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M.C. Ng, W.H. Lui, W.L. Yeung & H.Y. Mok

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NG Moon-chiu, LUI Wing-hong, YEUNG Wai-lung and MOK Hing-yim
Hong Kong Observatory

Abstract

Situated on the coast of southern China facing the South China Sea, Hong Kong is vulnerable to sea flooding due to storm surge caused by approaching tropical cyclones. Historically, a number of tropical cyclones over the western North Pacific moving westward through the Luzon Strait, approaching the coast of Guangdong and passing to the south of Hong Kong, have induced significant storm surges and brought great casualties to Hong Kong. Examples were the typhoons in 1906, 1937 and Wanda in 1962.

The forecast track of Super Typhoon Usagi, eventually making landfall near Shanwei on the night of 22 September 2013, was recognized to have the potential to bring severe storm surge to Hong Kong while the typhoon was still out over the Pacific. At such a great distance, a small change in the movement of Usagi might result in vast differences in the impact of storm surge to Hong Kong. Cyclones passing to the north would induce a less significant storm surge than those passing to the south. Furthermore, depending on the speed of Usagi's movement, astronomical high tide could produce an aggregate effect and an even higher sea level, leading to more uncertainty in predicting the storm surge impact. Such uncertainties had to be taken into consideration in assessing the risk of storm surge induced by Usagi and in formulating advisory messages to the general public for taking early precautionary measures.

This paper discusses the application of simulated results generated by the Sea, Lake and Overland Surges from Hurricanes (SLOSH) storm surge model for the assessment of potential storm surge risk of Usagi in Hong Kong, having considered the uncertainties in the direction and speed of Usagi's movement.

1. Introduction

Hong Kong, located on the coast of southern China, is vulnerable to sea flooding due to storm surges associated with approaching tropical cyclones over the northern part of the South China Sea. Historically, storm surges induced by typhoons in 1906, 1937 and Wanda in 1962 brought severe casualties and damages to Hong Kong (Peterson, 1975; Ho, 2003). Storm surges induced by Typhoon Hope in 1979 (HKO, 1980) and Typhoon Hagupit in 2008 (HKO, 2009), even though with no significant casualties, still brought severe flooding and damages to Hong Kong during their passages. Storm surge and sea level records, as well as the tracks of these typhoons, are shown in Table 1 and Figure 1 respectively.

Figure 1 shows that typhoons bringing storm surge impact to Hong Kong have similar tracks, forming and intensifying into at least typhoon strength over the western North Pacific, moving across the Luzon Strait without making landfall over the Philippines and Taiwan, approaching the coast of Guangdong and making landfall over or passing to the south of Hong Kong. Typhoons moving across the Luzon Strait without making landfall over the Philippines and Taiwan can maintain their intensity, and making landfall over or passing to the south of Hong Kong will generate onshore winds that bring severe storm surges to the territory.

Usagi was the most intense typhoon to affect Hong Kong in 2013. While still located over the western North Pacific, its forecast track was recognized to be similar to those shown in Figure 1, and hence had the potential to induce severe storm surge and to cause serious flooding in Hong Kong. Its closest approach would also coincide with the astronomical high tide, which was predicted to be 2.19 m at the tide gauge at Quarry Bay inside the Victoria Harbour.

However, the storm surge induced by Usagi would be quite different depending on its passage to the north or to the south of Hong Kong. In the latter case, prevailing southeasterly winds would push on the sea surface and pile up the sea water against the coast. Coupled with the low pressure near the centre of Usagi, severe storm surge would be a real threat. Furthermore, depending on the moving speed of Usagi, astronomical high tide would produce an aggregate effect that could lead to an even higher water level.

This paper studies the potential storm surge risk of Usagi in Hong Kong using the storm surge model SLOSH operated by the Hong Kong Observatory, taking into consideration the uncertainties in the track and movement of Usagi.

2. Storm Surge Forecasting in Hong Kong

Since 1994, SLOSH, developed by the National Oceanic and Atmospheric Administration of USA, was used by the Observatory to support the operation on storm surge prediction and warning services in Hong Kong. Earlier verification results using tropical cyclones affecting the northern part of the South China Sea from 1994 to 2008 showed that the root-mean-square error of predicted storm surge was about 0.3 m (黃永德等, 2008).

SLOSH operates on a polar grid, with grid size ranging from 1 km near the centre around Hong Kong to about 7 km to the open sea. The input parameters for running SLOSH are the 6-hourly locations (in latitude and longitude) of the tropical cyclones and their corresponding values of central minimum pressure and radius of maximum winds from 48 hours before to 24 hours after the time of closest approach to Hong Kong.

The radius of maximum winds is defined as the distance from the centre of a tropical cyclone to the location of the cyclone's maximum winds. In a well-developed tropical cyclone, the radius of maximum winds is generally found at the inner edge of the eyewall. In this study, the method developed by Hsu and Babin (2005) utilizing enhanced infrared satellite images was employed to estimate the 6-hourly values of radius of maximum winds of Usagi. For each infrared satellite image, the smallest distance between the coldest cloud-top temperature and the warmest temperature in the eye of Usagi was taken as the radius of maximum winds as the most intense convection should supposedly be closer to the eyewall rather than further away.

3. Track of Usagi

Usagi formed as a tropical depression over the western North Pacific on 17 September, intensified gradually into a super typhoon over the Pacific to the east of Luzon on 19 September and moved west-northwestwards across the Luzon Strait on 21 September.

Usagi tracked west-northwestwards and weakened into a severe typhoon when entering the northern part of the South China Sea on 21 September. At that time, Usagi was forecast to make landfall just to the east of the Pearl River Estuary, posing a severe threat to Hong Kong. However, after entering the South China Sea, Usagi took a track with slightly more northerly component from about 12UTC on 21 September to 00UTC on 22 September and made landfall near Shanwei in eastern Guangdong on 22 September evening. After making landfall, Usagi moved across the coastal areas and passed about 80 km to the north of Hong Kong on that night (Figure 2). The 6-hourly locations, values of central minimum pressure and radius of maximum winds of Usagi from 00 UTC on 20 September to 18 UTC on 23 September are shown in Table 2.

The change in movement after entering the South China Sea might be due to the slight weakening of the ridging flow north and northwest of Usagi which provided the main steering to Usagi. From 21 September night to 22 September morning, the ridging flow to the northwest of Usagi weakened and a small vortex even formed over Beibuwan (Figure 3(a) and 3(b)). The model run of ECMWF based on initial data at 00UTC on 20 September also predicted the weakening of ridging flow near Leizhou Peninsula and the formation of a vortex over Beibuwan (Figure 4(a) and 4(b)). It then successfully forecast that Usagi would make landfall at some distance east of the Pearl River Estuary (Figure 4(c) and 4(d)). On the contrary, an earlier model run based on initial data at 00UTC on 19 September forecast that the ridging flow would maintain its intensity near Leizhou Peninsula without a vortex forming over Beibuwan (Figure 5(a) and 5(b)), and Usagi would not gain much northerly component and would make landfall closer to Hong Kong (Figure 5(c) and 5(d)).

4. Observed Storm Surges induced by Usagi

Based on the information provided by the State Oceanic Administration (SOA), Usagi brought significant storm surges of 1.50 m at Shanwei where Usagi made landfall and 1.88 m at Shantou (about 150 km northeast of Shanwei) with Usagi passing about 110 km to its southwest. As the maximum storm surges occurred near the time of astronomical high tide, highest sea levels of 4.42 m and 3.50 m were recorded at Shantou and Shanwei respectively. It was reported that backflow of seawater caused serious flooding in many places in

Shantou. In Shanwei, there were interruptions to traffic, telecommunication links, water and electricity supply, with over 65 percent of the area without electricity.

As Usagi passed to the north of Hong Kong, off-land flow meant storm surge was relatively insignificant, with a maximum of 0.62 m at Quarry Bay in the Victoria Harbour at around 11 pm on 22 September. However, as the time of occurrence of maximum storm surge was quite close to the time of astronomical high tide, the highest sea level recorded at Quarry Bay reached 2.81 m and there was minor flooding in some low-lying areas in Hong Kong.

Figure 6(a), 6(b) and 6(c) show the time series of the astronomical tides, storm surges and sea levels recorded at the tide gauges at Shantou and Shanwei operated by SOA (hourly data), and at Quarry Bay operated by the Observatory (1-minute data) respectively during the passage of Usagi.

The estimated storm surges and sea levels at Quarry Bay generated by SLOSH utilizing the 6-hourly locations, values of central minimum pressure and radius of maximum winds from 18 UTC on 20 September to 18 UTC on 23 September in Table 2 are shown in Figure 6(d). A maximum storm surge of 0.62 m, exactly the same as observed at Quarry Bay, occurring at 1 am on 23 September was estimated by SLOSH. As the estimated maximum storm surge occurred slightly later than observed and did not coincide with the occurrence of the astronomical high tide, the estimated highest sea level was 2.66 m, slightly smaller than that observed. In general, the estimated results indicate that SLOSH has the capability of predicting reasonably accurate storm surge impact to Hong Kong induced by Usagi, on the basis of a reasonably good forecast of intensity and track.

5. Potential Storm Surge Risk of Usagi

Two hypothetical tracks, Track A and Track B, were constructed to assess the potential storm surge risks in Hong Kong should Usagi take on a more westward track. Both tracks would see Usagi passing over Hong Kong in Track A and passing 80 km to the southwest of Hong Kong in Track B (Figure 7).

Track A was close to the forecast track predicted by the model run of

ECMWF based on initial data at 00 UTC on 19 September. On this hypothetical track, Usagi would make landfall over Hong Kong at around 2 am on 23 September. On the other hand, Track B was the scenario predicted by some of the earlier ECMWF model runs generated before 19 September. For Track B, Usagi would pass about 80 km to the southwest of Hong Kong at around 5 am on 23 September and then made landfall over western Guangdong about 100 km west of Hong Kong.

In constructing the two hypothetical tracks, it was assumed that Usagi would maintain its intensity and structure while it was still moving over waters. The central minimum pressure and radius of maximum winds of Usagi at 06 UTC on 22 September in Table 2 was kept for subsequent 6-hourly location(s) before landfall. The central minimum pressure and radius of maximum winds of Usagi at 12 UTC on 22 September (when it made landfall at Shanwei) in Table 2 was used for the 6-hourly locations when making landfall. For 6-hourly locations after making landfall, the values of central minimum pressure and radius of maximum winds were set to follow the weakening trends after 12 UTC on 22 September in Table 2. The 6-hourly locations, values of central minimum pressure and radius of maximum winds of these two hypothetical tracks are shown in Table 3(a) and Table 3(b).

For Track A, Usagi would induce a maximum storm surge of 2.05 m at 4 am and a highest sea level of about 3.18 m at Quarry Bay at 3 am on 23 September as estimated by SLOSH. If Usagi's movement along Track A was shifted forward by about 5 hours, the maximum storm surge would coincide with the astronomical high tide and the highest sea level could rise to 4.24 m. Figure 8(a) shows the time series of the estimated storm surges and sea levels at Quarry Bay generated by SLOSH for this worst scenario for Track A.

For Track B, the situation would be even worse. With sustained easterly winds pushing the waters against the coast, Usagi would induce a maximum storm surge of 2.80 m at 6 am and a highest sea level of about 3.74 m at Quarry Bay at 7 am on 23 September as estimated by SLOSH. Similarly, if Usagi's movement along Track B was shifted forward by about 7 hours so that the maximum storm surge would coincide with the astronomical high tide, the highest sea level could reach 4.99 m. Figure 8(b) shows the time series of the estimated storm surges and sea levels at Quarry Bay generated by SLOSH for this worst scenario for Track B.

6. Discussion and Conclusion

The storm surge numerical model “SLOSH” used by the Observatory for operational storm surge prediction performed reasonably well in reproducing the storm surge and extreme sea level in Hong Kong during the passage of Usagi.

Using SLOSH, the potential storm surge risk to Hong Kong induced by Usagi was assessed. The results indicate that an uncertainty of less than 100 km in terms of distance from Hong Kong and several hours in terms of timing in the movement of Usagi forecast by state-of-the-art NWP models would result in significant differences in storm surge impact. A highest sea level of 4 - 5 m would probably affect Hong Kong, a hazardous storm surge event more severe than that induced by Typhoon Wanda in 1962. Compared to what actually transpired at Shanwei (where Usagi made landfall) and Shantou (with Usagi passing 110 km to its southwest), the assessment of what might have happened in Hong Kong in terms of highest sea level could be due to differences in topography and bathymetry.

In view of the potential storm surge risk involved, in tropical cyclone situations like Usagi’s, the uncertainty in storm surge impact arising from the uncertainty in the forecast movement of tropical cyclones should be taken into consideration in formulating advisory messages, so that the general public and stakeholders can take early precautionary measures against alternative scenarios.

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Table 1. Records of major storm surges in Hong Kong

Typhoon name	Year	Maximum storm surge at Victoria Harbour (above astronomical tide) (m)	Maximum sea level at Victoria Harbour (above Chart Datum) (m)	Number of deaths
-	1906	1.83^	3.35^	~15,000*
-	1937	1.98^	4.05^	~11,000*
Wanda	1962	1.77	3.96	183
Hope	1979	1.45	2.78#	12
Hagupit	2008	1.43	3.53	0

* According to press reports.

^ Based on tide pole observations, field surveys or reports by local residents. The operation of tide gauge network only started in 1952.

\# The maximum storm surge did not occur at astronomical high tide.

Table 2. Best track data of Usagi including locations and the corresponding values of minimum central pressure and radius of maximum winds

Date	Time	Intensity	Estimated minimum central pressure	Lat.	Long.	Radius of maximum winds
	(UTC)		(hPa)	^{o}N	^{o}E	(km)
20	0000	SuperT	920	19.3	125.5	56
	0600	SuperT	920	19.7	124.6	56
	1200	SuperT	920	20.2	123.7	46
	1800	SuperT	920	20.4	122.5	46
21	0000	SuperT	925	20.7	121.7	46
	0600	SuperT	925	20.8	120.7	46
	1200	ST	935	21.0	119.7	37
	1800	ST	945	21.4	118.8	37
22	0000	ST	945	21.7	118.0	46
	0600	ST	945	22.4	116.8	65
	1200	ST	950	22.8	115.4	37
	1800	T.	965	23.1	113.9	74
23	0000	T.S.	990	23.7	112.6	56
	0600	T.D.	994	24.3	111.2	46
	1200	LOW	998	24.8	110.3	--
	1800	LOW	1000	25.0	109.5	--

Table 3(a) Hypothetical locations and the corresponding values of minimum central pressure and radius of maximum winds of Usagi taking Track A

Date	Time	Intensity	Estimated minimum central pressure	Lat.	Long.	Radius of maximum winds
	(UTC)		(hPa)	^{o}N	^{o}E	(km)
20	0000	SuperT	920	19.3	125.5	56
	0600	SuperT	920	19.7	124.6	56
	1200	SuperT	920	20.2	123.7	46
	1800	SuperT	920	20.4	122.5	46
21	0000	SuperT	925	20.7	121.7	46
	0600	SuperT	925	20.8	120.7	46
	1200	ST	935	21.0	119.7	37
	1800	ST	945	21.4	118.8	37
22	0000	ST	945	21.7	118.0	46
	0600	ST	945	21.8	117.0	65
	1200	ST	945	22.0	115.7	65
	1800	ST	950	22.3	114.2	37
23	0000	T.	965	22.9	112.9	74
	0600	T.S.	990	23.5	111.5	56
	1200	T.D.	994	24.0	110.6	46
	1800	LOW	998	24.2	109.8	--

Table 3(b) Hypothetical locations and the corresponding values of minimum central pressure and radius of maximum winds of Usagi taking Track B

Date	Time	Intensity	Estimated minimum central pressure	Lat.	Long.	Radius of maximum winds
	(UTC)		(hPa)	^{o}N	^{o}E	(km)
20	0000	SuperT	920	19.3	125.5	56
	0600	SuperT	920	19.7	124.6	56
	1200	SuperT	920	20.2	123.7	46
	1800	SuperT	920	20.4	122.5	46
21	0000	SuperT	925	20.7	121.7	46
	0600	SuperT	925	20.8	120.7	46
	1200	ST	935	21.0	119.7	37
	1800	ST	945	21.4	118.8	37
22	0000	ST	945	21.3	118.0	46
	0600	ST	945	21.3	117.2	65
	1200	ST	945	21.2	116.1	65
	1800	ST	945	21.5	114.5	65
23	0000	ST	950	22.1	113.2	37
	0600	T.	965	22.7	111.9	74
	1200	T.S.	990	23.2	110.9	56
	1800	T.D.	994	23.4	110.1	46

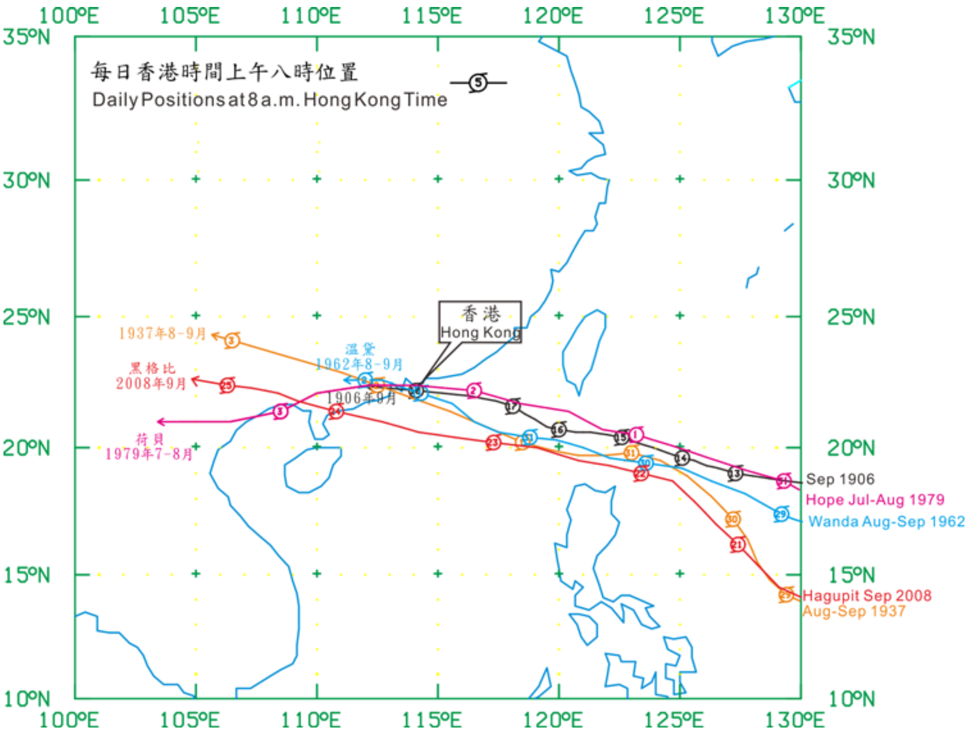
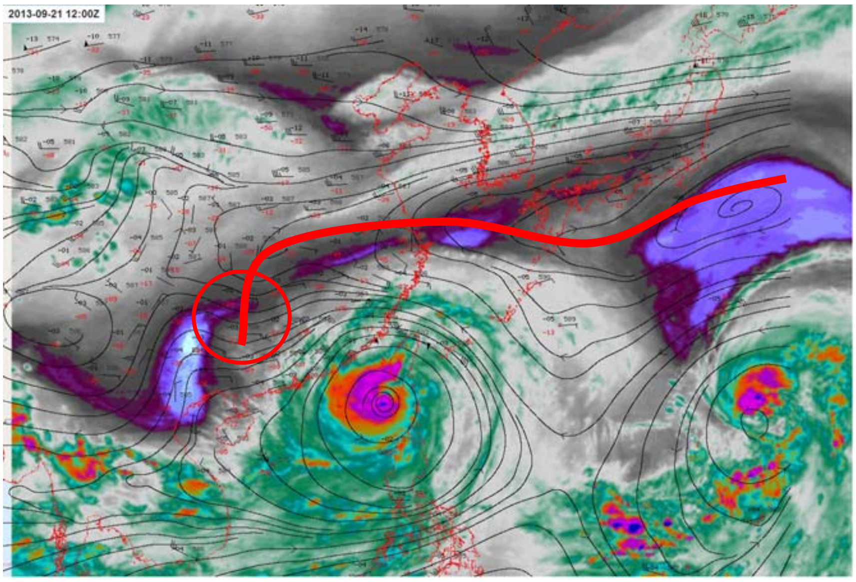


Figure 1. Tracks of the typhoons affecting Hong Kong in 1906, 1937, Wanda in 1962, Hope in 1979 and Hagupit in 2008.

Figure 2. Usagi took a track with slightly more northerly component after entering the northern part of the South China Sea and made landfall at Shanwei.

(a) 21-9-2013 12 UTC



(b) 22-9-2013 00 UTC

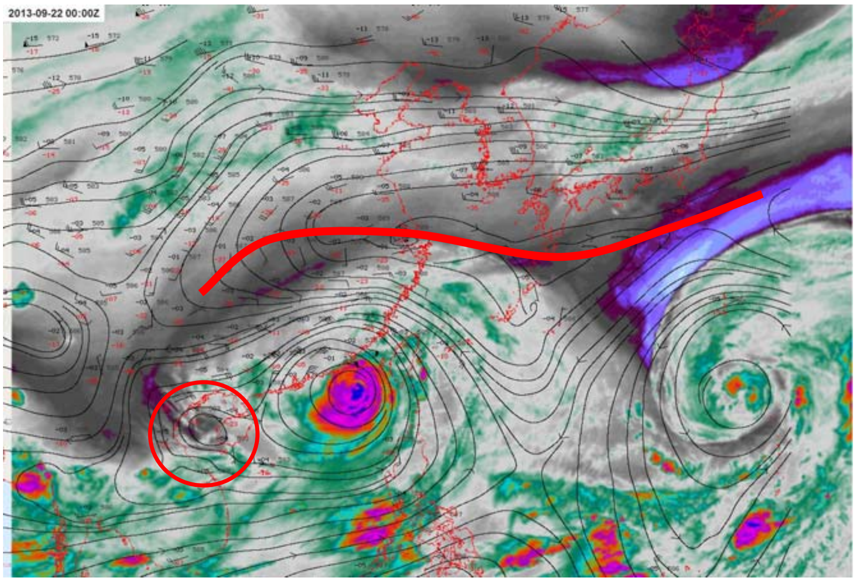
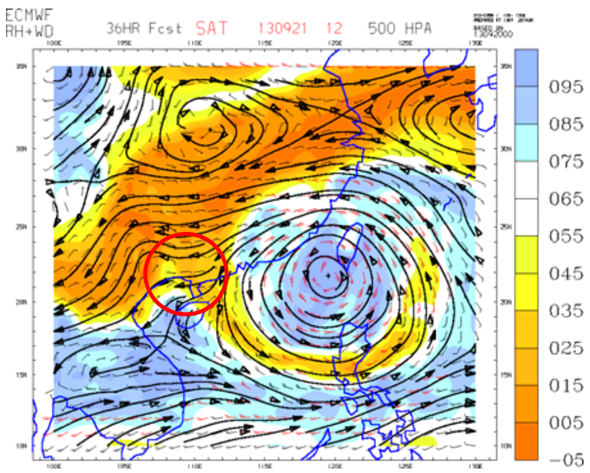
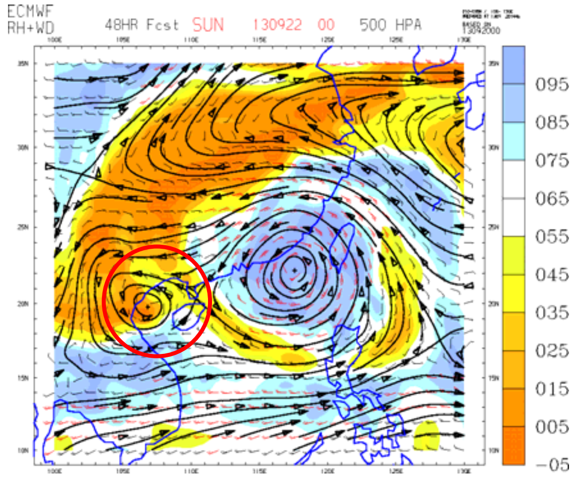


Figure 3. 500 hPa streamline analysis overlaid with satellite imagery water vapour channel for (a) 21 September night and (b) 22 September morning. The ridging flow near Leizhou Peninsula (red circle in Fig 2(a)) weakened and a vortex formed over Beibuwan (red circle in Fig 2(b)).

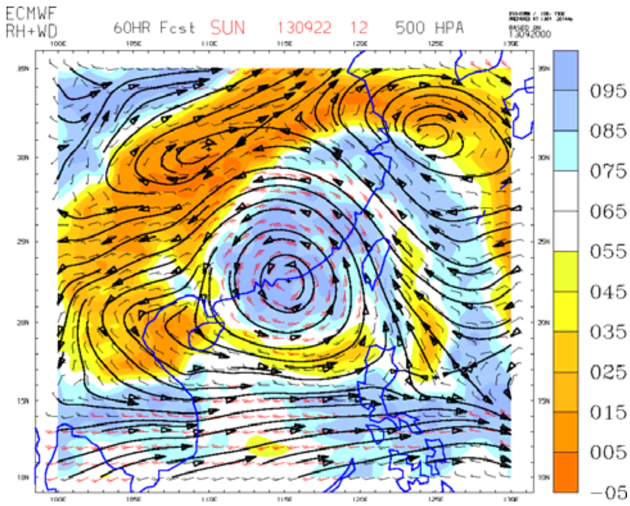
(a)



(b)



(c)



(d)

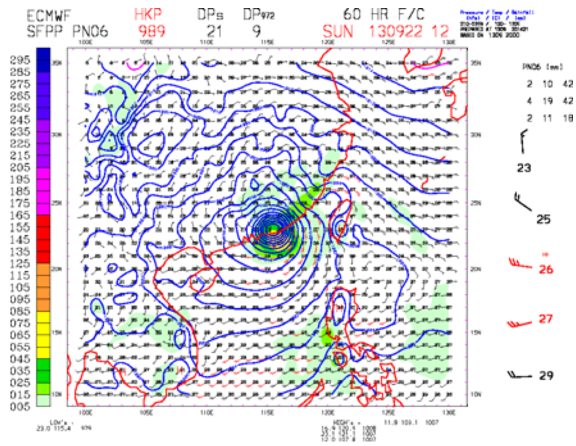


Figure 4. ECMWF model run based on 20 Sep 00Z initial data. (a) and (b) Model forecast that the ridging flow over Leizhou Peninsula would weaken and a vortex would form over Beibuwan from 21 September night to 22 September morning. (c) and (d) Forecast for 500 hPa and surface shows that Usagi will make landfall at some distance east of the Pearl River Estuary on 22 September night.

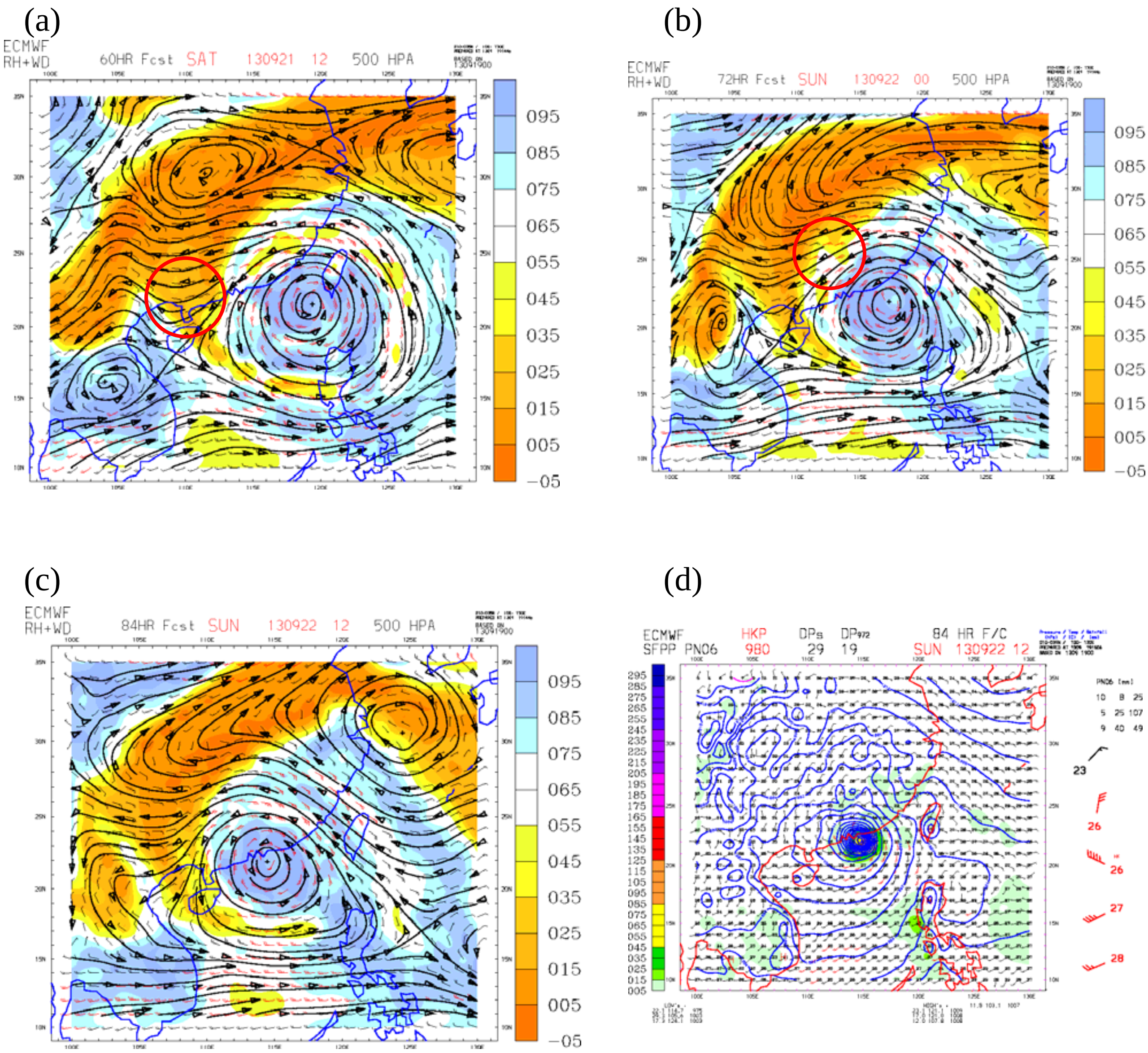


Figure 5. ECMWF model run based on 19 Sep 00Z initial data. (a) and (b): Model forecast that the ridging flow over Leizhou Peninsula would maintain from 21 September night to 22 September morning. (c) and (d): Forecast for 500 hPa and surface shows that ST Usagi will make landfall close to Hong Kong on 22 September night.

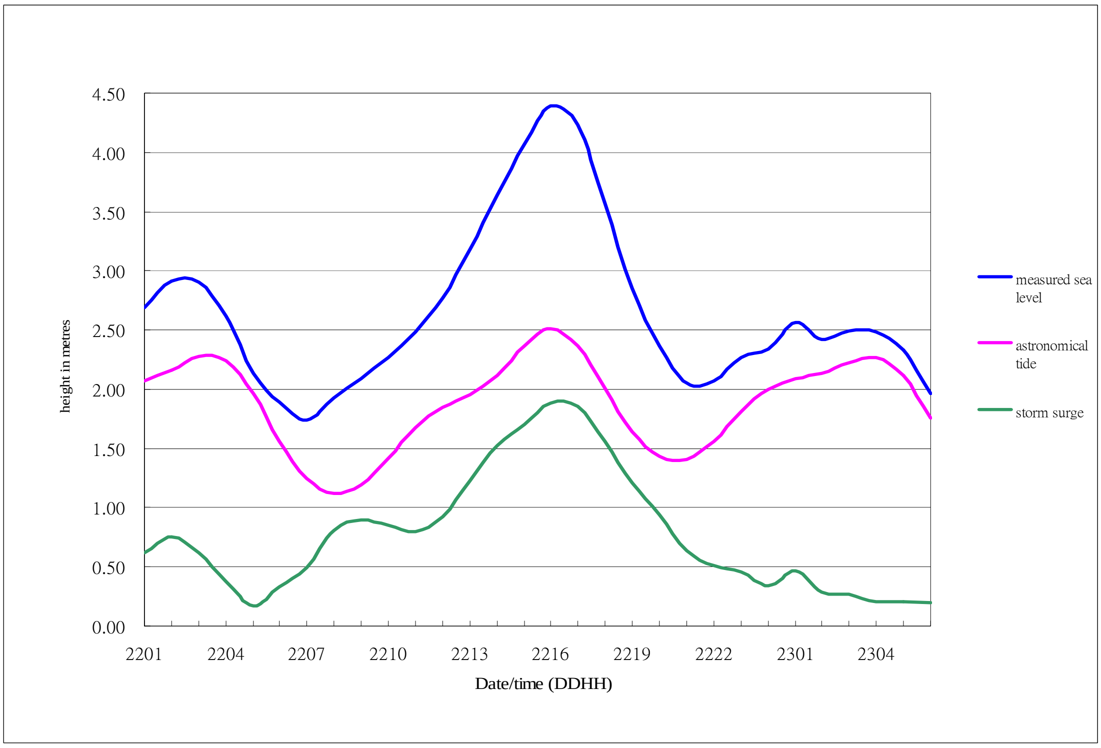


Figure 6(a) Hourly Storm surges and sea levels recorded by the tide gauge at Shantou during the passage of Usagi.

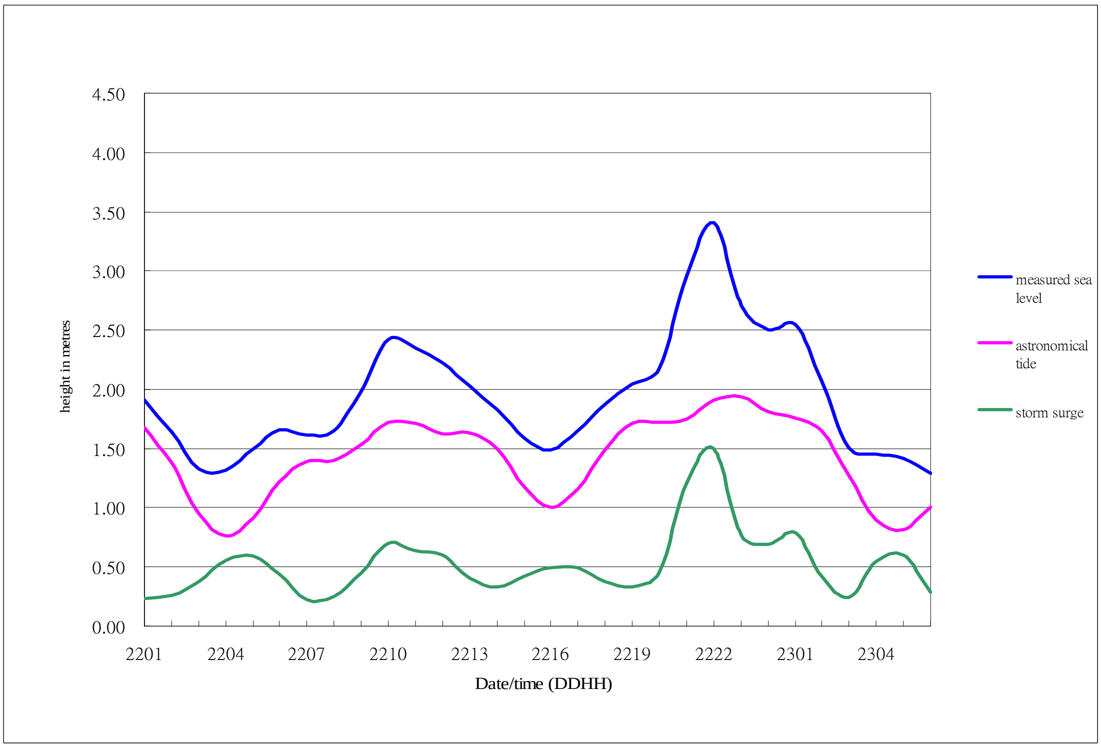


Figure 6(b) Hourly Storm surges and sea levels recorded by the tide gauge at Shanwei during the passage of Usagi.

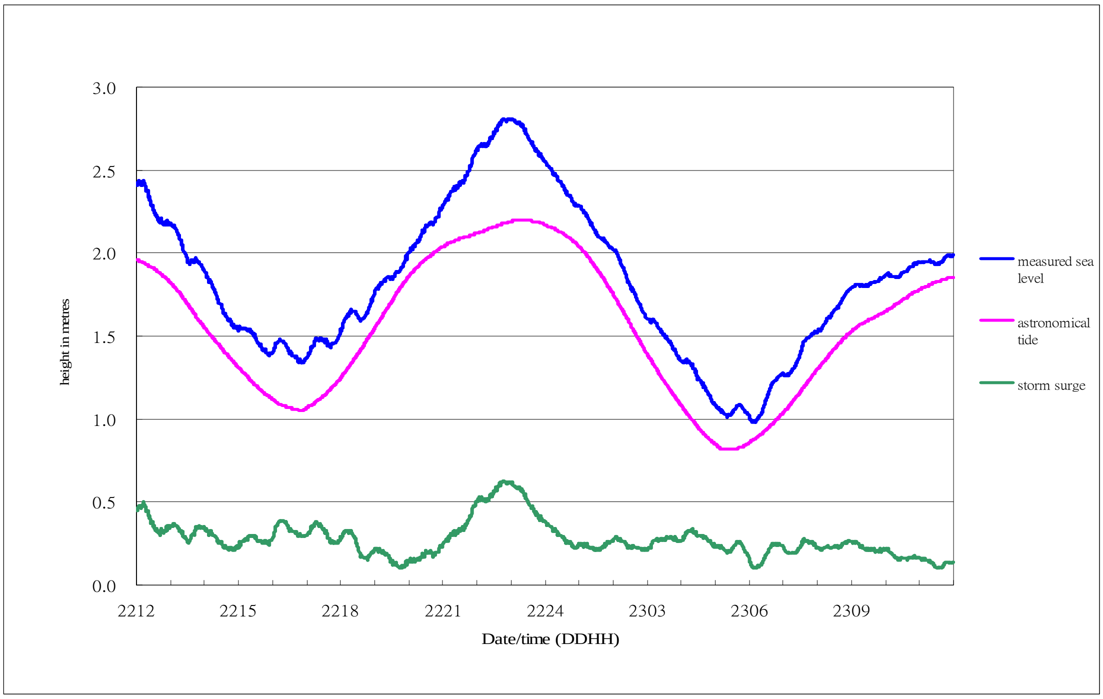


Figure 6(c) 1-minute Storm surges and sea levels (above Chart Datum) recorded by the tide gauge at Quarry Bay during the passage of Usagi.

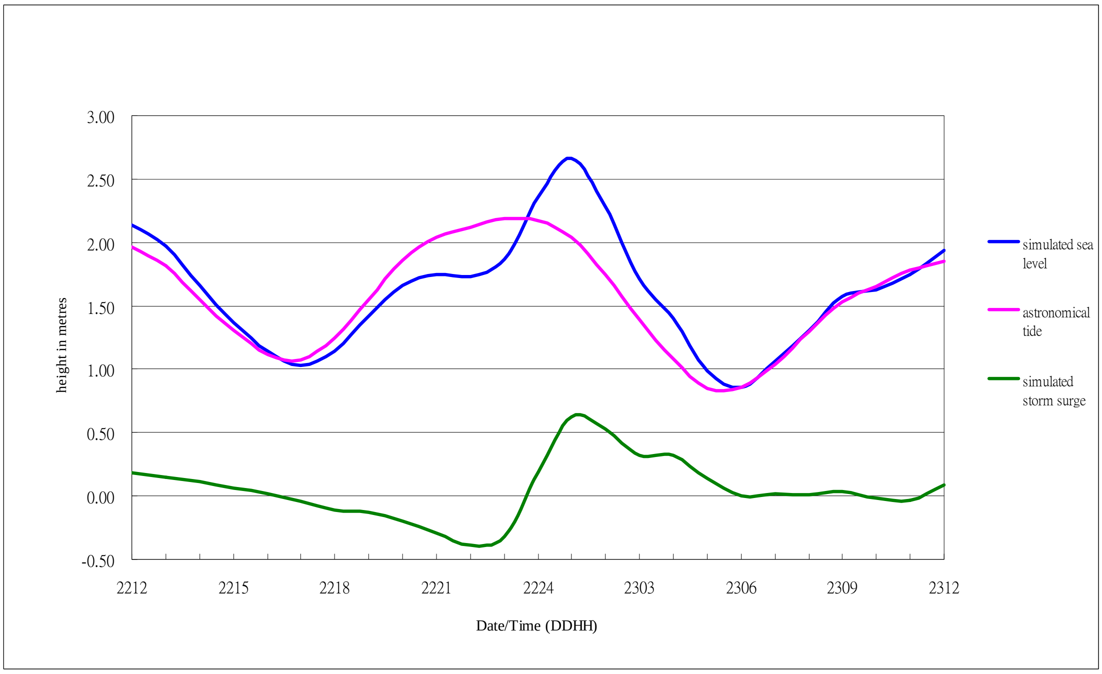


Figure 6(d) Simulated hourly storm surges and sea levels (above Chart Datum) at Quarry Bay based on best track of Usagi.

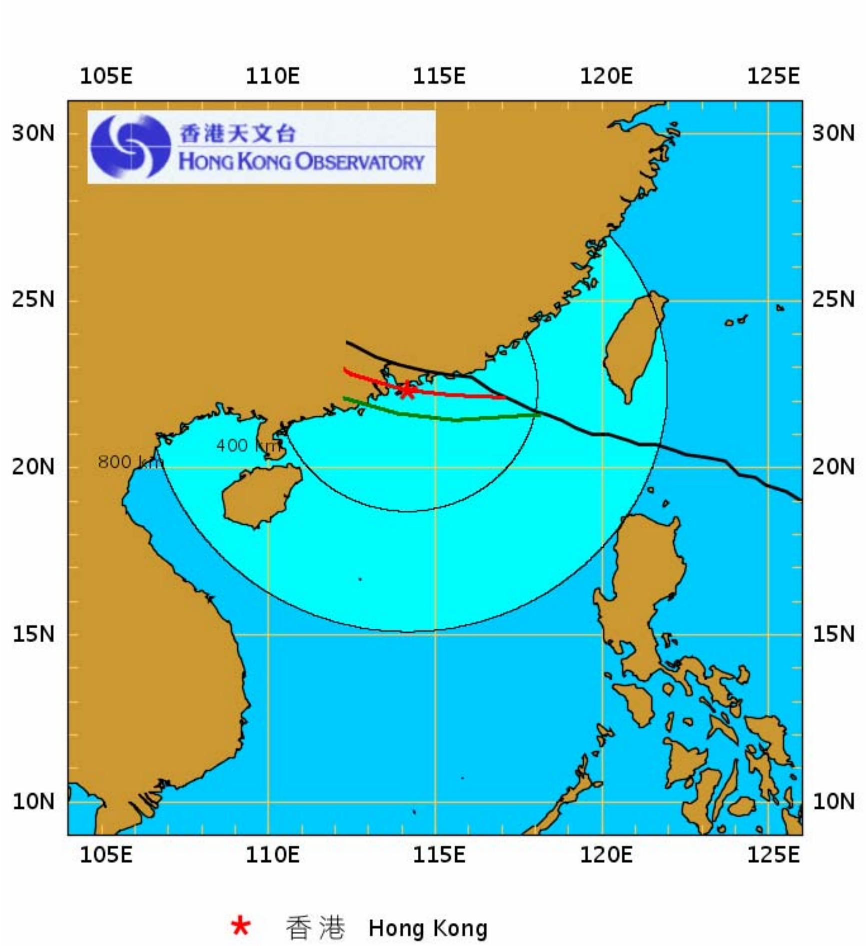


Figure 7. Schematic diagram of the actual track of Usagi (in black) and the simulated tracks if Usagi passed about 80 km (in red) or 160 km (in green) to the south when it was near Hong Kong.

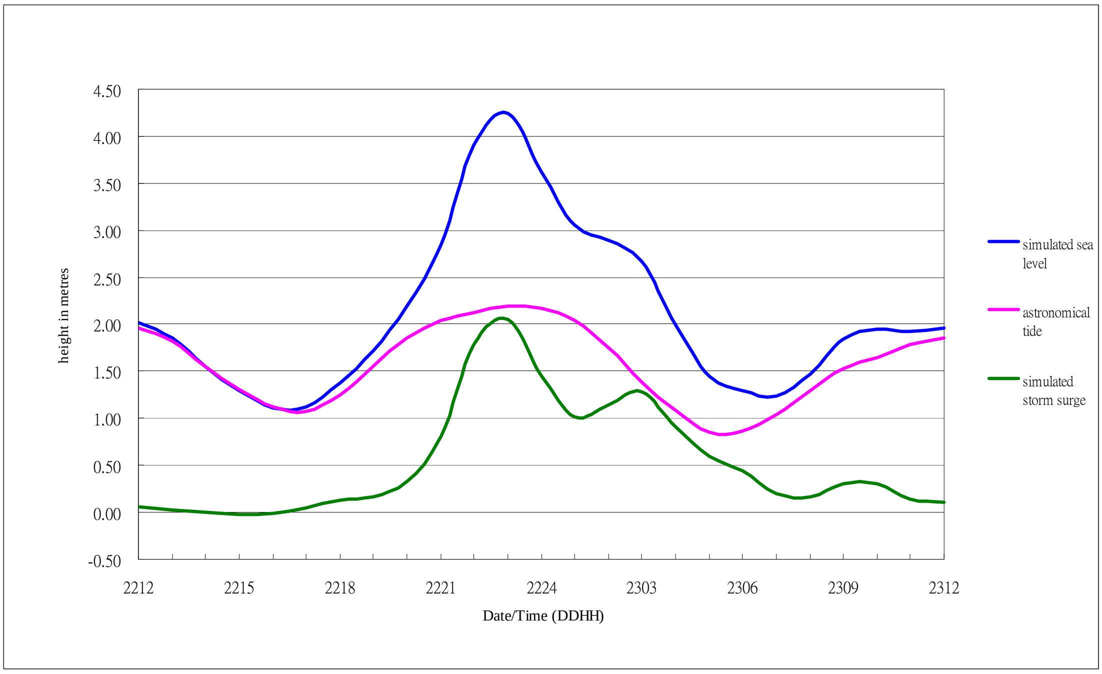


Figure 8(a) Simulated hourly storm surges and sea levels (above Chart Datum) at Quarry Bay for Usagi making landfall over Hong Kong and the maximum storm surge and astronomical high tide occurring at the same time.

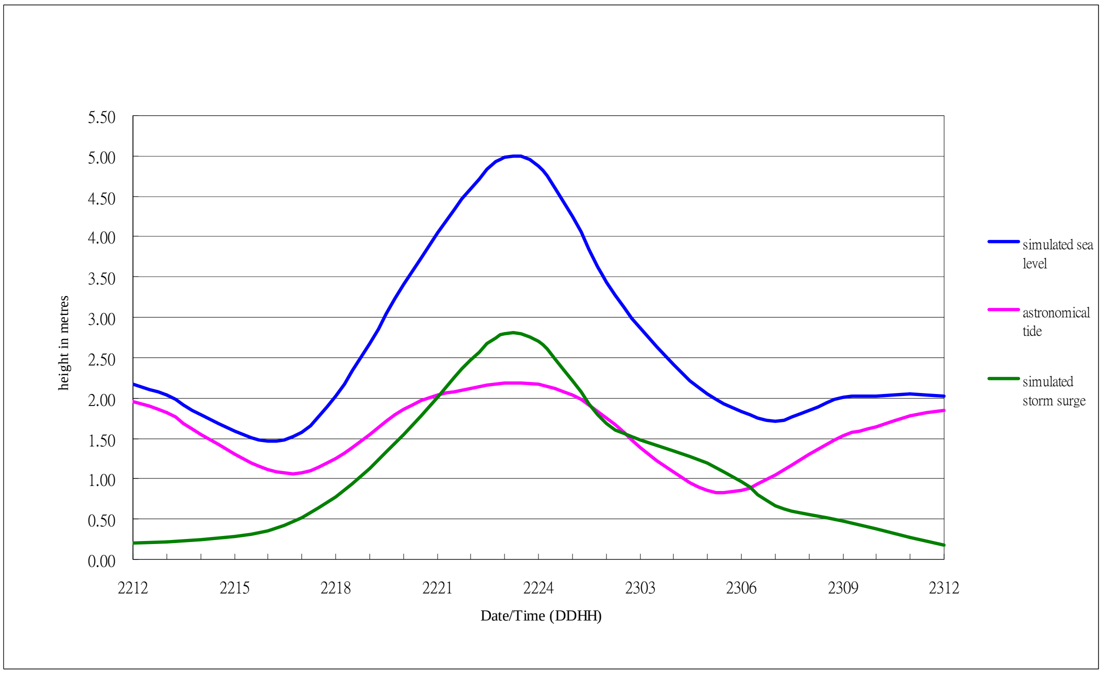


Figure 8(b) Simulated hourly storm surges and sea levels (above Chart Datum) at Quarry Bay for Usagi passing 80 km southwest of Hong Kong and the maximum storm surge and astronomical high tide occurring at the same time.