.

Strong winds were observed in the areas the typhoon passed nearby. In Okayama, the maximum wind of 21.1m/s (SW) and the maximum gust of 38.5m/s (SW) were observed at 15:20 and 12:51UTC on 30 August, respectively; those were the highest records there.

2.2 Storm Surges in the SIS by TY Chaba

The main storm surges in the SIS by TY Chaba occurred from 30 to 31 August. Fig. 3 shows the time series of hourly storm surges (the each

storm surge is defined by detracting astronomical tide from observed sea level) observed at tide stations. The magnitudes of the MSSs are generally about 1-1.5m.

The more east the observation point is located, the later the MSS was observed. (Table 1). For example, in the western part of the SIS, the MSS of 1.33m in Moji was observed at 06:36. The MSSs in Hiroshima and Matsuyama occurred at 09:35 (1.49m) and 08:49 (1.40m), respectively. MSSs in Takamatsu and Uno were observed after 13UTC, 4 hours later than that in Matsuyama. The MSS of 1.33m was observed at 13:23 in Takamatsu, and 1.37m at 13:16 in Uno. In Kobe and Osaka, that are in the eastern part of the SIS, the MSSs were observed just before 15UTC: 1.34m at 14:42 in Kobe and 1.32m at 14:30 in Osaka.

Fig. 4 shows the water levels at several tide stations. The magnitudes of the storm surges are not so different among these points, but the magnitudes of the storm tides are different each other because the timing of the astronomical tides are different each other. Since the time of MSSs were the same as that of low tide in Moji, storm tides did not become so high; the maximum tides were observed about 6 hours earlier than the time of MSS (around 00:30), this was mostly contributed by high tide, not the storm surge. The maximum storm tides of 2.58m (Matsuyama) and 2.69m (Hiroshima) were observed at 11:56 and 12:56 respectively, 2-3 hours earlier than the high tides. The maximum storm tide there results from combination of storm surge and astronomical tide. The maximum storm tides were observed in Takamatsu and Uno at 13:42 and 13:47, respectively, only 30 minutes later than MSS. Moreover, since it was period of spring tide,

water levels at high water were higher than usual. This also led to the highest record of maximum tides as 2.46m (Takamatsu) and 2.54m (Uno). This extraordinary high storm tide caused enormous disasters. and more than 12,000 houses were flooded to over floor level in these coastal areas. The maximum storm tides were

observed at 12:24 in both Kobe and Osaka to the east of Takamatsu, which was about 2 hours earlier than the time of MSSs.

In order to investigate the relation of storm surges to the relative position of typhoon, the



Fig. 3 Storm surges observed at several tide stations in the Seto Inland Sea.

time of MSS and the time when the minimum sea level pressure (MSLP) was observed, which corresponds to the time when the typhoon mostly approached, are listed in Table 1. The easterly wind was predominant in the western part of the SIS as the typhoon was approaching, and the sea level became higher from early stage in the Suoh-Nada. Around the Suoh-Nada area, the times of MSSs were almost the same as the time of the MSLP, since the typhoon passed through the Suoh-Nada. For example, in Moji, the time of MSS (1.33m) was only 6 minutes later than MSLP time. After the typhoon passed and made landfall at Chugoku region, the predominant wind turned to westerly in the wake of typhoon, and large storm surge area shifted to the eastern part of the SIS gradually.

 Table 1
 The maximum storm surges (MSS), the minimum sea level

 prossures (MSL P) and the difference of time

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Tide station	MSS (m) and	MSLP (hPa)	difference		
	time (UTC)	and time(UTC)	of time (min.)		
Moji	1.33 (06:36)	969.5 (06:30)	6		
Hiroshima	1.49 (09:35)	972.1 (10:16)	-41		
Matsuyama	1.40 (08:49)	972.8 (08:49)	_		
Uno	1.37 (13:16)	978.1 (10:48)	148		
Takamatsu	1.33 (13:23)	978.1 (11:01)	132		
Himeji	1.57 (14:50)	982.7 (13:13)	97		
Kobe	1.34 (14:42)	987.5 (14:05)	37		
Osaka	1.32 (14:30)	988.1 (13:42)	48		

The MSS was observed at almost the same time of MSLP in Matsuyama, but was 41 minutes earlier in Hiroshima. At the points to the east of Matsuyama, the MSSs were observed later than the time of the MSLP.

It is notable that the times of MSS in Takamatsu and Uno were more than 2 hours later than the times of the MSLPs, but in Himeji and Osaka, located in further east of Uno, the difference of times between MSS and MSLP became smaller again. This indicates that the storm surge area did not move monotonously to east while the typhoon was simply leaving northward.

3. SIMULATION RESULTS

Fig. 5 (a) shows the simulated storm surge distributions as well as the surface winds used in the calculations. The observation of winds is not



Fig. 4 The observed sea levels at several tide stations in the Seto Inland Sea The observed sea levels are indicated by a solid line; the broken line represents the astronomical tide. The arrows show the time of the minimum surface pressure.



Fig. 5 Horizontal distribution of (a)the simulated storm surge and the model wind, and (b) the surface wind of the hourly objective analyses.

The shades indicate simulated storm surges (m), and the contours in the left column show the model surface pressure. The barbs in both columns show the winds (long fletching is 10m/s, and short 5m/s)

so dense in this area, especially in the sea, for intensive comparison. Therefore, the surface winds of the hourly objective analysis, which is based on the operational Meso-Scale Model (MSM) prediction as a first guess and modified with the wind profiler observation, is shown in

Fig. 5 (b).

Storm surges are little detected in the whole area before the typhoon reached Kyushu and a gale wind started. In the Suoh-Nada, large storm surge area is generated by strong easterly wind ahead of the approaching typhoon (06UTC on 30 August). As the typhoon had passed the Suoh-Nada and moved northeastward, the wind turned to westerly, which led the large storm surge area to move eastward (10UTC). Around 13UTC, although the typhoon had already moved away northward, a large storm surge is notable in the central sea to the west of a narrow straight (just where Takamatsu and Uno exist). After that, although the typhoon continued to leave further, westerly wind continued to blow, and storm surge shifted eastward, to the Osaka Bay around 15UTC on 30 August.

The calculated MSSs at several points are listed in Table 2, and Fig. 6 shows the time series at Takamatsu: Observed and calculated storm surges, observed sea level pressures as well as those used in the model. According to Tables 1 and 2, all the calculated MSSs are favorably compared with observation and every error are within 0.30m. However, there are almost 1 hour differences in peak time at some points. This may mainly come from the error of meteorological data input, e.g. assumed pressure field, since the time of minimum surface



Fig. 6 The time series at Takamatsu

pressure given to the model is different from that of observation as shown in Fig. 6. The difference of pressure fields may also lead to the error of wind fields, but the wind fields in the time of MSS at Takamatsu was preferably estimated as shown in Fig. 5.

4. DISCUSSION

Generally speaking, storm surges are mainly caused by two factors: the inverted barometric effect and the wind set-up. Both of the effects are easily estimated to some extent by assuming the static balance. In addition, it is known that the dynamical effects such as resonance of the moving speed of meteorological disturbance and

Table 2The results of three calculations

Simulated magnitudes of the maximum storm surges (MSS), given MSLP with the occurrence time in parenthesis. Contribution ratio of the wind set-up in the MSS, CR, defined as the MSS in II divided by that in I is also listed.

Tide station	MSS(m) in I	MSLP (hPa)	MSS (m) in II	MSS (m) in III	CR	
Moji	1.61	969	1.35	0.52	0.40/	
	(05:40)	(07:20)	(05:20)	(08:40)	84%	
Hiroshima	1.44	969	1.01	0.70	((0)/	
	(10:10)	(10:20)	(08:50)	(11:10)	00 70	
Matsuyama	1.15	978	0.70	0.50	(00)/	
	(10:30)	(10:00)	(10:20)	(11:00)	60%	
Uno	1.19	983	0.89	0.49	740/	
	(12:40)	(12:00)	(12:20)	(14:00)	/4 /0	
Takamatsu	1.08	985	0.76	0.47	(0)/	
	(13:30)	(12:00)	(12:50)	(14:20)	69%	
Himeji	1.47	985	1.16	0.46	700/	
	(13:50)	(13:20)	(13:30)	(15:20)	1070	
Kobe	1.40	990	1.11	0.36	70.0/	
	(14:30)	(13:40)	(14:20)	(15:50)	19%	
Osaka	1.62	991	1.35	0.37	8 2 0/	
	(14:40)	(14:00)	(14:30)	(15:50)	82%	

surface water movement as ocean long wave may cause large storm surges[5].

Since the numerical simulation model enables to include such dynamical effects without any simplification of topography, we will be able to proceed to discuss how the two main effects functioned in the simulation.

To detect these effects, we carried out two additional simulations: One is that only the wind effects are considered by setting the pressure force is set to 0 (hereafter we refer to as the "wind calculation"), and the other is that only the pressure effects are considered by setting the wind stress to 0 (hereafter we refer to as the "pressure calculation"). We represent I as the control calculation, II as the "wind calculation", and III as the "pressure calculation". The MSSs by every calculation are listed in Table

The MSSs by every calculation are listed in Table 2.

4.1 The Inverted Barometric Effect

The results of III show that all the MSSs appeared after the time when the typhoon was nearest; especially the delay became large in the Hiuchi-Nada and the Osaka Bay, that is, Uno, Takamatsu, Himeji, Kobe and Osaka. The reason is supposed that the eastward movement of water piled up in the western part of the SIS was prevented at the narrow part of the east channel surrounded by the ellipse in Fig. 7 (a). In order to verify this hypothesis, a calculation with an experimental topography as shown in Fig. 7 (b) was conducted. (The channel part is enlarged and changed to the sea with 20m depth.) The result showed that the times of the MSS in the west of the Iyo-Nada were hardly changed. On the one hand, those in the east of the Iyo-Nada became earlier and the delay of time decreased (not shown). For example, the time became earlier about 20 minutes in Takamatsu and Uno, and about 40 minutes in the Hiuchi-Nada at most.

If the static balance (= 1 cm/hPa) is assumed, the amount of surge by inverted barometric effect can be estimated to be 30 -40cm from the minimum surface pressure, that are generally 10cm smaller than the MSSs of III. The reason of this difference may be that sea water was preferably piled up, due to the inertia of sea water and the narrow strait as an "obstacle". Therefore, the dynamical inverted barometric effect with an influence of sea topography is likely to give larger MSS than only static one would give in this area.



Fig. 7 (a) The original topography, (b) The test one where the east channel is extended.

4.2 The Wind Set-up

The wind set-up is the major effect of the large storm surges. The "contribution ratio" of the wind set-up in the MSS defined as the MSS in II divided by that in I, (hereafter CR) was calculated in several tide station points. CR shows high value in every point as 70 - 80% (except Matsuyama of 60%). This indicates that the wind change along with a moving typhoon had an important role.

4.3 The Characteristic Differences among Local Seas

Fig. 8 shows the amplitudes of the MSS at every grid point and surface wind corresponding to the occurrence time of the calculation I. This distribution reveals several clusters of large storm surge area and wind direction. The storm surge in each area behaves as if the area is a bay, where large storm surge is generated in the most inner part by an inflow wind. By considering this characteristic, we divide the SIS into 6 local seas as shown in Fig. 8.

① the sea opening to east with the Kanmon Straight as a wall (the Suoh-Nada)

The wind set-up is extremely predominant due to its shallow water depth. The inflow of sea water from the Bungo Chanel also influences on the storm surges.

(2) the sea opening to south with the north coast of Hiroshima (the Hiroshima Bay)

Since the typhoon passed nearby and the duration of southerly wind was long, the wind set-up continued longer than other areas.

③ the sea opening to southwest, closed by islands around Imabari (the Iyo-Nada and the Aki-Nada)

The wind set-up is not so predominant due to deep water. However, the coincidence of the time of the maximum inverted barometric effect and that of the wind set-up causes large storm surge.

(4) the sea opening to west, closed by the narrow channels (the Hiuchi-Nada)

The peak of inverted barometric effect appeared after the typhoon approached to the nearest because of the pile up of the sea water in the Aki-Nada. The coincidence of the time of the maximum inverted barometric effect and that of the wind set-up causes large storm surge similar to the Iyo-Nada.

(5) the sea opening to south with the north coast of Himeji (the Harima-Nada)

The wind set-up functioned well since the sea opens to south and southwest and water depth is shallow.

(6) the sea opening to south with the north coast of Osaka (the Osaka Bay)

The character is almost same as those of the



Fig. 8 The maximum storm surges (m) calculated in every grid and wind at same time

Harima-Nada.

5. CONCLUSIONS

The mechanism of the storm surges in the SIS caused by TY Chaba in 2004 was investigated and our conclusions are summarized as follows:

- (1) The storm surges by TY Chaba are mainly caused by the wind set-up effect, since the water depth in the SIS is generally shallow.
- (2) The SIS is divided into six areas in terms of the characteristics of the storm surge caused by TY Chaba. Each area is characterized by the preferred wind direction, relative importance of wind set-up effect and piling up of the sea water.
- (3) The time of the MSS was different among the areas. The time is almost the same as the time when the typhoon was nearest in the western part, although it delayed in the eastern part, especially the delay of time in the Hiuchi-Nada was over 2 hours. This indicates that storm surges in the SIS have good chances to occur after a typhoon passing away by the influence of sea topography. The timing of MSS was also influenced by the change of wind directions along with the typhoon movement.
- (4) The fact that storm surges in the SIS occurred after a typhoon passing away, should be strongly kept in mind for adequate timing of warning.

Since it is rather common for a typhoon to pass along the same course as TY Chaba, that made landfall in Kyushu and passed into the Sea of Japan, it is likely that similar storm surges also happen frequently. Therefore we will research other storm surge cases to detect the mechanism as well.

6. REFERENCES

- 1. Konishi, T.: Storm surges in the western part of the Inland Sea, caused by Typhoon 9119 –analyses of tidal records, documents on flooding and field inspection-, Umi to Sora (SEA AND SKY), 70, 1995 (in Japanese)
- 2. Konishi, T. and Y. Tsuji: Analyses of Storm

Surges in the western part of the Seto Inland Sea of Japan caused by Typhoon 9119, Continental Shelf Res., 15, 1995

- 3. JMA:Repot on the storm surges by Typhoon Bart (No.9918) in September 1999, Japan, Technical Report of JMA, 122, 2000. (in Japanese)
- 4. Kohno, N.: The mechanism of storm surges caused by TY BART (9918) in 1999, KAIYO MONTHLY, 32, 2000. (in Japanese)
- 5. Arakawa, H. and M. Yoshitake: Report on the 'Muroto Taifu' in 1934, 1935. (in Japanese)