Water level fluctuations in Guangxi near coast caused by typhoons in South China Sea

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Abstract. The increasing and decreasing water level in Guangxi near the coast is mainly caused by typhoon-induced storm surges. The maximum values of increase and decrease recorded at the Beihai Station over the last 42 years are 1.45 m and −1.87 m. The water level first decreases and then increases in Guangxi near the coast. Apart from the direct influence of typhoons, the westward coastal-trapped wave along the Guangdong continental shelf is also greatly affected. A portion of the westward coastal-trapped wave passed directly through the Qiongzhou Strait into Beibu Gulf, and the other portion passed through the southern part of Hainan Island into the Beibu Gulf. On July 2, 2001, the westward coastal-trapped wave caused by Typhoon Durian induced a strong westward flow along the Guangxi coast, and the geostrophic flow velocity on the surface reached 92cm/s. On July 6, 2001, though Typhoon Utor landed at the northern part of the Pearl River Estuary, it widely induced a 20-cm increase in the water level in Guangxi near the coast on July 8. Apart from the direct and indirect influences of typhoons on the fluctuation of the water level along the Guangxi coast, the particular topography and atmospheric gravity wave also have affect the fluctuation of the water level.

1. Introduction
Typhoons cause abnormal changes in water levels along the coast, which is usually regarded as increased or decreased water level or the storm surge. Storm surge is a typical maritime disaster. When a storm surge
caused by a typhoon exceeds the normal tidal level, i.e., the astronomical tidal level, it is referred to as a storm surge increase; the alternative decrease is called a storm surge decrease. Since the 1950s, storm surge theory and its numerical simulation have made much progress due to researchers both home and abroad [1-12, 22-23].

The Guangxi shore is located in the northern part of South China Sea, and its geographical environment is unique. Typhoons landing or passing by the coastal areas of Guangxi greatly affect the coastal areas each year. Storm surges caused by typhoons demonstrate a particular pattern, which has been rarely reported. In view of this pattern, this paper studies the mechanisms which cause fluctuation of the water level in Guangxi near the coast, as well as the typical current and residual current of coastal-trapped waves.

2. Increased water level in harbors and disasters caused by typhoons landing near the Guangxi Coast from 1965 to 2012

Each year, storm surges caused by landing typhoons lead to severe disasters in Guangxi coastal areas. According to the previous study [13-15], about 90 typhoons have affected Guangxi coastal areas from 1965 to 2012, 18 of which led to tremendous disasters caused by direct landing (Figure 1). The most notable change in water level is due to the direct landing of typhoons with an average increase of 111.2 cm, which is 2.6 times greater than the increase induced by typhoons which did not land. For example, the water level increased by 2.33 m in Tieshan Port and 1.03 m in Weizhou Island induced by Typhoon No. 7109, 2.00 m in Fangchen Port and 1.86 m in Pearl Port induced by Typhoon No. 8303, and 1.61 m in Beihai Port and 1.53 m Longmen Port induced by Typhoon No. 6509. During the landing period, the measured water level in major ports along the Guangxi coast is 5.08 m - 8.33 m, which represents 2 m higher than the normal water level [16-17], and storm surges caused by landing typhoons led to extremely heavy losses [18-20]. For example, on September 9, 1996, the Guangxi coastal areas were affected by Typhoon No. 15, which inflicted damage to 1.1148 million people including 61 deaths and 88 missing persons, the collapse of 34,700 houses, damage to 1,099 vessels with 173 vessels sank, and a direct economic loss of 2.555 billion yuan in Beihai City. Meanwhile, 20,000 houses collapsed and 300 m of seawall were destroyed in Qinzhou City. For another example, on June 26, 2001, Typhoon No. 3 Durian directly affected Beihai City, leading to a heavy rain in the city and a daily rainfall at the level of 425 mm. This heavy rain caused an increase in the water level along the coast, most of the roads in the city were destroyed, and streets and houses were drowned. Such a heavy rain over such a short time hasn’t occured in a century. More than half a million people were affected and 150,000 houses were flooded, 200 m of seawall were broken in 30 places, river banks collapsed in 150 places, and 16 weirs and water gates were destroyed. The water overflowed 16,900 mu fish and shrimp ponds including the destruction of more than 950 mu of shrimp ponds, 21,920 mu of crop fields and 548 km of roads.

In recent years, many typhoons have landed in Guangxi coastal areas. For instance, Typhoon No. 1330 Haiyan, which occurred on November 11, 2013, landed in the Philippines on November 8, passed by the northern part of Beibu Gulf and entered the Guangxi Region. The wind speed reached 12-13 scale, and rainfall reached 100 - 230 mm in Guangxi coastal areas, while the rainfall reached 451 mm in Fangcheng
Port. Heavy rainfall made the water level rise by 2.23 m in major river estuaries along Guangxi coastal areas. A total of 12,000 people were affected by Typhoon Haiyan, including one death in the cities of Beihai, Qinzhou and Fangcheng Port, and direct economic losses of about ten million yuan.

![Figure 1](image-url)  
**Figure 1.** Roadmap of typhoons that landed in Guangxi coastal areas from 1965 to 2013.

3. Case Study of current, residual current and water level fluctuations at the Guangxi near shore

3.1. The Influence of Typhoon Nesat

On the morning of September 24, 2011, Typhoon Nesat generated on the surface of the northwestern Pacific Ocean. At 7:00 on September 27, it landed on the eastern coast of Luzon Island of the Philippines. Around 14:30 on September 29, it extended into the coastal area of Wengtian Town, Wenchang City, Hainan Province. At approximately 21:15, it landed again on Jiaowei Town, Xuwen, Guangdong Province. At 11:30 on September 30, it landed on the coast of Quang Ninh in northern Vietnam (figure 2). Influenced by Typhoon Nesat, heavy storms affected Hainan, Guangdong and Guangxi. According to the reported data, the rainfall reached 332 mm in Fangcheng Port from 20:00 of September 28 to 14:00 of September 30. The wind speed reached 11-14 scale on the southern coast of Guangxi, representing it was the strongest typhoon which ever landed on the Guangxi coast in the past six years. Affected by Nesat, the current, residual current and water level along Guangxi coast changed greatly.
3.1.1. Changing Characteristics of current and residual current along Guangxi near shore under the influence of typhoons. During the Typhoon Nesat landing in the Guangxi Region, an AWAC acoustic Doppler current profiler implanted at a depth of 8 m near the southern Bailong Peninsula to monitor the current, wave and tide (F1 station in figure 1). The observation layer spacing of the current velocity and direction was set to 0.5 m. The profile data were stratified as surface (underwater 1 m), middle and bottom (approximately 1.5 m above the sea floor) for analysis. In the absence of typhoons, the actual velocity at the observation station is relatively low, and the maximum velocity at each layer was below 50 cm/s. The average velocity in the surface, middle and bottom layers were 10.8 cm/s, 8.6 cm/s and 8.4 cm/s, respectively. However, during Typhoon Nesat, the annual maximum velocity was 103.7 cm/s, 94.1 cm/s and 71.0 cm/s in the surface, middle and bottom layer, respectively. Additionally, outside of typhoon season, the velocity of the residual current is also relatively slow, and the maximum velocity generally falls below 20 cm/s with the average velocities in the surface, middle and bottom layer equal to 5.7 cm/s, 3.5 cm/s and 3.1 cm/s, respectively. However, the maximum velocities reached 39.7 cm/s, 32.4 cm/s and 20.7 cm/s, respectively, during the landing period of Typhoon Nesat.

3.1.2. Changing characteristics of the water level in Guangxi near shore under the influence of typhoons. On September 29, 2011, under the influence of Typhoon Nesat, the wind direction was primarily northwest along the coast of the Bailong Peninsula; the average wind speed reached 8.0 m/s in the four hours from 17:00 to 20:00 and the direction shifted to the north. At 8:00 on September 30, the typhoon center moved west and entered Vietnam, and the wind direction turned south around Bailongwei (figure 3). However, when the wind shifted to the north around Bailongwei, a decrease in the water level occurred near the observation station as a result of the wind moving away from the coast. At 2:00 on September 20, the decreased water level reached its maximum of –92 cm.
As the typhoon moved westward, the wind gradually turned to a southern direction, while the surface water simultaneously flowed toward the shore but was blocked by the coast. The water level therefore began to increase near the observation station. At 10:00 on September 30, water level increase reached its maximum of 65 cm (Figure 4), and then quickly decreased. Several fluctuations followed; the first water level increase was 45 cm, and the second increase was 20 cm.

**Figure 3.** Wind fields at the time of the maximum increase in water level in 2011.

**Figure 4.** Increased and decreased water level near Bailongwei Observation Station (F1) during Typhoon Nesat.
3.2. Influence of Typhoon Durian

In order to further study the increased and decreased water level during the typhoon landing along the coastal areas in the Guangxi Region, the water level fluctuation data at Shitoubu (F2 station in figure 1), Tieshan Port was selected and which recorded the details of the effects of Typhoon Durian from July 1 to July 3, 2001. Tieshan Port, located on the eastern coast of the Guangxi Region, is surrounded by land in the east, west and north, while it faces the sea in the south. Typhoon Durian moved from east to west and crossed over Tieshan Port at 6:00 on July 2 (figure 5); the southern wind gradually strengthened to a maximum windspeed between 25 and 30 m/s under the influence of the strong onshore wind around the Shitoubu area.

![Figure 5. Path of Typhoon Durian and its induced wind fields.](image-url)
While Typhoon Durian passed this area, the water level around the observation station of Shitoubu experienced a water level decrease followed by an increase. As the low pressure approached to Shitoubu from the east, the water level began to decrease around Shitoubu to a maximum decrease of \(-48\) cm at 8:00 on July 2. At approximately 10:00, the water level returned to the origin. The south wind then increased, and the water level around Shitoubu increased (figure 6) to a maximum value of 140 cm between 14:00 and 16:00 on July 2. The water level then gradually returned to normal as the low pressure moved westward and the wind weakened. The increase/decrease in water level accompanied the typhoon, and was subject to the distribution and variations of the typhoon field and the air pressure field.

**Figure 6.** Increase/decrease in water level around observation stations Shitoubu and Tieshan Port during Typhoon Durian as it passed the Guangxi Region.

4. **Fluctuations in water level caused by coastal-trapped waves**

Great attention has recently been paid to the study of coastal-trapped waves in the northern continental shelf of the South China Sea (SCS) caused by typhoons. Ding[21] performed a quantitative analysis of the fluctuations of water level in the coastal areas of the northern part of SCS of Typhoon Durian on June 30, 2001, Typhoon Ute on July 5, 2001, and the landing of Typhoon Yutu on on Guangdong Province on July 23, 2001. They reported that the wave tends to spread from northeast to southwest along the coast and its signal was very strong under the influence of typhoon when they came. The wave magnitude gradually decreased as the typhoon vanished. The spreading wave speeds caused by Typhoon Ute along the coast of the northern part of the SCS was approximately 4.2-11.4 m/s. When this wave propagated to the east coast of Hainan Island, the spreading speed significantly reduced to approximately 4.2 m/s.
A portion of the coastal-trapped wave caused by Typhoon Ute passed across the Qiongzhou Strait and entered the Beibu Gulf (figure 7); the other portion crossed the east mouth of Qiongzhou Strait and was blocked by Hainan Island, and then continued to spread in a clockwise direction around the southern part of Hainan Island and entered the Beibu Gulf. On July 6, Typhoon Ute landed in the north part of the Pearl River estuary, but caused an increase in water level of more than 20 cm in the Guangxi near shore on July 8. This increase in water level involved the entire coast.

Figure 7. Contours of abnormal distributions of water level along the coastal areas in the northern part of the South China Sea during Typhoon Ute (Ding, 2012).
Typhoon Ute landed in the east of Pearl River estuary, and caused a 20-plus cm increase in the water level. Therefore, the typhoons that landed in the western part of Guangdong Province should cause coastal-trapped waves, which have more significant impact on the Guangxi near shore.

Typhoon Durian generated within the SCS, formed a tropical depression approximately 650 km south of Hong Kong in the morning of June 30, and then moved to the northwest and developed into a typhoon. At 05:00 on July 2, it landed near Zhanjiang with a maximum wind speed reaching 35 m/s. A part of the coastal-trapped wave caused by Typhoon Durian crossed the Qiongzhou Strait and entered the Beibu Gulf (figure 8), while the other portion crossed the eastern mouth of the Qiongzhou Strait and was blocked by Hainan Island, then continued spreading in a clockwise direction around Hainan Island and entered the Beibu Gulf.
Figure 8. Contours of abnormal distributions of water level along the coastal areas in the northern part of the South China Sea during Typhoon Durian.

As shown in figure 8, a very important phenomenon can be observed at 18:00 on July 2. Not only does an increase in water level appear in the Guangxi near shore, but a strong westward flow also occurred along the Guangxi coast. Computational results indicate that its surface geostrophic flow velocity approached 92 cm/s. This remarkable westward flow along the coast would transport a huge body of water and would have an invaluable role in the diffusion of pollutants, water refreshment, and environmental protection in Guangxi coastal areas. The impacts of coastal-trapped waves on the water level and flow in the Guangxi near shore have not yet been comprehensively investigated, and represent a direction for future research.

5. Calculation of water level fluctuation in the Guangxi near shore

5.1. Increase of Water Level
The Beihai Observation Station was the most representative among the observation stations in Guangxi coastal areas because it reported long-term tidal data. Thus, the data observed at the Beihai Observation Station over 42 years from 1965 to 2006 was analyzed, and demonstrated the extreme value of water level increases each year, as shown in figure 9. Results indicate that the largest water level increase occurred in 1996 with an increase of 1.45 m, but there were several years without water level increases, i.e., 1969, 1970, 1972, 1975 and 2004. The average of water level increase was 0.71 m over 42 years.
Figure 9. Maximum annual increase in water level at Beihai Observation Station.

Figure 10 depicts the cases in which the return levels of water level increases in different return periods could be acquired, with the use of Gumbel form (or an extreme type I distribution). Because the results obtained from Weibull and Pearson-III are basically identical, the pictures are not presented. Results indicate that a 100-year return from water level increase was 1.78 m in Beihai. According to the synchronized observation statistics, an equation was built to calculate a 100-year return level in Bailongwei, which was equal to 1.69 m of water level increase.

Figure 10. Distribution of Gumbel extreme values for water level increases based on the data recorded at Beihai Observation Station.
5.2. Water level decrease

Figure 11 depicts the extreme value of water level decrease each year as observed at the Beihai Observation Station over 42 years from 1965 to 2006. The maximum extreme decrease occurred in 1985, when the water level decreased by -1.87 m. The minimum water level decrease occurred in 1965 when the water level decreased by -0.53 m. The average water level decrease was -1.11 m over 42 years.

![Figure 11. Maximum annual decrease in water level observed at Beihai Observation Station.](image)

Figure 12 depicts the cases in which the return levels of water level decrease in different return periods could be acquired, with the use of the Gumbel form (or the extreme type I distribution). Because the results obtained from Weibull and Pearson-III are basically identical, the pictures are not presented. As shown in Figure 11, results indicate that a 100-year return level of water level decrease was −2.15 m in Beihai. According to the synchronized observation statistics, an equation was built to calculate a 100-year return level in Bailongwei, equal to a −1.75 m water level decrease.
6. Analysis of major factors affecting water level fluctuation in the Guangxi near shore

6.1. Wind as a major affecting factor

According to the data recorded by the Dongxing Weather Station (table 1), the wind in Bailongwei Peninsula began to turn northward under the influence of Typhoon Nesat on September 29, 2011. The average wind speed was 3.3 m/s from 9:00 to 12:00, 4.9 m/s from 13:00 to 16:00, 8.0 m/s from 17:00 to 20:00, 5.8 m/s from 21:00 to 24:00, and the wind then gradually turned westward. Due to the effect of the north wind, the water level began to decrease along the coast of the Bailongwei Peninsula at 6:00, the water level reduced sharply at 20:00, and the water level decrease reached a maximum at 2:00 on September 30.

Obviously, this decrease was directly related to the role of the northerly wind. However, the wind then turned southerly from 1:00 to 4:00 on September 30, with an average speed of 7.3 m/s, and the maximum wind speed exceeded 14 m/s. From 5:00 to 8:00 the average wind speed was 7.7 m/s and the maximum wind speed exceeded 16 m/s. The average wind speed decreased to 5.5 m/s from 9:00 to 12:00, and the wind turned to southwest after 12:00 when the wind speed dropped to approximately 5 m/s. Because the wind turned southerly, the wind blew towards the shore, and the water accumulated along the coast resulting in the water level increase, which reached a maximum of 65 cm at 10:00.
Table 1. The wind speed and major daily wind direction in Dongxing from September 28, 2011 to October 1, 2011.

| Time (Month-Day) | Average Daily Wind Speed (m s⁻¹) | Major Daily Wind Direction | Average 4-Hour Wind Speed (m s⁻¹) |
|------------------|---------------------------------|---------------------------|----------------------------------|
| 9-28             | 1.5                             | NW                        | 21-24 1.0 1.2 1.1 1.3 2.1 1.6 |
| 9-29             | 4.2                             | N                         | 1.0 1.5 2.4 3.3 4.9 8.0          |
| 9-30             | 5.9                             | N-S-SW                    | 5.8 7.3 7.7 5.5 6.5 2.7          |
| 10-1             | 1.2                             | W                         | 1.9 1.0 0.9 1.8 1.5 1.0          |

6.2. **Terrain as a constraining factor**
Numerous semi-closed bays exist along the Guangxi coast, which deeply penetrate into the land with complicated geographical and environmental conditions. Moreover, the Beibu Gulf area is small, so the reflection of waves along the coast of Vietnam greatly impact the Guangxi coastal areas. Therefore, the fluctuation of water level in the bays of Guangxi demonstrate unique characteristics in which a water level decrease appeared prior to the sharp increase in the water level. The magnitude of the increase is large, and the water level rapidly increased. Every typhoon-induced water level increase generally reaches over 1 m, while the time necessary to decrease the water level is long, and which can continue for more than 10 to 20 hours. For example, during strong Typhoon No. 3 in 1983, the water level increased by approximately 2.0 m in less than one hour in Fangchen Port, but it took more than 10 hours for the water level to return to normal. Sometimes this process can last for more than 20 hours [16], and this phenomenon is rarely seen in other coastal areas.

Additionally, the speed and direction of flow recorded at observation stations is also subject to terrain conditions. Under the influence of Typhoon Nesat from September 29 to September 30, 2011, for example, the direction of the main flow was NE ~ E and SSW ~ WSW due to the terrain constraints of the Bailong Peninsula (F1 station), and the frequency of the northward flow increased gradually from the sea surface to the bottom. During this period, the maximum flow speed reached 103.7 cm/s on the sea surface, while the flow speed was small in other directions, usually less than 50 cm/s.

6.3. **Atmospheric gravity wave as a strengthening factor**
It was observed that the strengthening, distribution and extreme values of water level fluctuation were closely related to atmospheric gravity waves in coastal bays[19]. This study demonstrated that, under the same weather conditions and even on the same side of a bay, the water level fluctuations were also very different. This paper chose the total statistics of certain bays in which the water level fluctuation lasted for several days during the typhoons, and the water level energy spectra were analyzed. Results demonstrate that there many extreme values of the energy spectra correspond to different frequencies of oscillation of
waves in bays, but the maximum extreme value was always more closely associated with the intrinsic oscillation frequency of bays. For example, Typhoon No. 9 in 1986 was not very strong but the water level increased by 2 m, while the periodicity of the corresponding maximum extreme value of energy spectrum was 102 min, which was approximate to the bay’s intrinsic oscillation periodicity of 99 min. Similarly, this paper analyzed the energy spectra of simultaneous changes in air pressure, and also found that when the maximum extreme value of the energy spectrum was approximately equal to the bay’s intrinsic oscillation periodicity, the maximum extreme value of the increase or decrease in water level also appeared. In conclusion, the resonance between the atmospheric gravity wave and the bay’s intrinsic oscillation periodicity plays an important role in the occurrence of the maximum extreme value of the increase or decrease in water level, and also affects the strength and distribution of water level fluctuation in bays.

7. Conclusions
- The fluctuation of the water level in the Guangxi near shore is primarily caused by typhoon-induced storm surges. Using Beihai Observation Station as an example, the maximum extreme value of the water level increase was 1.45m, and occurred in 1996. Over the last 42 years, the average water level increase was 0.71m. The 100-year return level was equal to 1.78 m in Beihai, and 1.69 m in Bailongwei.
- The maximum extreme value of the water level decrease was -1.87 m and occurred in 1985, while the minimum was -0.53 m and occurred in 1965. The average of water level decrease was -1.11 m over the last 42 years. The 100-year return level of water level decrease was equal to -2.15 m in Beihai and -1.75 m in Bailongwei. The trend analysis showed that typhoon-induced storm surges led first to water level decreases followed by increase in the Guangxi near shore. Apart from the direct effects of the typhoon, the water level fluctuation in the Guangxi near shore was also indirectly affected by the westward transmission of coastal-trapped waves from the Guangdong coast. This westward transmission had two paths: one directly passed into the Beibu Gulf through the Qiongzhou Strait, and the other bypassed the eastern and southern coasts of Hainan Island and then entered the Beibu Gulf from the north. On July 6, 2001, Typhoon Utor landed at the north shore of the Pearl River estuary, causing a 20-cm increase in the water level in the Guangxi near shore on July 8. At 18:00 on July 2, Typhoon Durian landed at Guangxi, the westward transmission of the coastal-trapped wave induced a strong westward flow in the coastal areas of Guangxi, and the velocity of the surface geostrophic flow reached 92 cm/s.
- Besides the direct and indirect effects of typhoons, the terrain and the atmospheric gravity waves as a strengthening factor also played important roles in the water level fluctuation in the Guangxi near shore.

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