The Storm Surge Model

Associated With Tropical Cyclone Linda In

The Gulf of Thailand

A thesis presented as the requirement for the degree of Master of Science

By

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Contents

Abstract

A numerical model, COHERENS, is used to study the storm surge associated with tropical cyclone Linda (1997) in the Gulf of Thailand. The domain of the model is 98.5E-103E and 5N-14N with a resolution 5 min of arc. The core of the wind field in the model was created with the Holland (1980) equation modified with the translation speed. The required wind data is that of intensity and position of tropical cyclone Linda, provided by best track data from the Joint Typhoon Warning Centre. This numerical model also included the four main components of tides, from tidal charts provided by the National Tidal Centre, Australia.

The aims of this thesis were to hindcast the water level caused by the storm surge when tropical cyclone Linda came to the Gulf of Thailand in 1997. We also studied the sensitivity to different model parameters of the water level response to the tropical cyclone. The four parameters we tested were the radius of maximum wind of the model cyclone, the minimum depth of the storm surge model, the Holland's B-parameter and the track position displacement. The tidal model was used for testing the stability of the model. The surge results were added to the tidal result to hindcast the sea water level compared to the observed data from Royal Thai Navy at Kolak station.

The storm surge results did not fit well with the observed data from Kolak station, there being significant differences in amplitude, and a 13 hour time lag. The discrepancies have been investigated based on the accuracy of best track data from JTWC and the analysis of the sensitivity of the storm surge to model parameters. The results should help in understanding the complexity of both hindcasting water levels with limited storm data, and in the forecast problem.

Declaration

I certify that this thesis does not incorporate without acknowledgement any material previously submitted for a degree or diploma at any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

Anucha Srerurngla, 12 August 2010

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Chapter 1 – Introduction

Relevance and Context of study

Tropical cyclones are one of the most dangerous natural phenomena. They cause the loss of human life and large economic losses. Today, as the population in the tropical coastal regions grows very fast, knowledge of tropical cyclones becomes more important. Understanding tropical cyclone genesis, development and associated characteristic features has been a challenging subject in meteorology over the last several decades. Here we examine water level changes caused by wind stress and barometric pressure changes from a moving tropical cyclone.

This rise in water level can cause severe flooding in low lying coastal areas, push the water several kilometres inland and flood an area of over 100 square kilometres along the coast. It's the major cause of death when a typhoon comes ashore, which historically has claimed nine out of ten people who die in hurricanes are killed by storm surges.

This thesis discusses one storm surge caused by a tropical cyclone, Linda, that came into the Gulf of Thailand. The COHERENS Ocean Model (Luyten et al., 1999) has been used to hindcast this storm surge. Results are compared with the water level data from the Royal Thai Navy.

COHERENS is a three-dimensional hydrodynamic model for coastal and shelf seas developed by a multinational European group funded by the European Union. However, an aim of the work is to provide guidance for better predicting level changes from storm surges in the future. It is appreciated that the forecast is much more complicated than the hindcast (Harper 2002). For the hindcast, we have the observed wind data to use in the model, but not for the forecast. The wind speed, central pressure, track position and radius of maximum wind are just predicted data when we forecast the storm surge, and the error of these predicted data will lead to the error in surge height. By examining the sensitivity of the surge height to storm parameters, some guide to the forecast problem is to be gained.

Geography of the Gulf of Thailand

The Gulf of Thailand is located in Southeast Asia, in latitudes between 6° and 14° N, longitude 99° and 105° E (N=North, E= East), open in the south-east to the South China Sea – see figure 1.1. For the purposes of modelling, the boundary of the gulf is defined by the line from

Cape Bai Bung in southern Vietnam to the city Kota Baru on the Malaysian coast, and covers about 320,000 km^2. The Gulf of Thailand is a semi enclosed sea as defined by the Law of the Sea, that is approximately 400 km by 800 km. The Gulf is part of the Sunda Shelf and is relatively shallow. The mean depth is 45 m, and the maximum depth is 80 m at the mouth.

There are four nations around the gulf, the Kingdom of Cambodia, Malaysia, the Kingdom of Thailand and the Socialist Republic of Vietnam. The Gulf of Thailand has been a major resource for people around the Gulf for a long time. Millions of people derive their living from fish and petroleum from the Gulf. That means that changes in the environment of the gulf from the impact of tropical cyclones affects many industries and people.

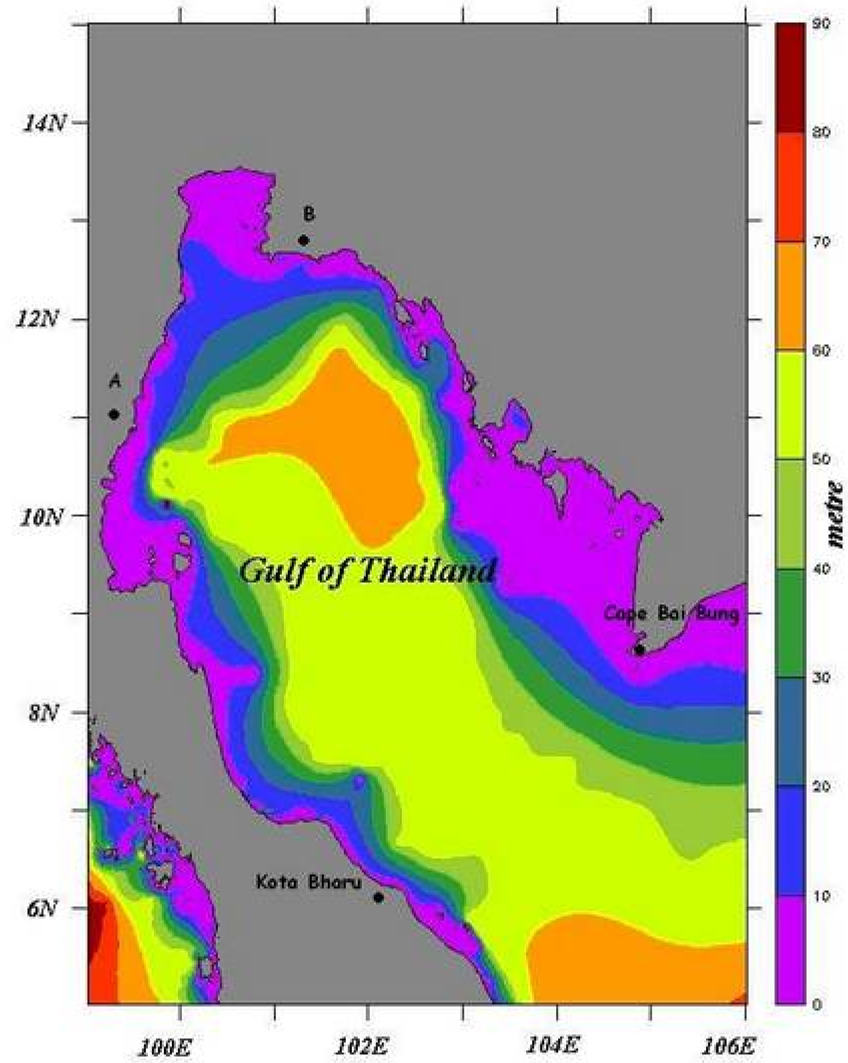


Figure 1.1 The gulf of Thailand with bathymetry data from GEBCO.

The Gulf of Thailand can be divided into the Upper and Lower Gulf. The upper gulf is the region of inverse U-shape at the head of the gulf and has a coastline of 700 km from Prachaub-Kiri-Khan Province (A, refer to figure 1.1) to Rayong Province (B). The Upper Gulf is very shallow with average depth of 15 meters. The lower Gulf is the region with an average depth 55 meters (Thongra-ar & Parkpian, 2002).

The Gulf is a two layered shallow estuary. The upper layer of the Gulf is from rain and fresh water from the Chao Phraya, Tha Chin , Mea Klong and Bang Prakong rivers that enter the gulf near its head, and the Mekong river that enters the Gulf on the Vietnam coast. "Fresh" water (low salinity around 30 psu) flows out of the Gulf at the surface, the higher salinity (around 34 psu), cool water flows into the Gulf from the South China Sea, underneath (Wyrtki, 1961). Although it is a two layer estuary, and although the model used can accommodate stratification, that feature is not included in the treatment presented here.

Tropical Cyclone Hazards

Even though there are many tropical cyclones in the North West Pacific region, tropical cyclones are rare in the Gulf of Thailand, (see next section on climatology). There have been only 18 tropical cyclones that entered the Gulf of Thailand in the 41 years period 1960-2000, and 2 more since 2000. However, this infrequency increases the danger to people and properties. Populations are lulled into a false sense of security. The tropical storm HARRIET that came on shore at Laem Taloom Pook killed more than 900 people in 1962 and Typhoon Linda in 1997 killed more than 330 with 2200 people missing. It is thus important to have adequate knowledge of disasters produced by tropical cyclones for forecasting, so that the danger can be announced several days before it happens.

There are several dangers of TC's: Strong winds, large waves, heavy rain, and flooding from the associated ocean storm surge. When a tropical cyclone makes landfall, the most destructive phenomenon associated with it is the storm surge. The term "storm surge" here means a superelevation of the still water surface due to a combination of direct wind driven water and an uplift induced by the low pressure in the middle of the tropical cyclone relative to the far field (i.e. related to the atmospheric pressure gradient). The surge reaches maximum heights when the hurricane centre arrives at a coastline. The combination of storm surge and the astronomical tide, is called a storm tide. Storm tide levels become extreme when storm-induced changes add to astronomical tides, especially in the period of high tides.

In deep water, the inverse barometer effect causes a hydrostatic rise of sea level (from the steep downward gradient of atmospheric pressure in the hurricane eye wall). It may amount to an uplift of about 1 cm for each hPa of pressure drop from the pressure in the far environment to the tropical cyclone's centre. It can become the dominant contribution to change the sea level. The wind effect dominates in shallow water (see page 23) whereas the pressure effect dominates in deep water. The wind stress that creates a surface-layer convergence of water mass towards the tropical cyclone centre does not have as much effect as the inverse barometer effect in deep water because the surface convergence is balanced by divergence at the bottom of the oceanic Ekman layer. Over deeper water, the circulating winds generate a water mass with some angular momentum. When the cyclone moves over shallow water, the angular momentum becomes constrained by the water depth, so there is a tendency for the water mass to spread out radially. However, the bottom Ekman boundary layer reduces the outflow. So the surface convergence generates a significant mound of water under the tropical cyclone, but limited by increased dissipation of angular momentum at the bottom (Simpson and Riehl, 1981).

Tropical cyclones may keep offshore and move parallel with the shoreline. It had been suggested (Simpson & Riehl 1981) that when the distance of the centre of the tropical cyclone from a shoreline is not more than two times the radius of maximum wind, there will be a storm surge on the coast. However, in 2005, a 2–3 m surge was observed at Apalachee Bay during Hurricane Dennis as it travelled along Florida's coast. This bay was 275 km east of the storm centre and the radius of maximum wind of Hurricane Dennis was only 30 km (Morey et al,2006). It is obvious that the domain of storm surge should far more than two times when tropical cyclone moves along shoreline. Harper (2001) indicated storm surge effects may be observed 100's and up to thousands of km from the storm centre. The greater distances are associated with long gravity waves that propagate away from the storm.

Climatology of tropical cyclones in the Gulf of Thailand

In general, the tropical cyclone peak season is always in late summer, when the difference between sea surface temperatures and temperatures aloft is the highest. However, the seasonal pattern is different depending on each particular basin. In the North Atlantic region, tropical cyclones occur during the months of June through November, reaching peak activity in September, whereas over the eastern North Pacific, peak activity occurs in July and August. For the North West Pacific region where the Gulf of Thailand is located, the cyclone season starts in April and ends in January next year.

The North West Pacific region (NWP), has an annual average number of tropical cyclones over the period 1960-2000 of 31.4 (including tropical depressions), this total number being more than any region in the world.

That region is the only one where tropical cyclone-genesis has been observed in all months of the year (the highest number of tropical cyclone in this region is observed in August). Moreover, the North West Pacific is particularly noted for the occurrence of very large and very intense tropical storms (McBride 1995).

According to the historical data of the meteorological department of Thailand, April is the first month in which tropical cyclones move across Thailand. The season of cyclones is over by December. September and October have the highest frequency. The cyclones usually pass through the Northern and Northeastern parts of Thailand in the early southwest monsoon season and move across the southern Thailand from October to December (Thai Met, 2006). This latter period is the time when storm surges in the Gulf of Thailand occur.

The table below shows the frequency of tropical cyclones moving through each part of Thailand (in the area between latitudes 5° 37'N to 20° 27'N and longitudes 97° 22'E to 105° 37'E) in the 49 years period 1951-1999.

This data shows there are many tropical cyclones that enter the region. Most of them enter from the South China Sea, and pass through the North and North-west of Thailand, that is, over land. Few enter the Gulf of Thailand.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	total
North	-	-	-	-	5	2	8	17	23	15	1	-	71
NE	-	-	-	-	1	5	4	15	27	22	4	-	78
Central	-	-	-	-	2	1	1	-	7	9	2	-	22
East	-	-	-	-	1	1	1	-	3	12	2	-	20
South	-	-	-	1	-	-	-	-	3	13	22	8	47
total	-	-	-	1	9	9	14	32	63	71	31	8	238

Table 1.1 The total number of tropical cyclones moving through Thailand during period 1951 – 1999 (Thai Met, 2006a)

The next frames show tracks of some tropical cyclones that entered the Gulf of Thailand. The colours show the different categories of the cyclones (outlined in the next chapter). With red representing the "severe" category, it is clear that few of these storms were severe.

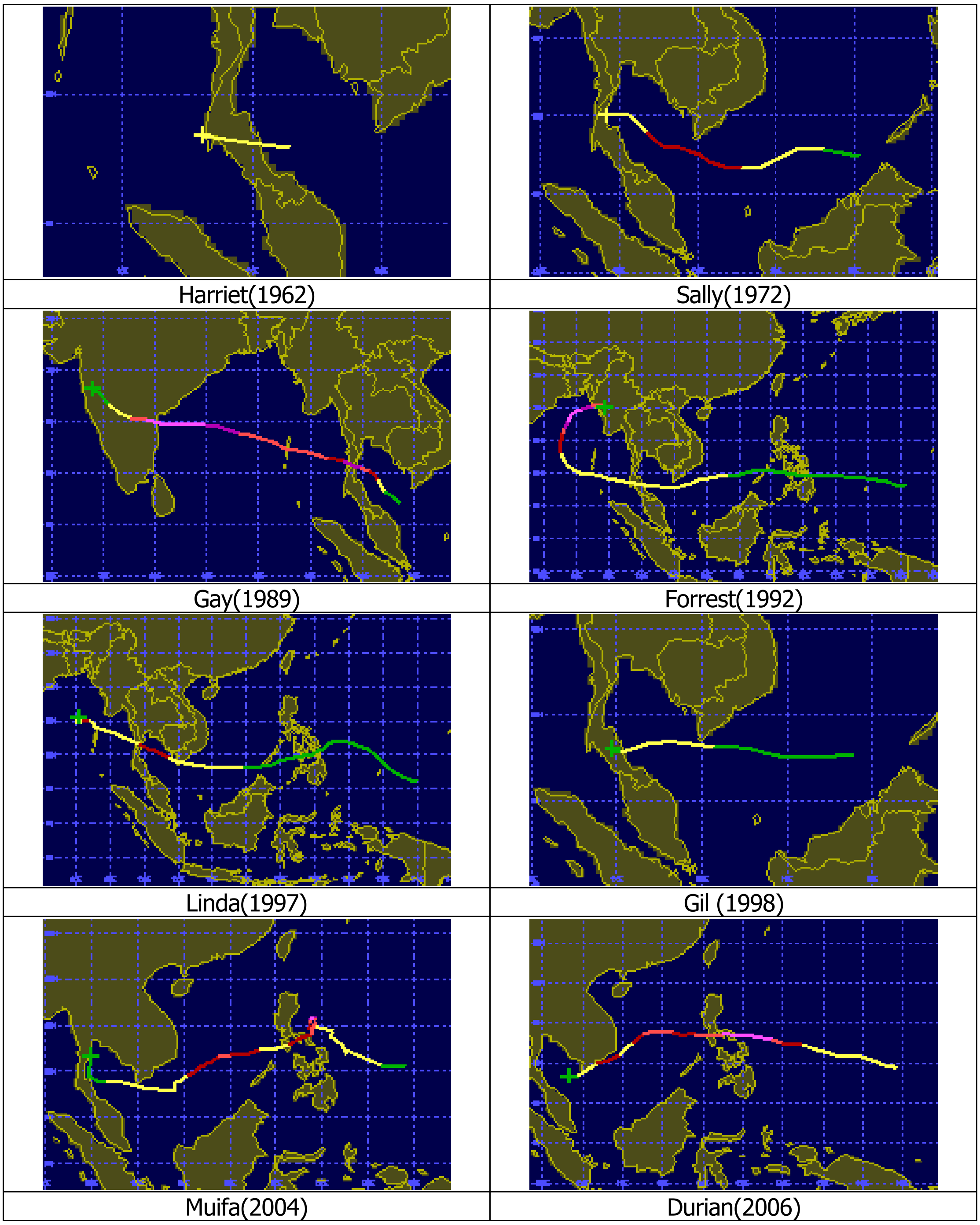


Figure 1.3 Some tropical cyclone tracks that came into the Gulf of Thailand in period 1960 – 2007. All the tracks show dominant movement from east to west (right to left). (pictures taken from UNISYS weather web site)

Aims and Objective

The aims of this thesis are focused on using the COHERENS numerical model to hindcast sea water elevation in the Gulf of Thailand in one period that a tropical cyclone came to the gulf. The model results are compared with observed data from the Royal Thai Navy. It also explores the limitations of COHERENS model and tropical cyclone parameterizations used in storm surge modelling.

Outline of Thesis

– In the chapter 2 is a literature review, covering tropical cyclone features, storm surge features, relationship between wind and central pressure of a tropical cyclone and the equations that describe fluid motion in a storm surge. Moreover, it also describes the wind field model and storm surge models that people have used before.

- We discuss the aspects of the storm surge and how a cyclone produces storm surges. The factors that affect the sea level change when a storm comes into the gulf of Thailand will be addressed.

- Chapter 3 is an outline of the method used in this study, the basic model equations, the source of observational & other data, and the experimental design for examining the effect of different parameters on water level.

– Chapter 4 is the presentation and analysis of the results from running COHERENS under different model scenarios. Here we compare results from the model with real time data from the Royal Thai Navy for different model scenarios and determine their sensitivity to model parameters.

– Summary and concluding remarks are in chapter 5.

Chapter 2 - Tropical cyclones, storm surges, and modelling

Tropical cyclone features

A tropical cyclone is a warm core, intensely developed low pressure system of synoptic scale that occurs over tropical or subtropical ocean with organized deep convection and a closed surface wind circulation about a well-defined center (Holland, 1993). It is characterized by very steep pressure gradients and strong cyclonic winds near the sea surface. The cyclonic winds in a tropical cyclone rotate counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. The maximum winds of a tropical cyclone occur around 500 m above the surface (Franklin et al, 2003), slowly decrease upward, and reverse direction to become anticyclonic at the storm top. Tropical cyclones frequently exhibit lifetimes of 2 weeks or more.

Tropical cyclones generally move westward and slightly poleward. If they survive long enough, or form at a relatively high latitude, they often recurve poleward and eastward and accelerate as they move into the strong west-to-east winds characteristic of the extra-tropical middle and upper troposphere.

Tropical cyclones can be classified into three groups according to their maximum wind speed, defined as the maximum speed of the wind at an altitude of 10 m, averaged over 10 min. The terminology for tropical cyclones differs from one region to another depending on the definitions used by Regional Specialized Meteorological Centers. In the NWP region, JTWC defines the tropical low pressure cells with a maximum wind speed of less than 29 knots as tropical depressions; when the maximum wind speed ranges between 30 and 55 knots, they are called tropical storms, and when the maximum wind speed lies between 56-114 knots, they are called typhoons. If the maximum wind speed exceeds 115 knots, it is named a Super Typhoon. But in NE Pacific & North Atlantic basin, they are called hurricanes if the wind exceeds 56 knots and if the maximum wind surpasses 86 knots, a major hurricane. The classifications also are different again in the Indian Ocean, Australia and SW Pacific as well (WMO, 1986).

A tropical cyclone can be considered as a self-sustaining heat engine, where energy is put into the system (by latent heat from condensation of water vapour evaporated from the sea surface, and warmth from the sea), and this generates air motion which sustains the energy input (Emanuel, 2003).

There are six main requirements for tropical cyclone formation: sufficiently warm sea surface temperatures -at least 26.5 °C and extending down to a depth of at least 50 meters (NOAA, 2006); atmospheric instability, so that cloud convection can be very deep; high humidity in the lower to middle levels of the troposphere; a preexisting low level focus or disturbance; sufficient Coriolis force to enhance any cyclonic circulation in the atmosphere (i.e. further than 5 degrees from the equator) and low vertical shear of the horizontal winds. Although these six parameters are not adequate conditions for cyclogenesis, tropical cyclone formation will be most frequent in the regions and seasons when the effect of the six parameters coincides. A tropical cyclone usually loses its intensity and dissipates when it move over land or cold water because its source of adequate water vapour is removed. But sometimes tropical cyclones dissipate over warm water because of unfavorable interactions with other atmospheric wind systems (Emanuel, 2003).

The tropical cyclone with the intensity of a typhoon or greater always has an eye. In the eye, air is nearly cloud free and warm because air descends and warms dry adiabatically in the eye. The winds there are also light. The region immediately surrounding the eye is the "eye-wall" where upwards convection is very strong. The strong convection produces the heaviest precipitation there. The winds increase very rapidly from the eye into the eye-wall to become a maximum some distance into the eyewall. The radius of maximum wind is in the region 20-50 km outward from the eye-wall (Emanuel, 2003). It has been hypothesized that, close to the radius of maximum, super-gradient wind flow drives air to be centrifuged out of the eye into the eye-wall and the friction between air in the eye and in the eye-wall also helps to entrain air from the eye, causing the subsidence in the eye (Gray,1991). However, the mechanics of formation of the eye-wall still need more study to be fully understood (Emanuel, 2003).

The surface wind of a tropical cyclone is not purely tangential to a circular path. Air flows inwards across the isobars because of surface friction. The angle of inflow is taken to be approximately 25 degrees in the outer region of TC but the variation of inflow angle decreased to zero near the radius of maximum wind (Harper, 2001). This inflow layer extends from the sea surface to a height of about 2 km, with the strongest inflow occurring near the surface within the eyewall. Inflow weakens upwards with the expansion of the eyewall and eye upwards. The layer appears to be around the eyewall near the surface but expands to a large area at the top (Frank 1982, 1984).

Storm Surge

A storm surge is defined as the long gravity wave defined as the superelevation of the still-water surface above predicted astronomical tide level that result from the transport and circulation of water induced by wind stresses and pressure gradients in an atmospheric storm. The surge may combine with normal tides to create storm tides which can increase water level well above mean sea level. If the tropical cyclone comes onshore in the period of astronomical high tides, the amplitude of a surge can add to the amplitude of high tides and build up a large sea level elevation. The figure below attempts to show these different effects.

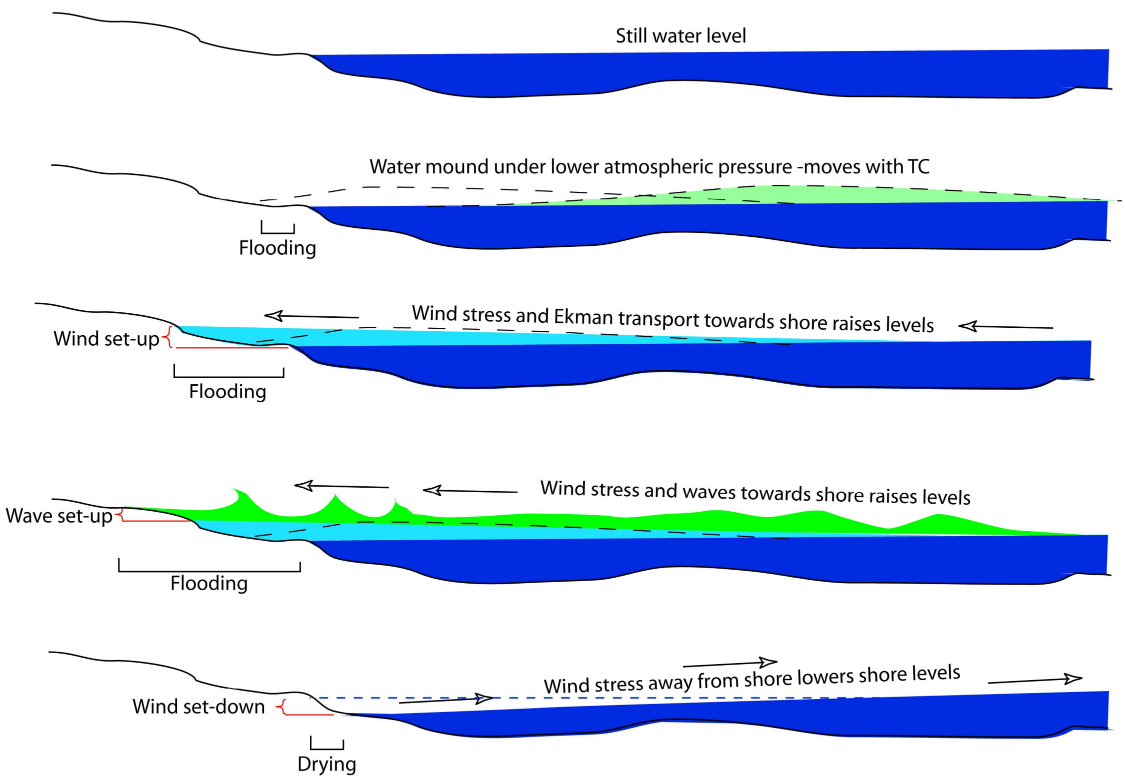


Figure 2.1 Sketches of water level changes arising from the inverse barometer effect, surface wind stress, and wave set-up, and wind set-down for offshore winds

We can say that every tropical cyclone that comes ashore can cause a storm surge but not all storm surges rise to dangerous levels. The height of a surge is depended on many factors, of which the main factors are:

- The intensity of the cyclone, defined here by the maximum mean wind speed over open flat land or water, sometimes referred to as the maximum sustained wind, will be experienced around the eye-wall of the cyclone (Australian Government, Bureau of Meteorology website). As the winds increase (because the central pressure decreases), the sea water is piled higher and the waves on top of the surge are taller. The drop of central pressure of a tropical cyclone generates an inverse barometer effect as already mentioned in chapter 1. Both pressure and wind effects are present in all storm surges, but their relative importance varies with location. The wind effect dominates in shallow water sea whereas the pressure effect dominates in the deep ocean, for reasons given in chapter 1. Major destructive storm surges occur when intense storm winds act over areas of shallow water. (Flather, 2001)

- The speed at which the cyclone approaches the coast. The faster the cyclone crosses the coast, often the more powerful is the surge because the translation speed of the tropical cyclone adds to the total wind speed. Higher total wind speeds pile up sea water more. The total wind cannot be a simple vector addition of the translation speed to the circulating speed because far from the centre, the actual wind is not influenced by the motion of the tropical cyclone at all. Instead, the effect of the translation speed is reduced with distance from the centre, because the wind streamlines show reduced curvature further away. Jakobsen and Madsen (2004) suggested a simple procedure to accommodate the speed of translation of a tropical cyclone in the circulation speed. This is considered in more detail in chapter 3.

  However, the effect of translation speed appears to vary with circumstances. Peng, Xie and Pietrafesa (2004) ran their numerical model for the Croatane-Albemarlee-Pamlico Estuary System (CAPES) in eastern North Carolina and got results which showed that a slower translation speed produced a higher and larger storm surge. The peak surge increased almost linearly as the translation speed decreased.

  But it also depends on the size of tropical cyclone. The faster a tropical cyclone moves, the less time it has for winds to build up water circulation. In the case of a smaller tropical cyclone, especially with a small radius of maximum wind, the less area the winds work over the surface, so the smaller the fetch, and the less the surge. But if the TC has a large radius of maximum wind, then the wind set-up does not get large if the fetch is not a limiting factor. If a TC is slowly moving, it has more time to work on the sea surface, so the larger the wind set-up and surge height.

  Weisberg and Zeng (2006) indicated support for Peng et al., that if the storm moves too fast so that the translation time scale of the storm is shorter than the surge set up time, the storm surge cannot build up to its full potential. The surge set up time is proportional to the square of the length of the bay, the inverse of the mean depth and the turbulent resistance coefficient. For Tampa Bay with length=50 km, mean depth=5 m and the turbulent resistance coefficient=0.0015, the surge set up time is approximately 6 hours.

So the higher translation speed may not really induce the higher surge. Sometimes it decreases the surge height by the fetch limiting factor.

- The angle at which the track of the cyclone intersects the coast. In general, if the track of a tropical cyclone is perpendicular to the coast, it can cause the highest surge. This is because in the northern hemisphere, tropical cyclones rotate anti-clockwise, so the wind at its right front is strongest since the vectors of rotational wind speed and translation speed add together in the same direction. If the track of a tropical cyclone goes straight to the shore, the water will be pushed directly against the shore with maximum wind speed at the right front. This will produce the highest surge. However, its height also depends on the physical characteristics of the coastline and the bathymetry of the water offshore.
- Local topography such as bays, headlands and offshore islands decrease or increase the height of storm surge. A narrow bay can cause a resonance of oscillation to increase the height of the surge but an island can prevent the water from piling up by the wind.
- The bottom slope of the sea floor. If the slope of the sea bed at the coast is shallow, the bottom friction in shallow water will slow down the rate of return flow underneath the surge. The surface water that is pushed by the wind will grow higher. If the slope is steep, then the surge will be less because the water can turn back easier that will decrease the surge height. (Simpson and Riehl, 1981)
- The increase of the radius of maximum wind of a tropical cyclone can also result in the higher surge. For the same maximum wind speed, the area over which the wind works is certainly larger. But if the rate of decrease of velocity either side of the maximum, with radius, is slower the bigger radius of maximum wind is, the whole area is subject to a bigger wind stress and that causes the bigger surge as well. But if the decrease of velocity is faster, the bigger the radius of maximum wind, the opposite applies. However, Peng et al (2004) show in their study that when the radius of maximum wind is between 40-60 km and the mean central pressure between 955-975 mb, the storm surge is more sensitive to changes in the mean central pressure than to the radius of maximum wind.
- Runoff from river and coastal catchments subject to heavy tropical cyclone's rainfall raises water levels at the head of estuaries. This adds to the coastal water levels caused by a storm surge, sometimes it as much as 30 cm height. (Simpson and Riehl, 1981)

- The Coriolis force steers the currents in both deep and shallow water –the geostrophic layer is a direct result of the Corilis force, and the Ekman layer is a direct result of the interaction between friction and the Coriolis force. In shallow water, friction dominates, the surface and bottom Ekman layers merge in the middle, so surface currents travel almost directly down the pressure gradient. The direction those currents approach the shore either enhances or reduces the surge height.
- The tropical cyclone path is hard to predict and often erratic. So it is hard to forecast exactly when and where a cyclone will cross the coast. And if we can't predict the time a tropical cyclone hits the coast, it will difficult to find how high the astronomical tide will be when the storm surge strikes, since the time difference between high and low tide is only a few hours. All these reasons cause errors in height and time of a predicted storm surge.

Tides

To obtain surge levels that are comparable with observations, it is necessary to specify the astronomical tide levels within the domain of interest. The astronomical tide is typically specified by the period, amplitude and phase of the various components generated by the gravitational effects of the Sun and moon on the oceans.

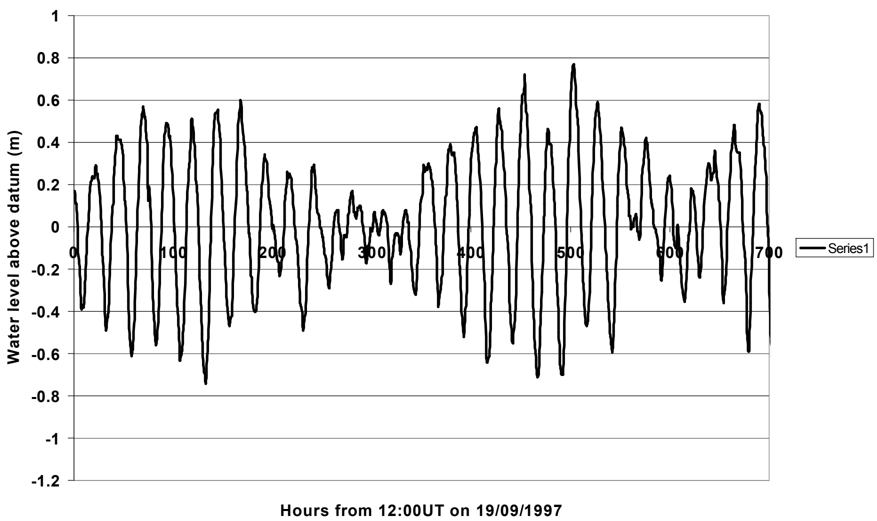


Figure 2.2 An example for a sequence of tidal record from Kolak

Main tidal periods

It is thus convenient to separate the tidal periods into two groups; tides produced by the moon or lunar tides and tides produced by the sun or solar tides. The major components of these are:

- Tides produced by the moon are M_2 (semidiurnal lunar) and O_1 (diurnal lunar). The period of the M2 component is 1/2 lunar day = 12h 25min and the period of O1 component is 1 lunar day = 24h 50min.

- Tides produced by the sun are S_2 (semidiurnal solar) and K_1 (diurnal solar). The period of S2 is 1/2 solar day = 12h and 1 solar day = 24h is the period of for K1.

In fact, the tides are the sum of hundreds of harmonic oscillations. Each harmonic (called a tidal constituent) has its amplitude, period and phase. In modelling the tides to a high precision, most tidal predictors use 120 tidal constituents. In this thesis, only the 4 major ones M_2, S_2, K_1 and O_1 are used.

Tidal observation in Thailand began in 1904, and the work on the tidal datum was started in 1910, 6 years later. The first tide pole was placed at Ko Lak in Preachubkereekarn Province in September 1910 and started operation in October 1910 via the hydrographic department, Royal Thai Navy. Tide prediction utilizing computers was introduced to the hydrographic department in 1977. Today, there are 27 tide gauge stations operated in Thailand (in the Gulf of Thailand and Andaman Sea); 11 stations belong to the Hydrographic Department, 12 stations belong to the Harbor Department and 4 stations belong to the Port Authority of Thailand. The Hydrographic Department predicts hourly height for all stations and high - low waters for some station by using 112 harmonic constituents together with software provided by National Tidal Centre (former National Tidal Facility at the Flinders University, Australia) which we obtained tidal data from.

The tidal constituents of the 4 main components for Kolak are as follows:

Tidal constituent	**Amplitude (m)**	**Period (hr)**
M2	0.06	12.43
S2	0.01	12.00
K1	0.38	23.93
O1	0.17	25.80

Table 2.1 Amplitude and period of M2, S2, K1 and O1 derive from Thai Navy data at Kolak station.

These tidal amplitudes make it clear that at Kolak, the tide is quite dominated by the diurnal K1 component.

Tetsuo Yanagi and Toshiyuki Takao (1998) used the horizontal two-dimensional momentum and continuity equations for tide and tidal current of a homogeneous fluid under Cartesian coordinates and found that the natural oscillation period of the whole Gulf of Thailand is near the semi-diurnal period and the direction of its phase propagation is clockwise, mainly due to the propagation direction of the large amplitude part of the incoming semi-diurnal tidal wave (M2, S2) from the South China Sea. In the Gulf of Thailand, the semi-diurnal tide propagates clockwise in the middle part of the Gulf but the diurnal tides (K1 and O1) propagate in a counter clockwise direction. These aspects make the tide propagation in the gulf of Thailand complicated (Yanagi and Takao, 1998). Anyway, the tidal record shows that the dominant tidal component at Kolak is mostly diurnal (as in Figure 2.2), rather than semi-diurnal.

In principle, the addition of the storm surge directly to the astronomical tide does not properly account for the fact that currents and bottom friction, and hence water levels, depend non-linearly upon water depth. But Harper (2001) stated that a combined surge and tides modelling is only necessary for inland flooding when the linear addition of surge and tide is to be used for the production of surge statistics and for real-time forecasting purposes.

For the storm surge model with tides, if we just add the astronomical tides to the surge directly, the result tends to overestimate the sea level elevation. (Prandle and Wolf 1978). Davies and Lawrence (1994) use the M2, M4, M6 tidal components to test the 3 dimensional ocean model of the eastern Irish Sea with a grid resolution of order 1 km and including wave-current interaction and a single point model, to show that in shallow regions, tidal elevation amplitude and phase are significantly changed due to the enhanced friction effects related to wind driven flow and wind wave turbulence.

The wind and pressure fields of a tropical cyclone

The wind field of a tropical cyclone relative to its centre can be considered in terms of the radial variation of the tangential and radial components of the wind speed. Variations of wind speed and pressure with radius have been directly measured via aircraft flights through the eye of many tropical cyclones. (e.g. Willoughby et al. 1989,) The study of radial wind profiles and relationships between minimum pressure and maximum wind have been developed over the years in many ocean areas. The first successful numerical simulation of a tropical cyclone was published by Ooyama in 1969. His model showed the capability of simulating the typical life of a tropical cyclone with a remarkable degree of reality and also showed the response to changing parameters such as sea surface temperature and the coefficient of air-sea energy exchange. His computed cyclone compared very well in rate of total rainfall and energetic characteristic with available observed tropical cyclone data but it still wasn't good enough to predict realistic behaviour of individual tropical cyclones because of some weak approximations in his model. He said in his paper that the restrictive assumption of the axisymmetry of a tropical cyclone, and the use of gradient winds within the boundary layer of his model were the weak points of his study. The axisymmetry of a tropical cyclone cannot be completely realistic since the tropical cyclone has a forward speed that causes the asymmetric shape, producing different wind speed at different azimuthal directions.

The gradient wind (above the surface friction layer) can be modelled from pressure distributions. But the surface wind is the wind that does work on ocean surface, so it is smaller than the gradient wind and so needs to be reduced by some factor before using in the model.

Dvorak (1975) developed a technique for setting tropical cyclone intensities by using satellite pictures. He estimated the tropical cyclone intensity from its cloud features, described in terms of central features and outer banding features. These features are analyzed to assign a T-number to the tropical cyclone at a particular stage of development, The T-number ranges from one to eight, from minimum to the maximum intensity tropical cyclone. Based on the statistics and his empirical relationship, he also estimated central pressure of the tropical cyclone from its T-number and its region of formation. However, Dvorak's original procedure requires clear images of the eye region in order to establish the T-number.

In 1977, Atkinson and Halliday analysed 28 years of maximum wind speed and minimum sea level pressure of tropical cyclones in Western North Pacific and present a relation between maximum wind and minimum pressure as:

$$V_m = 6.7(1010 - p_c)^{0.644}$$ **------------------------- (eq. 2.1)**

V_m is the maximum sustained (1 min) wind speed (knot) and p_c is the minimum sea level pressure in hPa in the centre of tropical cyclone. The "1010" hPa represents the far-field mean sea level pressure in which the tropical cyclone is embedded. Note that the sea level pressure over Thailand is 1009-1010 hPa after the monsoon onset (Sangwaldach et al.,2006).

The Atkinson and Halliday formula is used widely to estimate the wind speed of a tropical cyclone from its central pressure. Harper, (2002) states that "Atkinson and Halliday procedure giving a 5% overestimate of wind speed at 50 m/s and about an 8% overestimate at 70 m/s". But Knaff and Zehr (2006) have tested this equation for tropical cyclones of typhoon strength over 1974-1987. They indicate that it results in a systematic underestimation of the maximum wind speed of typhoon wind strength in the period. Their reanalysis of tropical cyclone intensity in the period of 1966-1987 increased the mean intensity of tropical cyclones in that period by about 3.1 m/s or 6 knot, proportional to maximum wind. Anyway, since the Atkinson & Halliday tropical cyclones only report speeds rounded to the nearest 5 knot, there is a fair uncertainty in their speeds in the first place.

Holland (1980) deduced a radial pressure variation in a tropical cyclone that is of a similar form to that of several other authors

$$p = p_c + (p_n - p_c)e^{-A/r^B}$$ **------------------------- (eq. 2.2)**

Earlier and later authors use B=1. Holland shows that different storms have different B values, and an individual storm may have a B value that changes over the storm's lifetime. B values range from about 0.5 up to 2.5. See more below.

We use Holland' s radial pressure profile equation to define the surface pressure field at each time step as COHERENS input, for the inverse barometer effect. There, Pn, the ambient pressure, is set to 1010.0 hPa by reference to the reanalysis data by NOAA (2006a).

Applying the pressure distribution in the gradient wind equation gives

$$V_g = \sqrt{A\,B\frac{(p_n - p_c)}{\rho}\frac{e^{-A/r^B}}{r^B} + \left(\frac{rf}{2}\right)^2} - \frac{rf}{2} \quad \textbf{----------------------- (eq. 2.3)}$$

In the above two equations, V_g is the gradient wind at radius r, p_n is the ambient pressure far from the center, p_c is central pressure of the tropical cyclone, ρ is air density and f is the Coriolis parameter. A and B are scaling parameters: B defines the way the profile varies with radius –strongly peaked at the radius of maximum wind, or flatter. A is related to the radius of maximum wind. Holland concludes in his case studies that his model gives the most realistic profiles if the radius of maximum wind is accurately known. Simplifications are possible to the gradient wind equation in the region of hurricane force winds because then the Coriolis force is small compared with the centrifugal force, and so can be neglected. That results in the cyclostrophic equation that has also been widely used. This equation gives too large speeds at large radii from the centre, however. The wind speed created by the Holland equation 2.3 is assumed to be the same at different azimuthal directions. (Foley and Fuentes, 2008)

Holland's axisymmetric pressure profile and gradient wind (and cyclostrophic) equations are widely used for modelling these fields under tropical cyclones.

The B-parameter that is, with the radius of maximum wind, a most significant parameter for defining the radial wind profile shape, is a tricky parameter to define well. There are many suggestions from different papers on ways to calculate a value. The most reliable are based on having good wind observations at a known distance from the tropical cyclone centre. (Harper 2002, Holland, 2008). Where these are absent, empirical relations have to be used.

Hubbert el al.(1991) used the empirical equation 2.4 to calculate B:

$$B = 1.5 + \frac{(980 - p_C)}{120} \quad \textbf{-------------- (eq. 2.4)}$$

Flather (1994) calculated B from the cyclostrophic wind equation using Holland's pressure profile, with the maximum speed given by (Holland, 1980)

$$V_m = (B\Delta p / \rho e)^{1/2} \qquad \text{--------------- (eq. 2.5)}$$

This could be used provided Vm (at the top of the boundary layer) can be established properly from other observations.

Jakobsen and Madsen (2004) provided a formula with the regression parameters calculated from the maximum wind at 500m above sea surface, and the central pressure drop to get the B value.

Holland (2008) produced equations giving the B-parameter in terms of surface winds (as well as gradient wind). The B in his formulations varies with intensity changes, pressure drop into the cyclone center, latitude of centre, and the cyclone translation speed. These also cannot be easily used as not all parameters are known, and those formulae have empirical constants in them that have been derived using North Atlantic data. Those empirical constants are likely to differ from the NWPO, since parameter values are already known to differ between these basins.

But for TC Linda, we have only the maximum surface wind from JTWC,and no measured winds from the typhoon stage at all, so these formulae cannot be used properly. Instead, the Holland gradient wind equation is used to create the wind field of tropical cyclone Linda in this thesis. The radius of maximum wind and B are taken to vary to investigate their effect on the storm surge, and for comparison with observed levels.

To these circulating winds must be added motion arising from the movement of the centre of the TC, as outlined in chapter 1. This changes the axisymmetric motion to one with asymmetry. Jakobsen and Madsen (2004) suggested adding vectorially a radially modified track motion to give the total wind (V):

$$\vec{V}(x,y) = \vec{V}_g(x,y) + \vec{V}_E(x,y) \qquad \text{--------------- (eq. 2.6)}$$

where

$$\vec{V}_E(x,y) = \vec{V}_T(x,y).\exp\left(-\frac{r}{R_G}\right) \qquad \text{--------------- (eq. 2.7)}$$

$\vec{V}_E$ is the wind vector in environmental scale which considered as geostrophic wind field related to the large scale pressure fields. $\vec{V}_T$ is the translation speed of the tropical cyclone. "r" is the distance from the cyclone centre and R_G is the length scale of the environmental scale process (taken to be about 500 km, Jakobsen and Madsen, 2004). Note that a different value of R_G will make a difference to the onshore winds as the cyclone approached Kolak.

The figure below shows an example of the resulting wind pattern when TC Linda was in its typhoon stage, the track speed of TC is not included here.

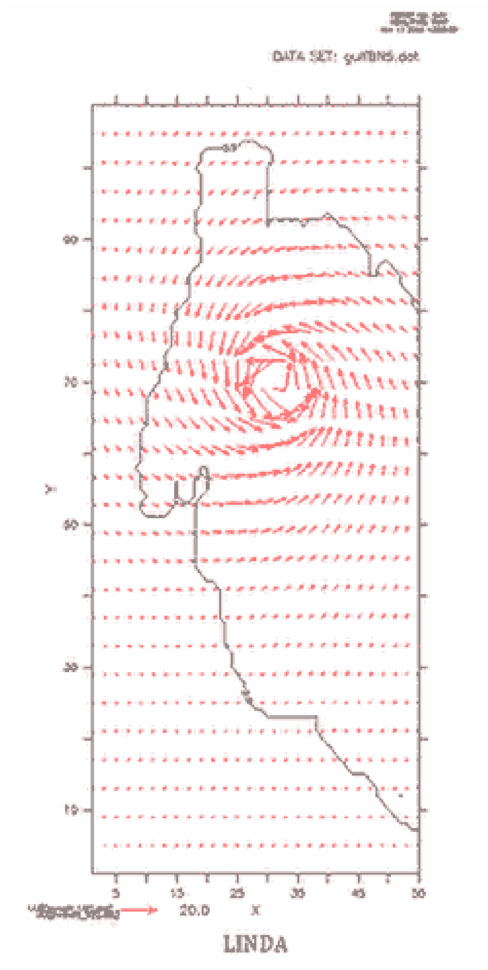


Figure 2.2 The surface wind patterns of tropical cyclone Linda in the Gulf of Thailand on 03/11/1997 0900UTC created by Holland's equations

Typhoon Linda

Typhoon Linda formed within an area of convection east of the Philippine Islands on 26 October 1997. It reached tropical storm intensity within 24 hours as it tracked over the South China Sea westward toward the southern tip of Vietnam. Linda reached typhoon intensity shortly after entering the Gulf of Thailand. It struck the Malay Peninsula on 03 November 1997. And it was the first tropical cyclone since Typhoon Forrest in 1992 to cross from the Western North Pacific to the North Indian Ocean. As it crossed the Malay Peninsula, Linda weakened as it encountered the region's mountains and lost its source of water vapour.

However, once over the warm waters of the Andaman Sea to the west of the Peninsula, the system began to reconsolidate and became a typhoon once again. This was short-lived. Linda stalled in the Bay of Bengal and slowly weakened over several days. It had dissipated by 10 November 1997. This typhoon caused damage in Vietnam, Cambodia and Thailand as already mentioned in chapter 1.

In this thesis, we use Atkinson and Holliday's equation (2.1 above) to calculate p_c from the maximum wind speed obtained from JTWC best track data for typhoon Linda. Then we use Holland's equation to create the wind fields. The term p_n in the equation is taken as the representative environmental pressure for a tropical cyclone (Holland, 1993).

Note that the wind speeds that JTWC provides are one-minute average maximum surface wind speeds. To relate the gradient winds from Holland's equation to surface winds applicable to stress calculations in COHERENS, we first need to convert the JTWC winds to 10-minute averages. The factor used to convert to 10 minute averages is 0.88 as indicated in Table A-2 of the Tropical Cyclone Forecasters Reference Guide. Following Powell (1980), the gradient winds from Holland's equation are multiplied by 0.8 to give a reasonable estimation of surface winds in hurricanes.

Storm surge model

For the reason that storm surges are the worst effect of tropical cyclone in causing loss of life, numerical models of storm surges have been developed in several location around the world over the last few decades. Jelesnianski (1965) says in his paper that a significant cause of the storm surge is the cross isobar flow of wind, where as the motion of the storm shows less effect.

In 1972 Jelesnianski developed the SPLASH model and used it to forecast hurricane surges along the east coast of the United State. The same year, DAS (1972), developed the first numerical model of storm surges for the Bay of Bengal to simulate the storm surge of November 13, 1970. He also established a model solving the linearized equations and from simulations of a variety of storm derived results to estimate the maximum surge height from basic cyclone parameters. (DAS et al., 1974)

Storm surge models have long been used operationally for flood forecasting and warning in several countries. Operational numerical models of storm surges are employed in several locations around the world, such as the North Sea (Flather 1976), the Gulf of Mexico, and the Atlantic Coast (Jelesnianski and Chen, 1979). Some of the storm surges models in the Bay of Bengal are reviewed in Murty et al. (1986). These forecast systems are based on two-dimensional shallow water equation models. In shallow seas, these models provide a good simulation of the water levels and they have good forecasting capabilities. (Madsen and Jakobsen, 2004).

Hubbert et al-(1991) used the Holland wind equation, and their B relation (eq. 2.4 above) to run their depth averaged storm surge model on a personal computer. They tested the model by hindcasting a tropical cyclone in Australia. This predicted the surge peak accurate to about 0.1-0.2 meter and arrival time of peak within 1 hour.

Most storm surge modeling is based on depth-averaged hydrodynamic equations applicable to both tides and storm surges and including nonlinear terms responsible for their interaction. The equations can be written as follow;

$$\frac{\partial \zeta}{\partial t} + \vec{\nabla}.(D\vec{q}) = 0$$ ------------------------- **(eq. 2.8)**

$$\frac{\partial \vec{q}}{\partial t} + \vec{q}.\vec{\nabla}\vec{q} - f\vec{k} \times \vec{q} = -g\vec{\nabla}(\zeta - \xi) - \frac{1}{\rho}\vec{\nabla}P_a + \frac{1}{\rho D}(\vec{\tau}_s - \vec{\tau}_b) + A\vec{\nabla}^2\vec{q}$$ ----- **(eq. 2.9)**

where t is time; ζ the sea surface elevation above the mean level,; ξ the equilibrium tide; q the depth-mean current; τ_s the wind stress on the sea surface; τ_b the bottom stress; P_a atmospheric pressure on the sea surface; D the total water depth (D=h+ζ , where h is the undisturbed depth); ρ the density of sea water, assumed to be uniform; g the acceleration due to gravity; f the Coriolis parameter; k a unit vector in the vertical; and A the coefficient of horizontal viscosity. (Flather, 2001)

Equation 2.8 is the continuity equation expressing conservation of volume. Equation 2.9 shows the relation of the accelerations (left-hand side) to the force per unit mass (right-hand side).

In equation 2.9, because the wind stress term is divided by the total depth, whereas the surface pressure gradient force is not, this makes the wind forcing the most significant parameter when tropical cyclones come over shallower water.

In 1993, Roger A. Flather ran a numerical model over the Northern Bay of Bengal and Ganges Delta with the data of a disastrous tropical cyclone in April 1991. The data were collected from the Joint Typhoon Warning Centre in Guam (JTWC). The wind fields were created by Holland's equation. The storm surge model he used ran the surge over the tides to include their interaction. The model made use of a modified depth-average equation with a numerical scheme, using 1-dimensional equations for narrow channels, and 2 dimensions where the domain is an open sea. And an approach to modeling coastal inundation was also included. After he applied it to the North Bay of Bengal, the result from his model predicted the location of landfall accurately but the timing was about 5 hours late from observation data. This result shifted the area of highest sea water level northwards.

Tang, Grimshaw, Sanderson and Holland (1996) ran two dimensional numerical models, with a modified Orlanski-type validation boundary condition, domain on the North Queensland Coast, and demonstrate that with tides included in the storm surge model, the effect of a quadratic bottom friction law in the model is to make the sea elevation lower than from simply adding the astronomical tides to the surge. Additionally, a quadratic bottom friction law had very little effect on the phase shift between the simulation of storm surge alone and simulating it with tides. They recommended simulating the storm surge alone and then added the astronomical tide for predicting storm sea levels. Although it will give an overestimated level, that is safer for evacuation purposes than underestimating it.

Peng, Xie and Pietrafesa (2003) do a storm surge model for the coast of Eastern North Carolina. They used the Holland equation to calculate the wind speed with mean central pressure and radius of maximum wind, the sensitive factors. Their paper shows that both the radius of maximum wind and mean central pressure of tropical cyclones influence the peak surge but the peak surge is more sensitive to mean central pressure than radius of maximum wind in the range of 955-975 mb for central pressures and 40-60 km for the radius of maximum wind.

Of the many parts of the world that have a serious problem about storm surge, the Bay of Bengal is the famous one. A number of modelers ran their model for the Bay of Bengal as a test case and improved them a lot by comparing observations with models. Murty, Flather and Henry (1986) have concluded the very interesting development of wind model and storm surge model in the Bay of Bengal in their paper. Jacobson and Madsen also trialled a model for the Bay of Bengal in 2004. There, the central pressure and velocity were updated from observations. Their model showed an accurate forecasting up to 24 hours before the real cyclone made landfall.

Work that is relevant to the Gulf of Thailand and this thesis is that of Kanbua et al., (2005) :whom his work on a storm surge associated with tropical cyclone Linda presented on Thai Met website leading the intention of improving the storm surge hindcasting in this thesis. Wattana Kanbua presented an investigation of the wave field during the attack of typhoon Linda. He compared two numerical ocean models in his work, WAM Model that is widely use for global wave forecasting and GRNN model, a model that uses a neural network technique in addressing simulation and forecasting in oceanographic problems. He obtained wind data from NOGAPS with a 1 degree resolution. He used bathymetry of the Gulf of Thailand from ETOPO5 data. His model covers the domain at 95-105E and 5-15N. No air pressure data was included. The wave height that resulted from WAM model was about 20% underestimated compared to observed data. He suggests that improvements to the accuracy of the wind data should improve the wave height results. Another thing he pointed out with the WAM model is it doesn't consider some important processes in coastal regions such as diffraction, wave induced breaking and bottom friction. The GRNN model gave a better result, with a wave height of 4.0 meter compared to 4.06 meter from observation. And he suggests that for short term prediction, the data driven model is a strong alternative for forecasting system. Anyway, in this thesis, we consider surges independently of waves–even though COHERENS has the capability for treating wave effects.

The COHERENS model

To model storm surges in the Gulf of Thailand, first of all, we want a suitable numerical model. There are a number of ocean models around. We need an ocean model that has a response to meteorological forcing, includes tides and is suited for shallow water. Some are well known such as the Princeton Ocean Model (POM), developed at Princeton University. At an early stage of this project, the Bergen Ocean Model (BOM), developed at the Institute of Marine Research, Norway and at the Hydrodynamics group, Department of Mathematics, University of Bergen, Norway was trialed for this thesis in order to develop some skills at using a model. But, at Flinders University, the COHERENS model was in use by others at the time we began working on the problem, so it was convenient to use that model for this thesis. Some of the features of COHERENS were appealing because there was the possibility of exploring more oceanography topics for the Gulf of Thailand in the future such as the effect of river discharges on water levels because of discharge and salinity stratification in the head of the Gulf, and resulting 2-layer water circulation. (These topics have not been explored here however).

The full COHERENS model is a three-dimensional hydrodynamic multi-purpose model for coastal and shelf seas developed by a multinational European group as part of the MAST projects PROFILE, NOMADS and COHERENS. This model was written in FORTRAN 77, can be used to solve numerical flow problems in a physical component, with modules for currents, salinity and temperature, and also the module for simulating biological cycling processes. There is a sediment module describing the deposition and erosion of suspended organic and inorganic material, and Eulerian and Lagrangian modules to simulate the advective-diffusive transport of contaminants. It does not include a wetting and drying capability for treating flooding and retreat from shallow water at coastlines, in contrast to some others (e.g Murty 1984);In this thesis we just use COHERENS as a 2D numerical model only to calculate the sea water elevation caused by a tropical cyclone advecting through the model domain.

In the COHERENS model, the time step and horizontal and vertical resolution can be defined by the user so it's easy to adjust these for the physical forcing data. The 2-D time step has to be small enough to satisfy the Courant-Friedrichs-Lewy (CFL) criterion and the 3-D time step is a multiple of the 2-D time step. The model also requires the meteorological data of surface winds and pressures, and astronomical tides. It resolves mesoscale to seasonal scale processes such as basin seiches, the passage of atmospheric and oceanic fronts, high and low atmospheric pressure systems, tropical and extra-tropical cyclones, and the seasonal cycle of heat flux on the ocean. The duration of the model can be set to a few hours, few weeks, few months or several years. Cartesian or spherical computational grids can be selected. And the program can run as a full 3 dimensional model, 2 dimensional model or as a point model in the vertical (1 dimensional model) where all horizontal gradients are neglected in the momentum and scalar transport equations except for the slope of the sea surface. Horizontal pressure gradients are still taken into account (Luyten et al., 1999). In this thesis, the effort is focused on the physical aspects of the modelling as a storm surge model.

The COHERENS model uses the mode-splitting technique to solve the 2-D and 3-D momentum and continuity equations as done in the Princeton Ocean Model. The program incorporates a variety of turbulence closure schemes. Density effects in the momentum and turbulence equations are included via an equation of state. Various types of bottom friction and surface friction can be used. It can include the effect of wave-current interaction on the bottom shear stress. And the user can select different formulations for the wind stress and surface heat fluxes. We only use some functions that are available in COHERENS for this thesis. The detail is given later in chapter 3.

The model equations

COHERENS allows the model equations to be formulated either in Cartesian coordinates (x1, x2, x3) or in spherical coordinates (λ, φ, x3), the x3-axis is directed upwards along the vertical.

The design of the program consists of a "core" part and of a series of modules. This modular design allows easy updating of any particular process, selecting the forcings and boundary conditions, and enabling/disabling any modules. The core updates the current field by solving the Navier-Stokes equations and contains the advection-diffusion module. A series of switches allows the user to select whichever processes are required, for a particular numerical simulation. (Luyten et al.,1999).

The core of physical model of COHERENS is based on the Navier-Stokes and continuity equations, and the equations of temperature and salinity. But in using COHERENS as the storm surge model in this thesis, the effect of temperature and salinity are not included.

- The momentum equations using the Boussinesq approximation and the assumption of vertical hydrostatic equilibrium are:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x_1}+v\frac{\partial u}{\partial x_2}+w\frac{\partial u}{\partial x_3}-fv=-\left(\frac{1}{\rho_0}\right)\frac{\partial p}{\partial x_1}+\frac{\partial}{\partial x_3}\left(\upsilon_T\frac{\partial u}{\partial x_3}\right)+\frac{\partial \tau_{11}}{\partial x_1}+\frac{\partial \tau_{21}}{\partial x_2} \quad \textbf{----- (eq 2.10)}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x_1}+v\frac{\partial v}{\partial x_2}+w\frac{\partial v}{\partial x_3}-fu=-\left(\frac{1}{\rho_0}\right)\frac{\partial p}{\partial x_2}+\frac{\partial}{\partial x_3}\left(\upsilon_T\frac{\partial v}{\partial x_3}\right)+\frac{\partial \tau_{12}}{\partial x_1}+\frac{\partial \tau_{22}}{\partial x_2}$$ **----(eq. 2.11)**

$$\frac{\partial p}{\partial x_3}=-\rho g$$ **-------- (eq.2.12)**

- The continuity equation;

$$\frac{\partial u}{\partial x_1}+\frac{\partial v}{\partial x_2}+\frac{\partial w}{\partial x_3}=0$$ **-------- (eq. 2.13)**

In the Cartesian coordinates (x,y,z) equations, t is time, ρ is density, p is pressure, (u,v,w) are velocity components, τ (11,12,21,22) are horizontal components of the stress tensor,f = 2Ωsinφ, is the Coriolis frequency, Ω = 2π/86164 rad/, is the rotation frequency of the Earth, g is the surface acceleration caused by the gravitational attraction of the Earth and v_T is vertical eddy viscosity (Luyten et al.,1999).

The method consists in solving the depth-integrated momentum, continuity equations and the sea surface elevation for the "external" or barotropic mode (Luyten et al.,1999). Note that, when equations 2.10 and 2.11 are vertically averaged, the result is equation 2.9.

In this thesis we use spherical grid co-ordinate to accommodate the small changes to the Coriolis force in the domain, so the basic equations are transformed to spherical coordinates.

Chapter 3 – Methodology

Region of interest

The geographic domain of the model used in this thesis is 98.5°E- 103°E and 5°N – 14°N, and covers the part of the Gulf of Thailand (see figure 3.1 below). The size of the model is 4.5° x 9 degrees or 55 x 109 grid spacings or 502 x 1004 square kilometers. The spatial resolution of the model is 5 minutes of arc. The open boundary for this domain is located only on the east side from North-South grid point 8 to grid point 75.

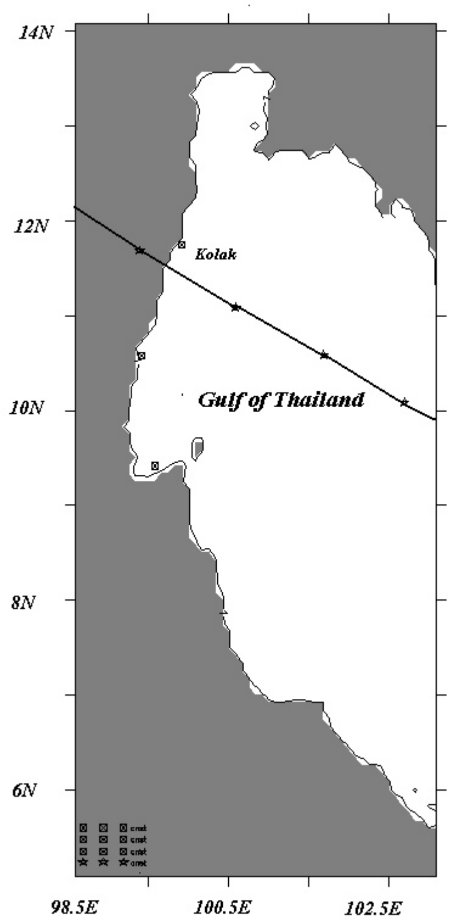
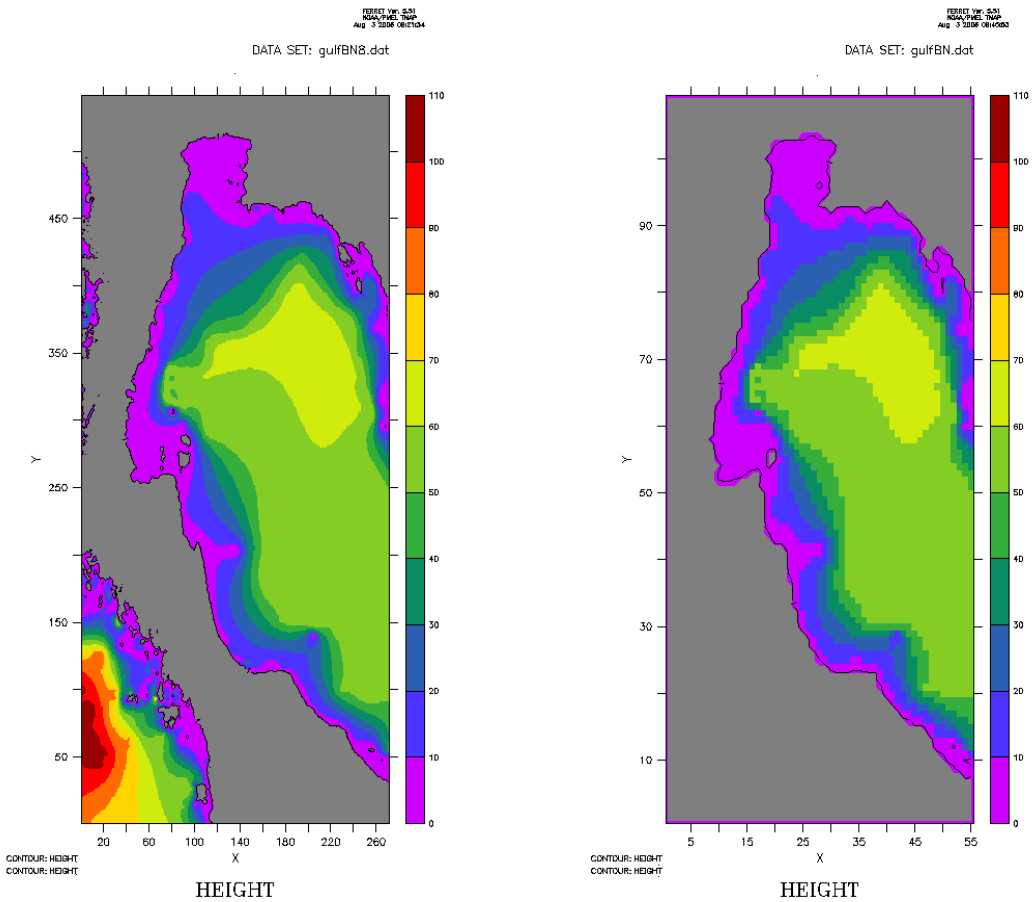


Figure 3.1 The domain of the storm surge model (east longitudes, north latitudes) with the track of tropical cyclone Linda shown, and Kolak station where water levels were observed.

Bathymetry

The bathymetry of the Gulf of Thailand is taken from the GEBCO Digital Atlas (GDA) CENTENARY EDITION 2003 on CD-ROM. GEBCO stands for General Bathymetric Chart of the Oceans. The GEBCO bathymetric grid uses a 3-D mathematical model to represent the data derived from bathymetric information. It is a high quality, digital bathymetric contour chart of the world's oceans.

The resolution of bathymetry data from GEBCO is 1 minute of arc, which corresponds to 1.85 km. For the reasons of limitation of computer memory and speed when running the models, we transformed it to a 5 arcmin grid. The interpolation was done by the Ferret program (see later). The bathymetry data from GEBCO (1x1 arcmin) and interpolated data (5x5 arcmin) are shown in the figure 3.2



A **B**

Figure 3.2 the bathymetry of the gulf of Thailand, A is the data from GEBCO with resolution 1 min, B is the data after interpolation by Ferret, to a resolution of 5 min and elimination of the Andaman Sea at the left hand side.

The resolution of GEBCO in depth data is 1 meter. The accuracy is 0.5% of the depth in deep water (Goodwille, 2004). But for the shallow water, GEBCO resolution is limited at 1 meter. If the data computed by GEBCO are in fractions of a meter, GEBCO rounds the result to the nearest whole meter. This may or may not produce a significant error in the shallow water.

In the interpolation, Ferret computes the average weighted by grid box size, to give a single number. In the case of two dimensions, it integrates values from both axes to find the average rather than sequential single integrations.

When we ran the model with the 5 minute bathymetry data and shallowest water to 1 m depth, COHERENS model crashed because the bathymetry nearshore is too shallow to accommodate wetting/drying coastline at the shallowest water in the modeled tide and surge. So we set the minimum bathymetry at 5 m in the model after some trials to prevent it from crashing, for the Gulf of Thailand bathymetry.

Meteorological forcing

In this thesis, we used two sets of meteorological data as input to the COHERENS to induce the storm surge, pressure field data and wind field data. The best-track data from the western North Pacific, maintained by the Joint Typhoon Warning Center (JTWC) was used in the calculation of the meteorological data input files, as given in chapter 2. JTWC provides the best track data of tropical cyclone Linda for every 6 hours from 25/10/1997 to 09/11/1997. This data was the 1-minute average of maximum wind speed and the latitude and longitude of the cyclone track. There are other sources that supply the tropical cyclone Linda data such as the Japan Meteorological Agency (JMA). They provide the 10-minute average wind data and the track position somewhat different from JTWC including the location where that Linda came on shore. Unfortunately, the data set from the Japan Meteorological Agency website was too short to run the model to get the full surge, for comparison with the JTWC data.

The wind fields

With the JTWC data, we model the tropical cyclone wind field using the Holland (1980) equation as presented in chapter 2, equation 2.3.

In that equation, we need p_n, p_c, A, B, ρ and f for any given radius from the centre of the tropical cyclone. For p_n, we used the outermost isobar from the NOAA(2006a) reanalysis data, covering the passage to Linda. This was 1010 hPa while Linda was in the Gulf of Thailand.

To use the Holland' equation to build the wind field for the storm surge model, we need the radius of maximum wind, central pressure and position of the tropical cyclone. However, the data we can get for Linda are only the maximum wind speed, position and track speed. We tried to find the radius of maximum wind of tropical cyclone Linda from a satellite image, but cirrus covered the eye and was not clear enough to define where the eye wall of Linda was. So we cannot estimate the radius of maximum wind from that, following Dvorak (1975).

Instead, we ran model experiments with different assumed radii of maximum wind to see their effect on predicted water levels, for comparison with observations. As a guide from the paper of Anthes (1982), the typical radius of maximum wind is about 40 km. So we investigated the effect of various Rmax around this value.

To get p_c, we used Atkinson & Hallidays' formulae as presented in equation 2.1 with the maximum wind of tropical cyclone Linda from 1-minute sustained wind provided by JTWC best-track data (1997).

To establish B-parameter, we used the formula suggested in Hubbert el al.(1991) presented in equation 2.4 that has B as a function of central pressure. The result for the B-parameter is equal to 1.53 when the extreme minimum pressure of Linda is 976 mb.

After that we can calculate A-parameter from;

$$A = (R_{\max})^B \qquad \textbf{--------------- (eq. 3.1)}$$

The speed from Holland's gradient wind equation is tangential to the isobars, and does not include any inflow to the centre of the tropical cyclone. To accommodate inflow, we set the inward flow to be 25 degrees toward the centre of the tropical cyclone. This inflow angle is in the range for the North-west Pacific region of about 23°- 25° (Frank, 1977), and corresponds to the near eyewall values outlined in chapter 2.

The V_g from Holland' equation (equation 2.3) is the gradient wind. To convert the gradient wind to surface wind, we multiplied it by the factor 0.8 (Powell, 1980).

In addition to the wind field of the tropical cyclone, we allowed for the movement of the tropical cyclone by using the result of Jakobsen and Madsen (2004) as shown in equation 2.6 and 2.7. For every grid point, we added a modified tropical cyclone movement (V_E), vectorially, to the gradient wind (V_g) to get the total wind (V).

The translation speeds of the centre of Linda were calculated from the 6-hourly positions of the centre of tropical cyclone Linda provided by JTWC. We took the distance in metres that Linda moved in each time step and divided by 6 hours x3600 s/hr to give the translation speed in m/s –as north and east components.

In this thesis, when the storm surge model is used to hindcast the sea water elevation for comparing to Kolak station data, care has to be taken in applying the translation speed to the tropical cyclone wind distribution. The maximum surface wind from JTWC already includes the translation speed. If we add more translation speed into it, the total wind will be higher than it should be. We cannot subtract the translation wind speed from the JTWC maximum wind when using the Atkinson & Halliday equation because this equation is a relation between the 1-minute average maximum wind (which included the translation speed) and minimum pressure.

We solved the problem of getting the right Holland wind field with its appropriate B value that matches the same surface wind as the adjusted JTWC 10 minute value by varying the B-parameter. Instead of using B=1.53 from Hubbert et al., we varied B from 0.9-1.8 in the process of creating the wind fields as described above. Then, for each wind field created from each B-value, we plotted a speed cross-section through the centre of the TC to find the maximum wind. This maximum was compared with the JTWC maximum wind. The results showed that, when B=1.4 the maximum wind was closest to the maximum JTWC' maximum wind. We used this wind field along with the wind fields with B=1.53 by Hubbert' formulae to run the storm surge model with tides and compared both results to station data at Kolak.

Figure 3.3 below shows an example calculated wind field and speed contours (left), and the pressure pattern from Linda, based on the preceding equations.

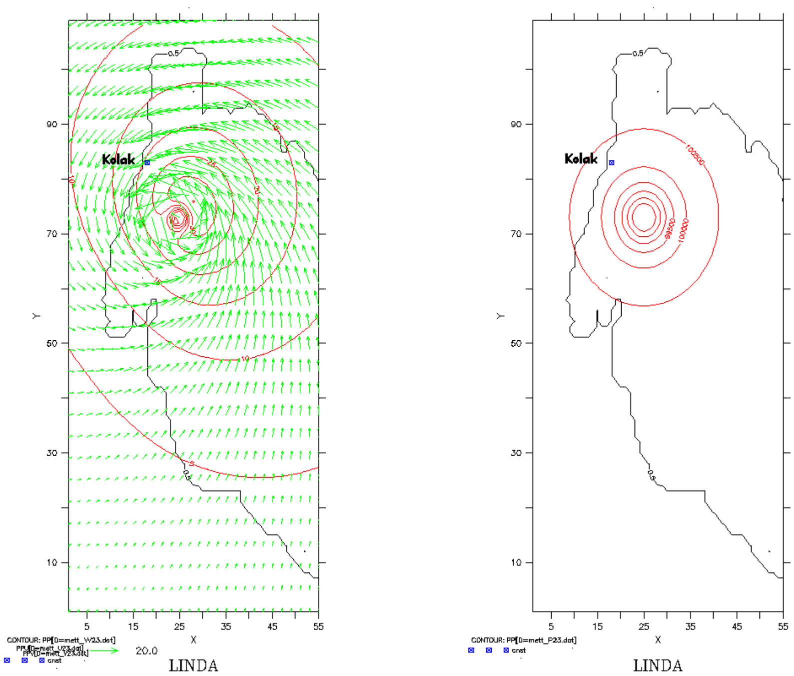
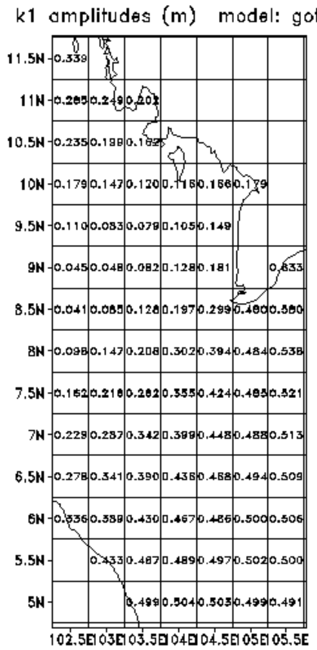
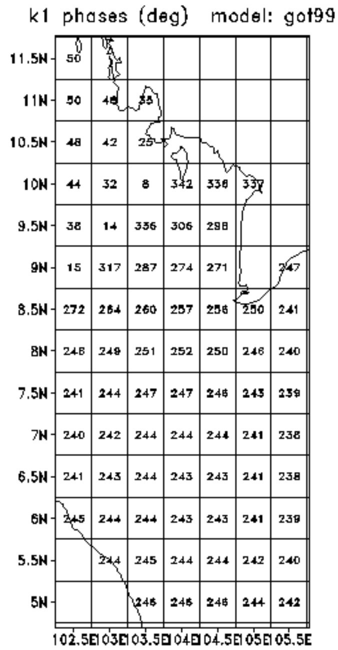


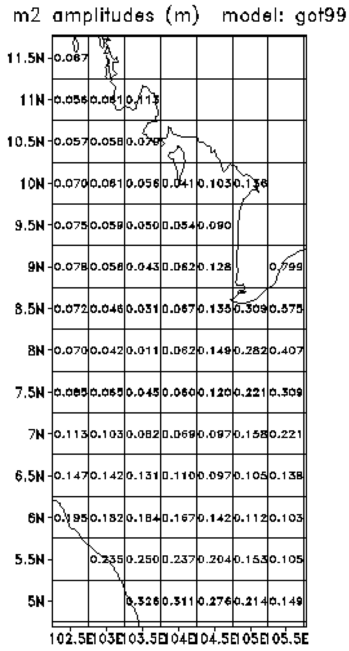
Figure 3.3 An example of the calculated wind field (left) and pressure field (right) (For 0900UT, 3/11/1997)**.**

Tide Data

To forecast accurate water levels at all times wherever the tropical cyclone is, we needed tidal data. We obtained tidal data for the Gulf of Thailand from the Australian National Tidal Centre (NTC). This organization specializes in sea level monitoring and analyses for the purpose of deriving trends in absolute sea level and producing national tide predictions, tide streams and related information. Their tidal charts are given in terms of the four major components, M2, S2, K1 and O1 components with a spatial resolution of 0.5 degree. We interpolated the resolution of the tidal charts to 5 minutes of arc to correspond with the model domain resolution. The tides were forced along the North-South model open boundary at longitude 103E.






m2 amplitudes (m) model: got99
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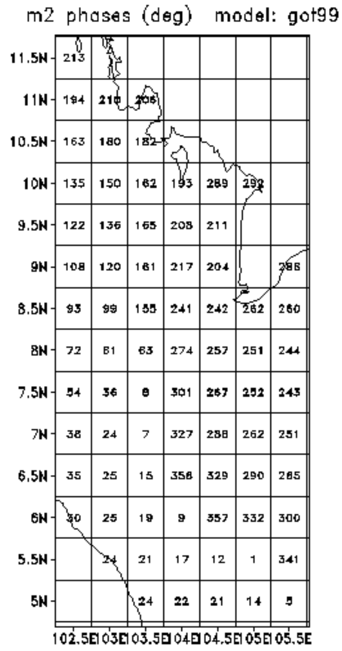
m2 phases (deg) model: got99
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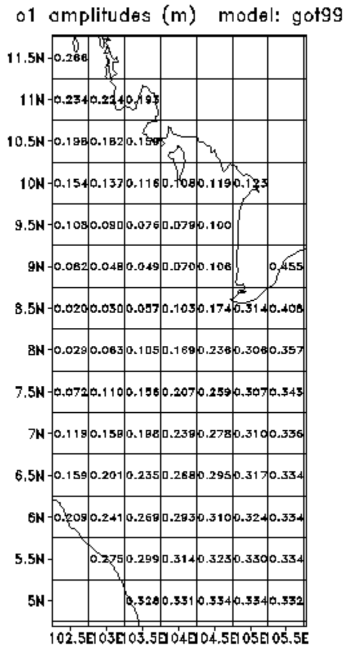
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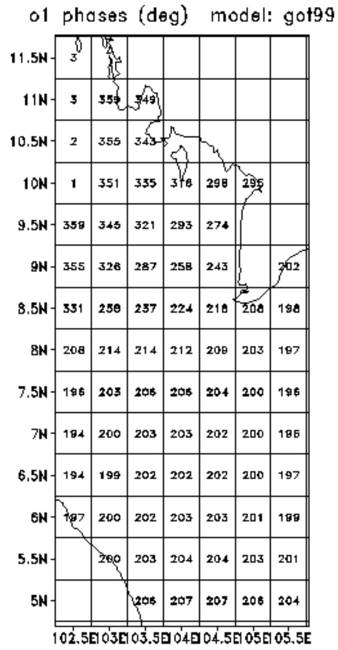
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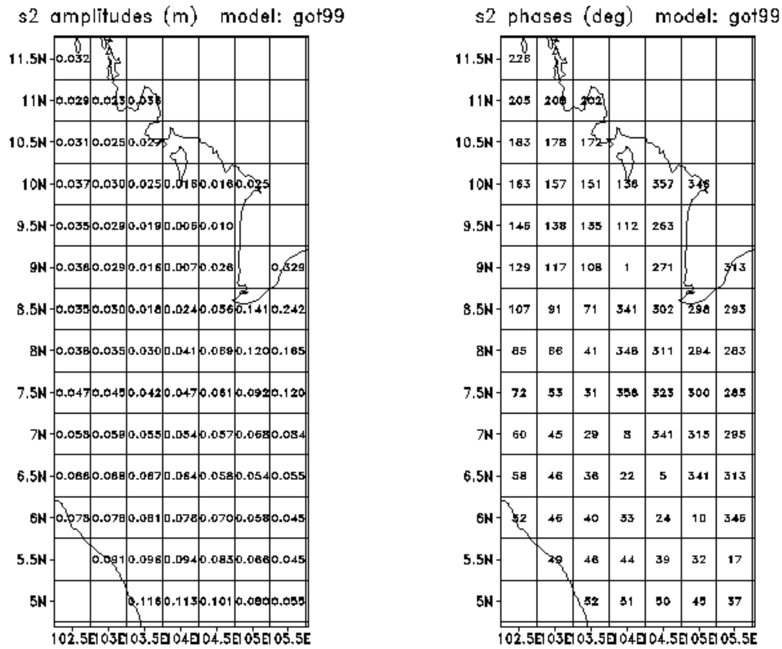

Figure 3.4 The tidal charts of amplitude and phase for the Gulf of Thailand (K1, M2, O1 and S2) taken from National Tidal Centre (NTC, 2006). Phases are with respect to UTC. K1 is the dominant component in the Gulf.

For testing the behavior of COHERENS, we ran the model with only tidal forcing (no meteorological forcing) and compared the results with tides from Kolak station. and the model was run for 4 months duration The minimum depth was varied from 5m to 20m for testing. The different bottom friction formulae and bottom friction coefficient value had also been tested to get the best agreement with station data. The fast Fourier transform (FFT) was also used to compare the spectral component amplitudes in the Kolak and model results.

Basic model setting

The model runs were started at 06:00 UT 15 October 1997 and ended at 18:00 UT 5 November 1997. The total real-time duration is 21 days and 12 hours. The wind and pressure data files were applied to the model at 18:00 UT 31 October 1997, equal to the run-time of 16 days and 12 hours after the model started. We used the spherical grid in the model to allow for the effect of changing Coriolis force on currents in the model domain. The output from the model was taken every hour.

There are many meteorological inputs that we could have set for the model. In this storm surge model we set only the critical factors that affect the sea level elevation: the surface wind components in x and y direction (East and North) and surface air pressure. The time step of meteorological input was set to 6 hours while the model was spinning up and then changed to 1-hour time step at 06:00UT 2/11/1997 when Linda came in to affect the Gulf of Thailand.

Other meteorological inputs we have set to constants. Fractional cloud coverage was set to 1.0, air temperature = 25^{o}C and relative humidity = 0.9. (These parameters are more relevant to the surface heat fluxes, and would take effect when running COHERENS in 3-D mode to find the effect of stratification on currents in the Gulf but not on the 2-D model). Air temperature and relative humidity make a very slight difference to the surface shear stress, via air density and stability in the model.

We ran the 2-dimensional model by setting the depth to 1 level. The number of horizontal grid points in the domain is 55 x 109. The number of grid points at the open boundary is 68. This boundary lies on the east of the domain, from where the tropical cyclone entered. The horizontal diffusion coefficient is set to take a constant value calculated by COHERENS. The temperature and salinity equations are not solved even though they are initialized at the start of the program but not updated in time. The bottom stress is evaluated using the quadratic friction law for the bottom boundary condition. The surface drag coefficient is only a function of the wind speed and stability and follows the Smith and Banke (1975) formulation. The zero gradient condition is used for current at the eastern boundary.

The sea level record

To ensure reasonable behaviour of the model under non-surge conditions, model runs of the astronomical tides using the COHERENS model were compared with real data to tune the model with a known input from the major component of the tides, by adjusting the bottom friction and water depth. We used the measured sea level height from Kolak station (lat 11^{o} 47′ 42″N, long 99^{o} 48′ 58″ E) in the period of 19th October 1997 – 10th November 1997, provided by the Royal Thai Navy with a time resolution of 1 hr. From the record data, we subtracted the mean sea level (2.50m) to get the level deviations at Kolak station for each time. These deviations throughout the period of the model run are then compared with the model results at Kolak station as an indicator of model hindcast storm surge that was associated with tides. The results are reported in chapter 4.

There are 2 extremes in the station water level data below that are important in this thesis. One is at the 457th hour in the diagram when the trough of seawater elevation is well below the mean sea level. We call it the "negative surge". Another is at the 477th hour, the highest peak of the data. We call it the "positive surge" peak. Both peak and trough are the result of the sea water level changes associated with tropical cyclone Linda.

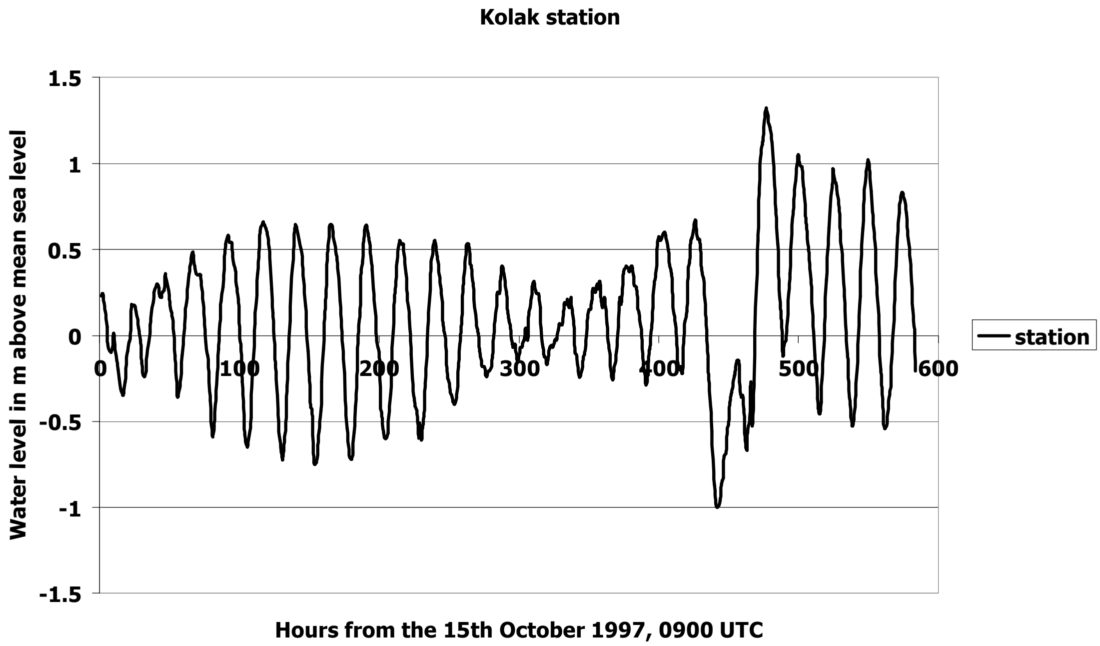

Figure 3.5 The sea water level taken from KOLAK station in period of tropical cyclone Linda

In figure 3.5, the negative surge is lowest at 18:00 UT, 02/11/1997 and the positive surge peaked at 05:00 UT 04/11/1997. It is these extremes that we wish to model. (This station record was very slightly edited to eliminate an erroneous point, replacing the data at hour 49 by the average of data at hour 48 and hour 50).

Experimental design

To test the sensitivity of parameters that influenced the storm surge in the Gulf of Thailand, we ran 5 experiments in the period of typhoon Linda's transit, to investigate the effects of varying radii of maximum wind, B-parameter, central pressure, minimum depth of bathymetry and track position on the sea level elevation.

The parameters to study the effect of minimum depth of bathymetry on storm surge model

The depth of water close to the shoreline can change the height of the surge (Chapter 2). As described above, we have set the minimum depth to 5 meters. This minimum depth means that if the bathymetry at a grid point is less depth than the minimum, it will be changed to the value of the minimum depth. These model run experiments vary the minimum depth in COHERENS as 5, 10, 15 and 20m. Changing the minimum depth means the bathymetry of the shallow area is changed too (as you can see in Figure 4.6). If the minimum depth is set too great, the area that has this same minimum depth is broad around the coastline of the Gulf and so affects the surge height produced by a tropical cyclone. This experiment establishes the greatest value of the minimum depth to use that still produces some accuracy in the surge result.

For this section, we used the radius of maximum wind Rmax=40km and B =1.4 for 5 model runs as listed in the following table: (the value of Rmax and B as tested to give the surge peak close to the station record at Kolak when minimum depth = 5m)

Experiment number	Minimum Depth (m)
1	5
2	10
3	15
4	20

Table 3.1 The experiments setting to study the effect of different minimum depth of the model on the sea water elevation in storm surge model.

The parameters to study the effect of different radii of maximum wind on storm surge model.

The bigger radius of maximum wind causes the bigger area that the wind stress can push over the sea surface. This should produce higher surge. But another factor in the wind fields that influenced the surge is the wind distribution in the tropical cyclone. The B-parameter is the parameter that shapes the wind distribution in tropical cyclones. So, in this experiment, we used a sequence of radii of maximum wind (R_{max} = 20, 30, 40 and 50 km) to run the model. The B-parameter used to create the wind and pressure fields was also varied (B=0.9, 1.2 and 1.5). The minimum water depth was still set to 5 meters. The experiments are set in the table below.

Radius of maximum wind (km)	20	30	40	50
B parameter	Experiment number			
0.9	1	2	3	4
1.2	5	6	7	8
1.5	9	10	11	12

Table 3.2 The experiments setting to study the effect of different radius of maximum wind and B parameter on the sea water elevation in storm surge model

The parameters to study the effect of the B parameter on the storm surge model

As we discussed previously, to calculate the Holland wind fields, we need to know the value of the B-parameter. In the classic model, Holland used only one B value for one tropical cyclone. He later allowed B to vary (Holland, 2008), with B depending on Rmax and central pressure. In this thesis, we still used the constant B-parameter that does not vary with time

Instead, in this experiment, we varied the B-parameter over 3 values (0.9, 1.2 and 1.5) with the radius of maximum wind equal to 20 km, 30 km and 40 km. The minimum depth was set to 5 m. The 9 model experiments are set as experiment number 1, 2, 3, 5, 6, 7, 9, 10 and 11 in Table 3.2 above.

The parameters to study the effect of tropical cyclone track position on storm surge model.

As we know, the position where a tropical cyclone comes onshore is significant for the height of the storm surge there. Where the right-front of the tropical cyclone hits the shore, it will produce the highest surge. Given that the JTWC best track position differs from the JMA one as described earlier, it is useful to examine the effect of changes in the track. In this study, we investigate the sensitivity of the surge at Kolak to the position of the centre of the tropical cyclone. The track of the TC was moved up (to the North, positive) and down (to the South) in the domain. The size of the tropical cyclone should of course affect the surge when the track, so different radii of maximum wind were also tested. The distance the track was shifted varied from 40 to 120 km with the radius of maximum wind 20 and 40 km as shown in the table below.

Track displacement (km)	Experiment number
+120	3
+80	2
+40	1
-40	4
-80	5
-120	6

Table 3.3 The experiment settings to study the effect of tropical cyclone track position on the sea water elevation in the storm surge model, B=1.4 and Rmax=40 km.

Data processing aspects

For some data processing and graphic results in this thesis, Ferret was used. This program is freeware from the NOAA website (NOAA, 2006b). This program was developed by the Thermal Modeling and Analysis Project (TMAP) at PMEL in Seattle to analyze the outputs of its numerical ocean models for comparison with gridded, observational data. Ferret is widely used in the oceanographic community to analyze data and create graphics. Ferret offers a Mathematica-like approach to analysis.

Chapter 4 - Results and Analysis

The storm surge caused by typhoon Linda (1997)

In this chapter, we present the model results at Kolak station as a function of mean wind speed and central pressure of the typhoon Linda that came to the gulf of Thailand in October 1997. We compare the model results with the observed water level record from Kolak station taken by the Royal Thai Navy. We investigate which model conditions give results that are closest to the station data. We also find the response of the modelled water elevation to variations of input parameters.

In this chapter, we compare results from models with different input parameters. This shows the sensitivity to the following parameters: the radius of maximum wind, Holland's B-parameter, the minimum model water depth and the cyclone track position, with settings as outlined in chapter 3. We also model the surge on top of the tides to compare the model results with the station data. This comparison shows which model conditions give the closest results to reality.

Tidal Modelling

A storm surge is always associated with the tides in the Gulf of Thailand. If the storm surge happens in the period of high tides, it can cause destruction or damage to coastal properties and the loss of many lives. In forecasting storm surges, we should forecast tides as well. In this part, we ran the model to hindcast the tides in the period of weeks before Linda. We did not include any meteorological data so that the accuracy of the model to regular physical forcing can be established, before we examine the effect of wind forcing. We do this by comparing the modelled tides with the real water elevation at Kolak. A quadratic bottom friction factor of 0.0035 and minimum water depth of 5 m was applied to the model. The results are shown below.

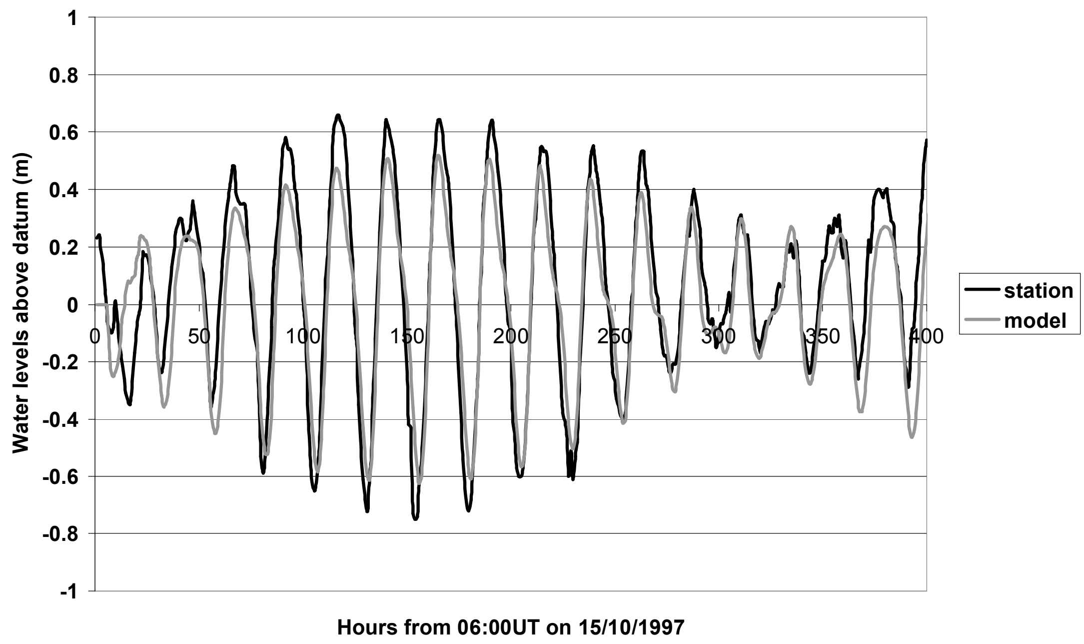

Figure 4.1 The results from the simulated tides with model minimum depth= 5m compared with the station data from Kolak.

The results show excellent agreement in the phase, period and overall pattern but the amplitude of tides created by the COHERENS model is about 19% less than the station data. Part of the reason for this should because we use only the 4 major components of tides to run the model (chapter 2), but mainly, it is because we do not reproduce the amplitude of the diurnal components, which dominate at Kolak, correctly. To see this, we used the Fast Fourier Transform method to analyze the tides from the model and the station data from Kolak (Figure 4.2). The amplitudes of the 2 main diurnal tidal constituents from the model are slightly less than those for the station data from Kolak (12% on K1 and 15% on O1), whereas the modelled semidiurnal components (much weaker) are slightly more. The modelled tides are the result of tidal constants interpolated across the mouth of the Gulf so there may be some error arising from the specified values there.

The amplitude spectrum of the observed data shown in Figure 4.2 also shows additional small components at other periods which are not reproduced in the modelled data.

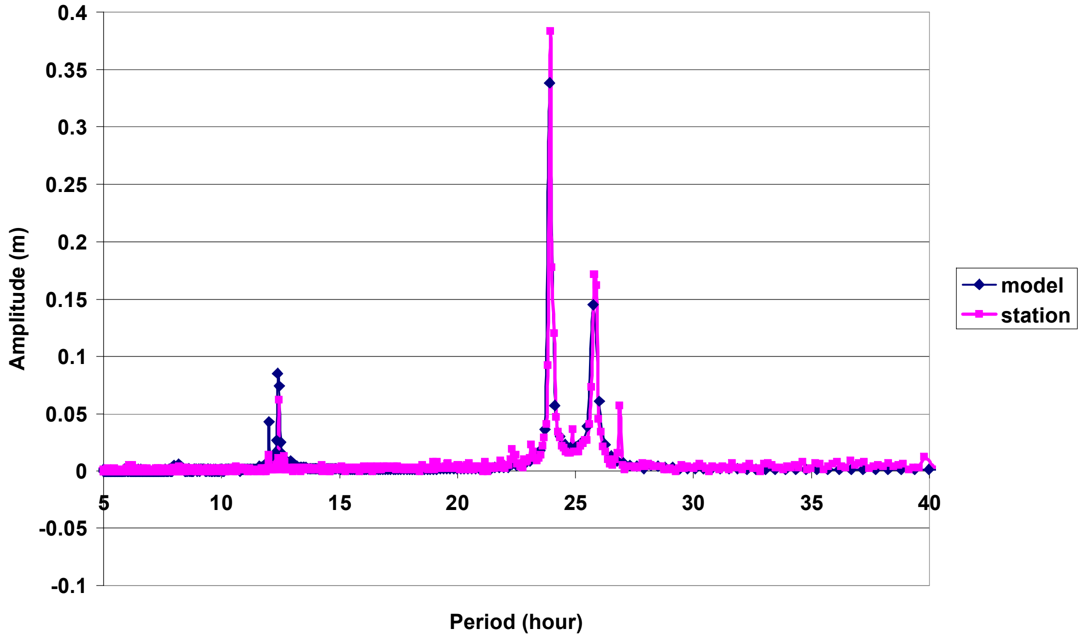

Figure 4.2 The Fast Fourier Transform analysis of the tidal components, for comparing between the model result and station data from Kolak

Different values of the quadratic bottom friction term in the range between 0.01-0.0001 were tested to see changes to the modelled tidal amplitude. Figure 4.3 shows the results that the smaller friction gives the larger amplitude in tidal level but the difference is small.

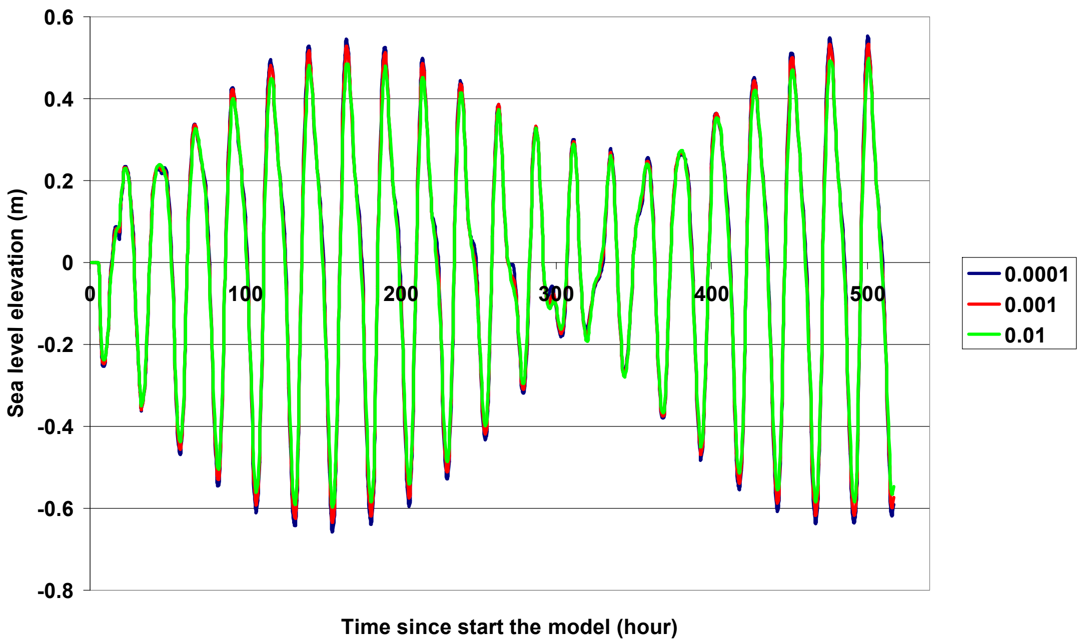

Figure 4.3 Changes in tidal amplitude when the bottom friction is changed.

However, by changing the minimum water depth in the model from 5 to 20 m, the agreement between the modelled and observed tides was improved significantly. For the weeks before Linda came onshore, this result is shown next.

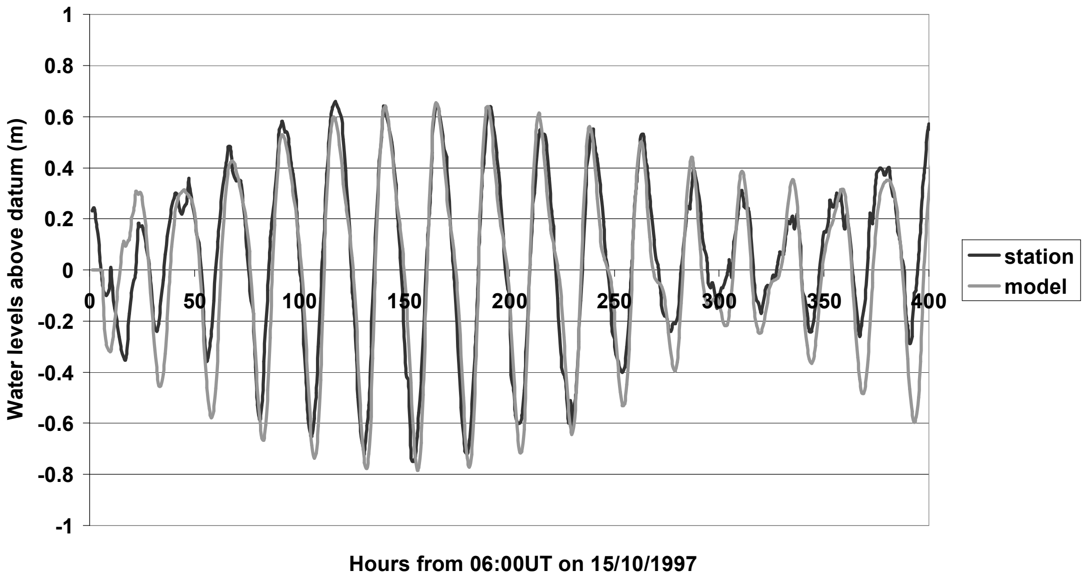

Figure 4.4 The simulated tides using a minimum depth= 20m compared with the station data from Kolak

So from this result, when modelling the storm surge, the tides, modelled with the minimum water depth of 20 m, were added to the surge modelled without tides and water depths less than this, to force the modelled levels to better reproduce the sea water elevation at Kolak.

Computing limitations.

Most of the analysis of model performance in this updated thesis has been performed in Thailand, where we had access to limited computing facilities compared to when we started at Flinders University. Because of that, we ran into problems with computer memory and speed.

When we ran the model using the original meteorological time interval of 6 hours, the storm surge showed multiple peaks, as in Figure 4.5. It was realized that the time interval between meteorological inputs was probably the cause. We found that when we ran the model with a time interval of 1 hour for meteorological input, the model showed the expected smooth result, without multiple peaks at all –Figure 4.5 again. However, we could not run that 1 hour meteorological interval for many days because we quickly ran out of memory to hold all the required input files. We could run the model for about 3 days only. That meant that there was extremely limited time to spin up the model –the wind had to be applied effectively at the start of a model run, and to accommodate the surge, the start had to be close to when the typhoon was approaching the coast. So that will cause an error in the surge height.

We solved this problem by using two different time steps in the model, the 6 hours time interval when the model was started and then 1 hour time interval when Linda was close to the Gulf of Thailand (as discussed in chapter 3).

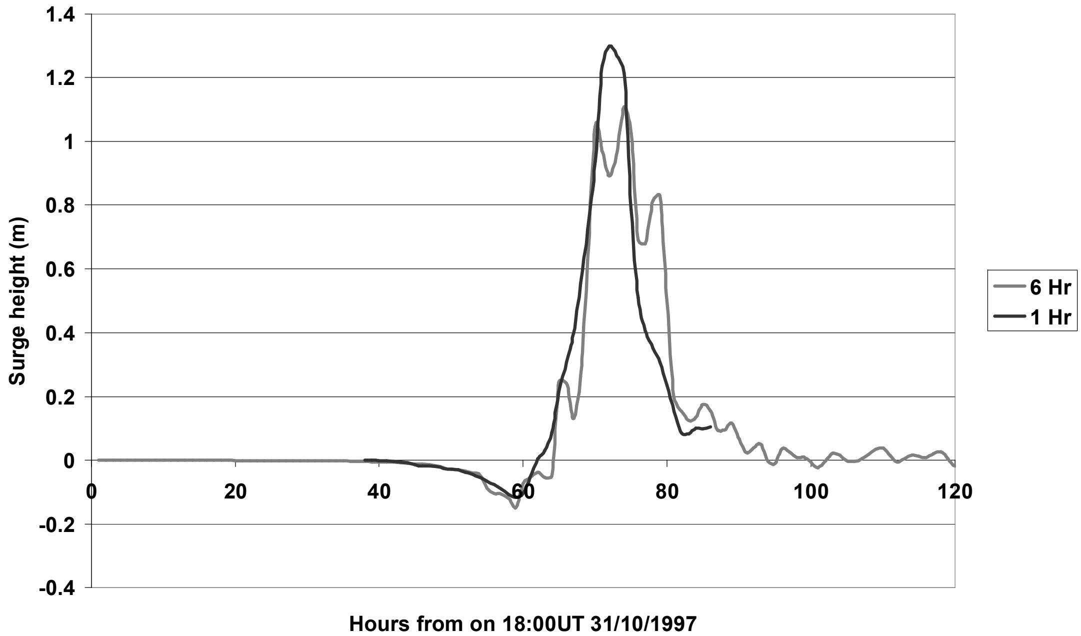

Figure 4.5 Comparing the surge results from the model with 6 hours time interval and 1 hour time interval for meteorological data input. (The 1-hour time interval model started at 38th hour in this figure)

The effect of minimum depth on the modelled storm surge

For the storm surge, the bathymetry affects the sea water elevation near shore. As in equation 2.4 in chapter 2, a smaller water depth increases the influence of wind stress on surge height. In this thesis, when we run the model we had to set the minimum bathymetry to overcome instability in the model numerics, since it cannot accommodate drying/flooding of shorelines. So if the modelled depth of sea water was less than a minimum value, it was set to the minimum value. All of the storm surge model runs in this thesis were set to a minimum depth of 5 meters except in this section. We ran the tests to check the sensitivity of the storm surge height to the minimum model water depth. In this section, we used the wind radial profiles with Rmax=40 km, B-parameter=1.53 to create the wind fields from the JTWC data, other parameters as set in chapter 3. The minimum depth was varied from 5 m to 20 m. The results are shown in the picture below.

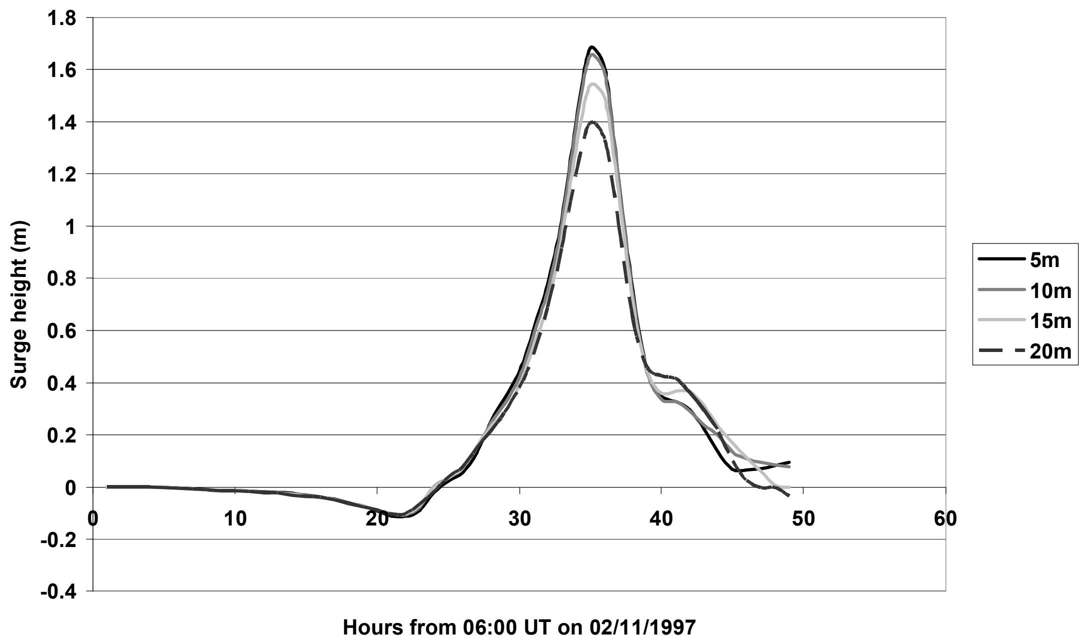

Figure 4.6 The results from the model with various minimum depths (5m, 10m, 15, 20m).

The peak heights were then extracted, and plotted against the minimum model water depth.

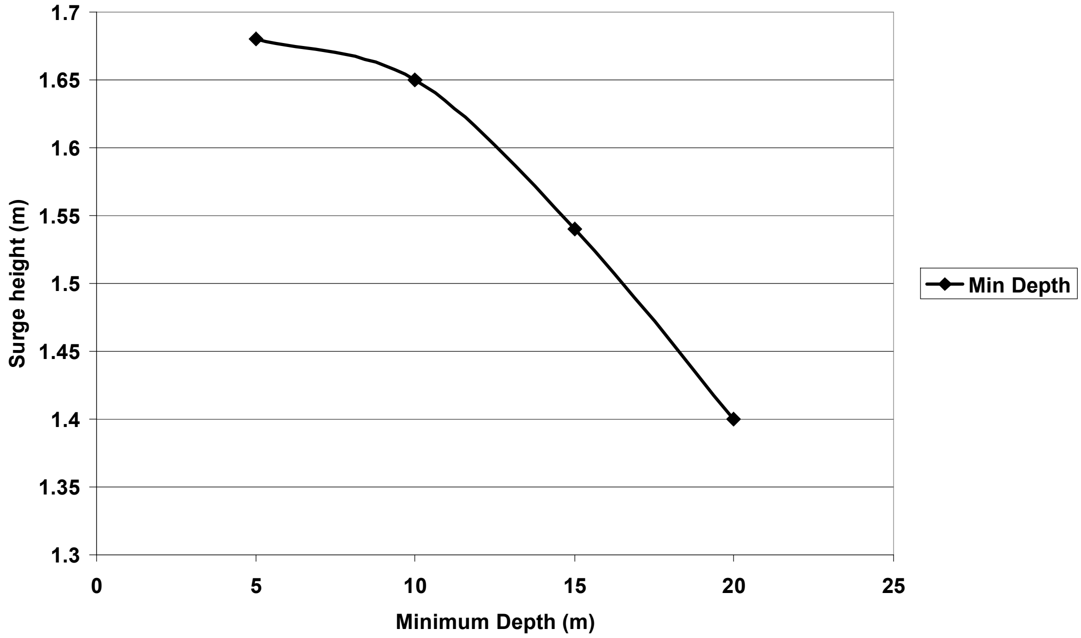

Figure 4.7 The effect of different values of the minimum depth on surge height.

The results show that the surge height decreases when the minimum depth increases. Increasing the minimum depth from 5 m to 10 m decreases the surge height about 3 cm. From 10 to 15 m and 15 to 20 m, it decreases about 11 cm and 14 cm. The evident non-linearity for model minimum depths means that the model surge height is least sensitive to water depths between about 5 and 10 m, so errors in specifying the depth are not critical for the surge height.

The above behaviour arises from the changed bathymetry in the model that generates changes in the areas of shallow water. The effect of changes to the bathymetry of the nearshore region is shown in Figures 4.8. For 5m and 10m minimum depths, the coastal area covered to the minimum depth differs only slightly, and corresponds closely with that around the Kolak station. But when the minimum depth is changed to 15m and 20m, the area of the nearshore region is expanded into the Gulf. This reduces the effect of wind stress on the storm surge nearshore, and gives the above modelled more rapid decrease in surge height for these minimum depths.

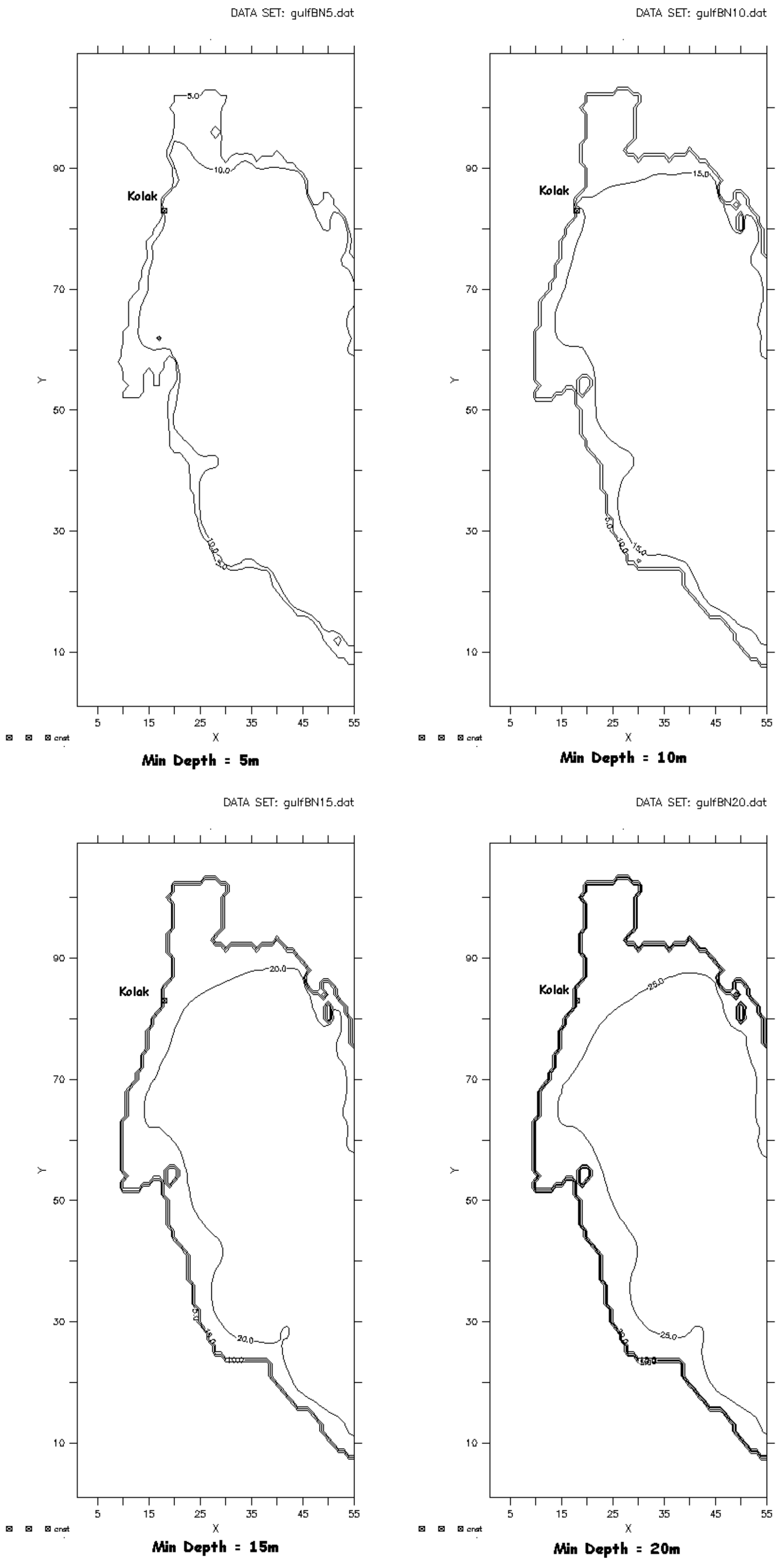

Figure 4.8 The minimum depth setting for the storm surge modeling in Gulf of Thailand

The effect of different radii of maximum wind of the tropical cyclone on the modelled storm surge

Here, we ran the model with various radii of maximum wind and compared the results to station data. A larger radius of maximum wind means that the maximum wind speed which circulates around the eye blows over a greater ocean distance. This longer fetch allows the wind to work over a greater area to enhance deep water surface convergence, and shallow water Ekman enhancement, as outlined in Chapter 2. This should affect the height of any storm surge as well.

We used the sequence of radii of maximum wind as follows: R_{max} = 20, 30, 40, 50 kms. The model was also run with 3 different Holland's B-parameters: B=0.9, 1.2, 1.5. The minimum water depth was set to 5 m. A quadratic bottom friction function was chosen, but we assumed a reasonable value for it: 0.0035 is in the range that is mostly found in other ocean models for bays and gulfs. The results of this experiment are presented as Figure 4.9-4.12.

The minimum depth that we selected for running the storm surge model here is 5 m, even though the minimum depth that gave the best result for the tidal model was 20 m (p45). The reason is that the 5 m minimum depth gave the bathymetry closest to reality and the experiments on minimum depth showed the validity of 5 m for the surge height. (We used the 20 m minimum depth for the tidal model just to compensate for the error in amplitude and the lack of modelled tidal constituents to get the tide result close to the station data, for use in predicting the sea water elevation in the period of the storm surge).

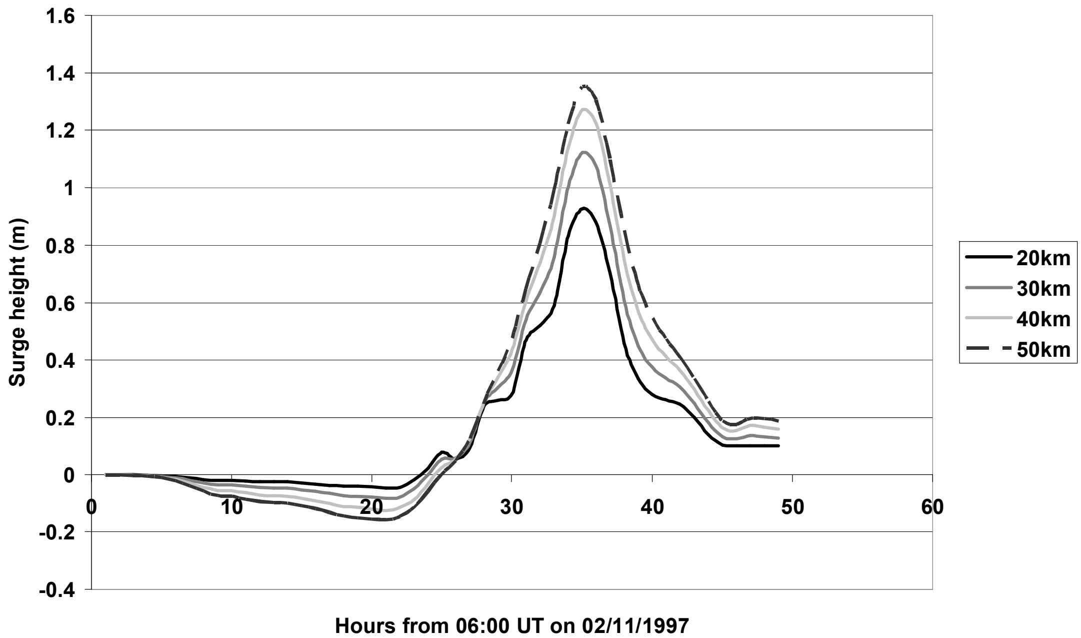

Figure 4.9 Modelled Kolak surge heights for various radii of maximum wind when B=0.9.

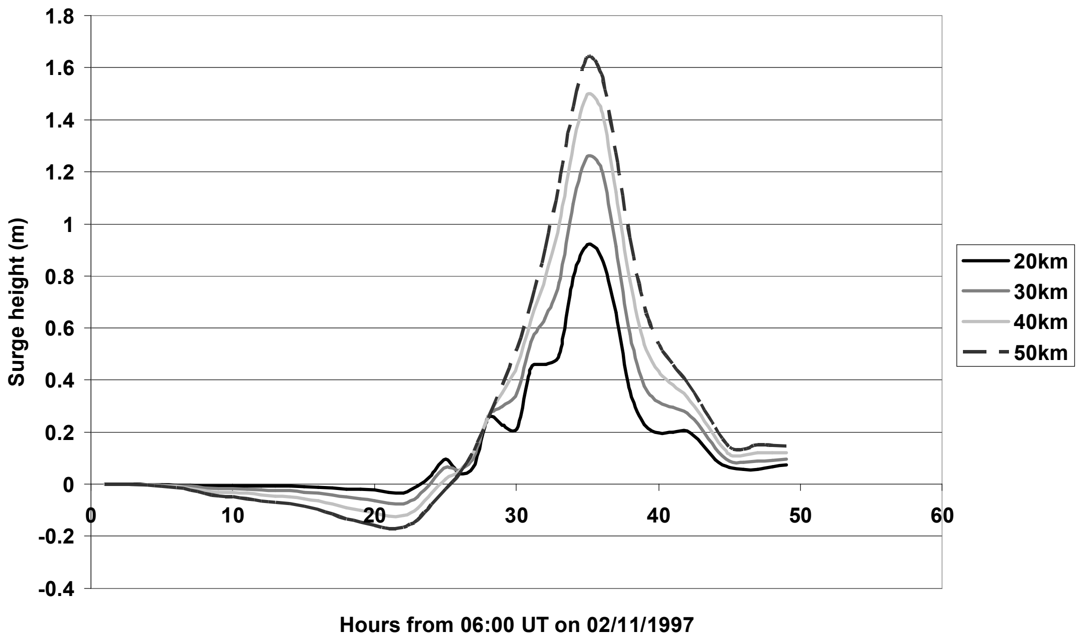

Figure 4.10 Modelled Kolak surge heights for various radii of maximum wind when B=1.2.

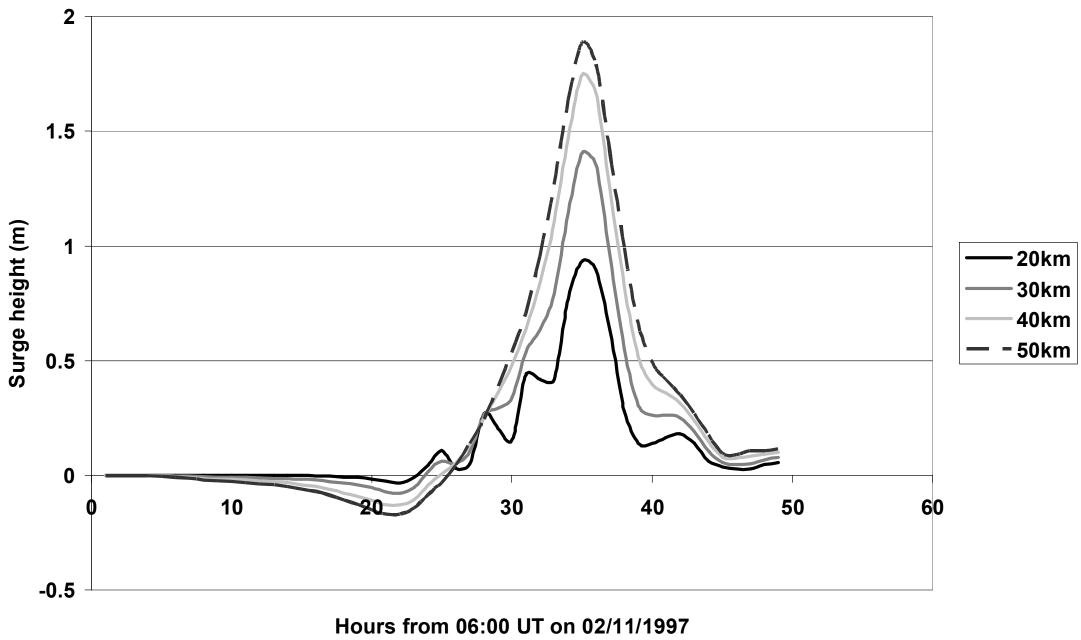

Figure 4.11 The results from the model with various radii of maximum wind when B=1.5.

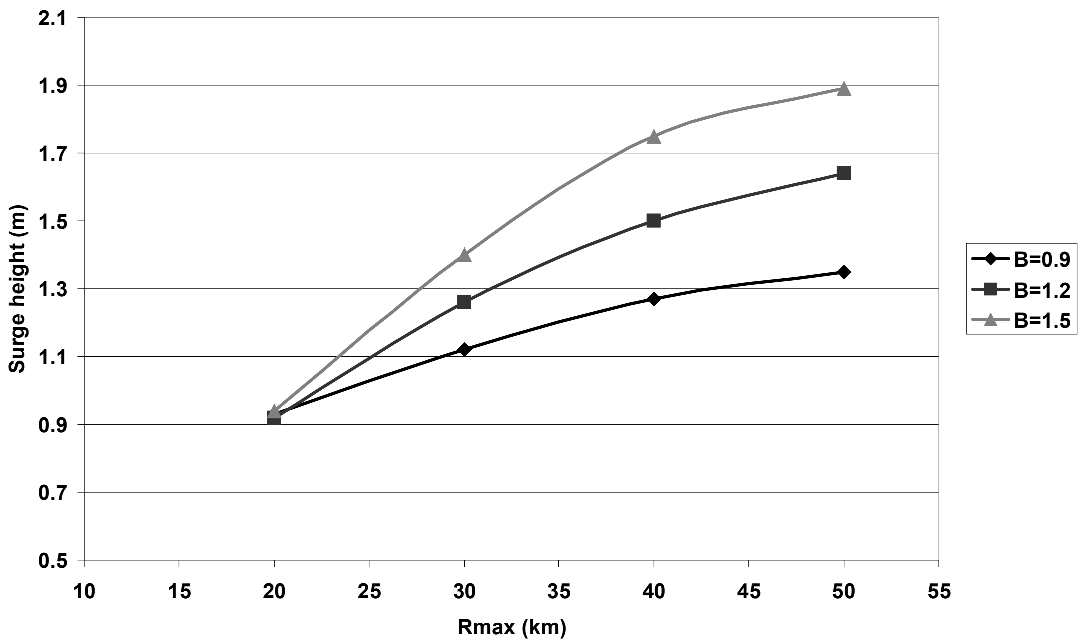

Figure 4.12 The effect of various radii of maximum wind on the height of the positive surge with various Holland's B-parameters (0.9, 1.2, 1.5)

Positive surge

Referring to Figure 4.12, it is obvious that larger Rmax give larger surge heights. But for larger B-parameters, the rate of change of surge height with Rmax is larger. As we know, the different B-parameters affect the maximum wind speed and the wind distribution in a tropical cyclone, especially at radii larger than Rmax. The quantitative effect of the B-parameter on the maximum gradient wind comes through Holland's equation (Chapter 2, equation 2.3, or more clearly in eq. 2.5 for the cyclostrophic wind). Its effect on the radial distribution of winds comes mostly through the exponentials in equation 2.3. The results here show that the higher B gives a more rapid increase in surge height with Rmax. For the approximately linear range of variation of surge height with Rmax (between 20 to 40 km), the slope equals $1.7x10^{-2}$, $2.9x10^{-2}$and $4.0x10^{-2}$ m/km for B=0.9, 1.2 and 1.5 respectively. Moreover, when the radius of maximum wind is equal to 20 km, all these B-values create the same surge height.

This result shows that, if the radius of maximum wind is approximately 20 km, any change in the B-parameter does not appreciably affect the surge height at all. That result is unexpected, since the B parameter alters the radial wind profile. This is presumably arising from the different wind radial profiles. To see the changes in profiles, the corresponding wind profiles with radius of maximum wind = 20 km and the above B parameters are presented below.

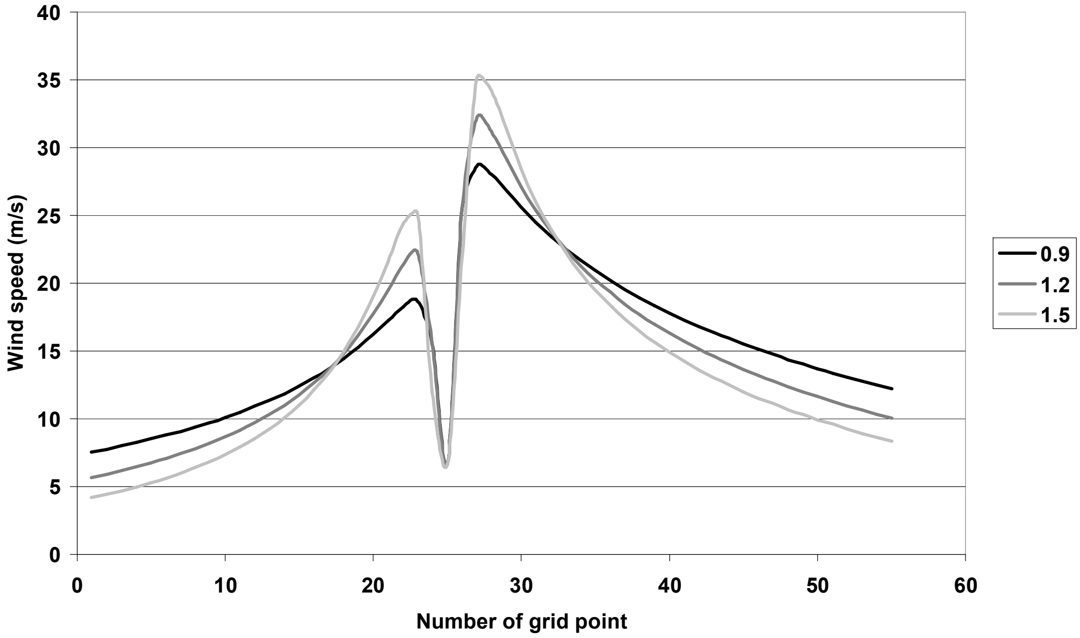

Figure 4.13 The longitudinal section of the wind profiles generated by Holland's equation including cyclone track motion, with radius of maximum wind = 20km, different B-parameters.

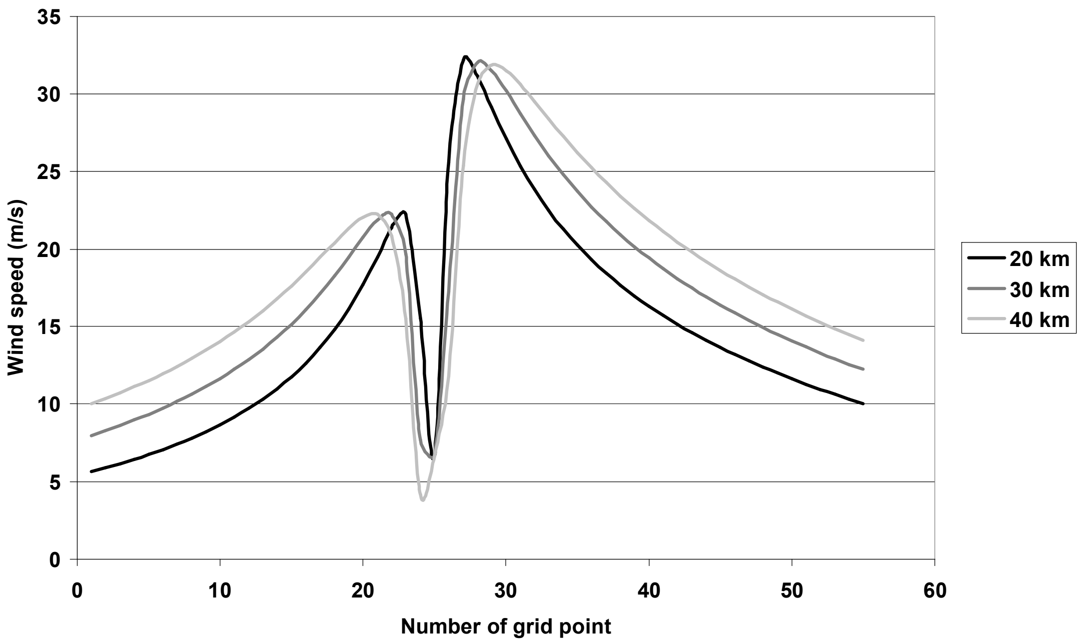

Figure 4.14 The longitudinal section of the wind profiles generated by Holland's equation including cyclone track motion, with B-parameter = 1.2, different radius of maximum wind.

From the pictures above, we can see that larger B-parameters increase the maximum speed and narrow the radial distribution in wind profiles. It appears that the influence on the surge height by higher maximum speeds is compensated by the smaller area of high winds at radii larger than the radius of maximum wind. The fetch of a tropical cyclone with Rmax = 20 km seems too short for full development of the sea water elevation, so the higher maximum wind speed does not dominate in its effect on the wind radial distribution. We can also see the more irregular curve for the surge of Rmax = 20 km in Figure 4.9-4.12. This is because the wind speed of the tropical cyclone changes more rapidly for a smaller radius of maximum wind (as in Figure 4.14). So, when the tropical cyclone moves, the 1 hour time interval is still possibly too large to produce a smooth curve, and resulted in the oscillation in surge height.

This experiment shows that, if the Rmax is more than about 20 km, the maximum wind speed dominates over the width of the radial distribution in changing the surge height.

Negative surge

The negative surge becomes more negative when the radius of maximum wind increases like the positive peak becoming larger. Straight lines fitted to these results of surge height vs Rmax have the slope -4.6×10^{-3} m/km for B=1.2 and B=1.5, and for of B = 0.9, -3.7×10^{-3} m/km.

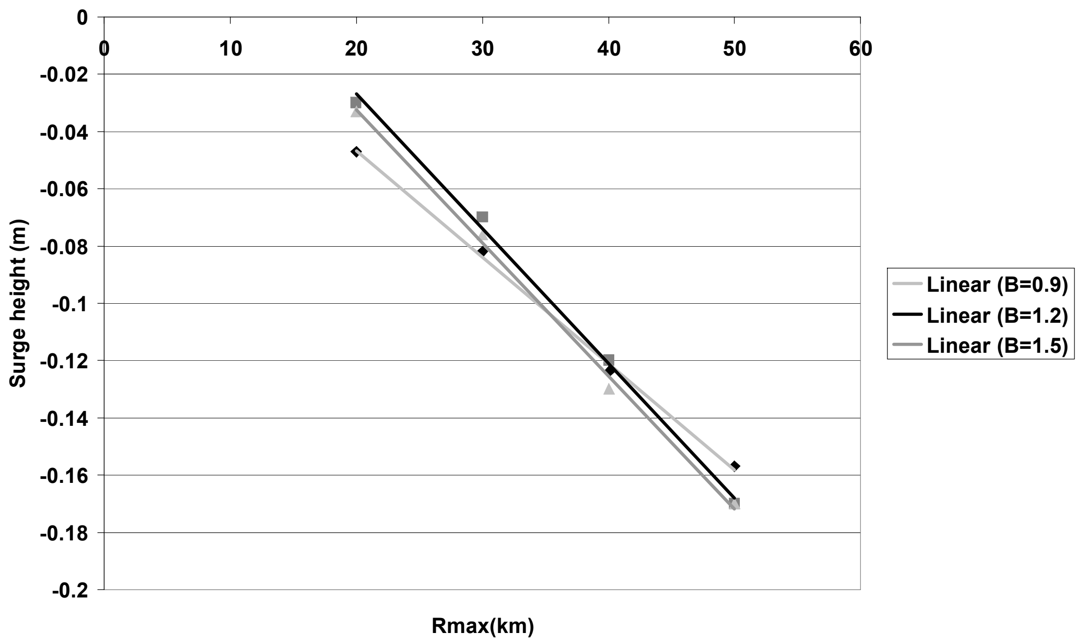

Figure 4.15 The dependence of the depth of the negative surge on the radius of maximum wind, for various Holland B-parameters (B=0.9, 1.2, 1.5)

The effect of Holland's B-parameter on the modelled storm surge

For creating wind fields by Holland's equation, the B-parameter is the critical parameter that affects the maximum wind and the radial distribution of wind profile as discussed in chapter 2. There are different formulae to calculate a B-value. Moreover, the B-parameter is always calculated from or using the central pressure but different sources of data (such as JTWC and JMA) gives a different central pressure for Linda. This fact thus produces different B-values when those data are used to calculate B. We take the results from the previous part and re-arrange them to study the sensitivity of the storm surge height to the B-value, varying B-parameter (0.9, 1.2 and 1.5) while fixing the radius of maximum wind at 20 km, 30 km and 40 km.

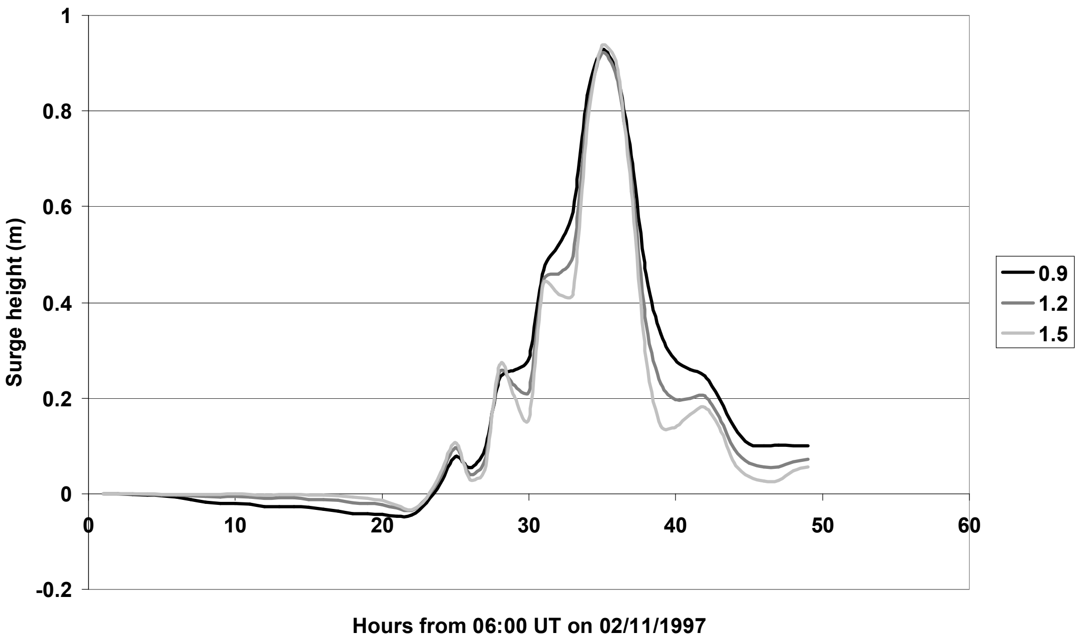

Figure 4.16 The results from the model with various B-parameters when radius of maximum wind = 20 km (B=0.9, 1.2, 1.5)

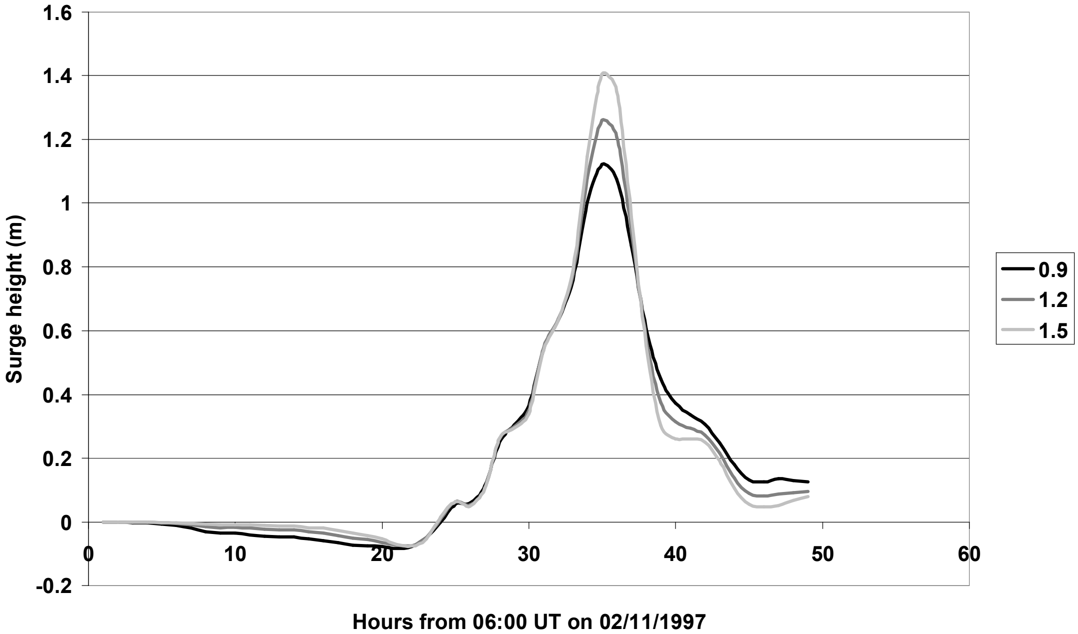

Figure 4.17 The results from the model with various B-parameters when radius of maximum wind = 30 km (B=0.9, 1.2, 1.5)

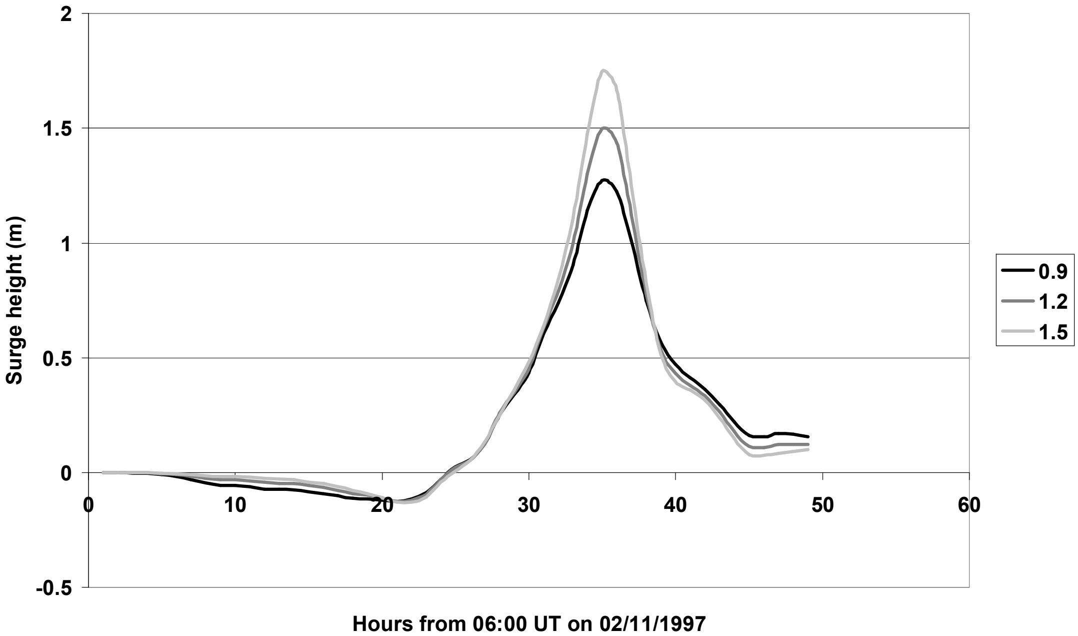

Figure 4.18 The results from the model with various B-parameters when radius of maximum wind = 40 km (B=0.9, 1.2, 1.5)

Again examining the peak surge heights but now varying with B, we get the results shown in Figure 4.19 below. As we have seen before in the previous section about the sensitivity of the surge to the radius of maximum wind, with the 20 km radius of maximum wind, a change in B-value does not effect the surge height, but for Rmax= 30 km and 40 km, larger B-values leads to the higher surge. When the radius of maximum wind equals 30 km, the slope of surge height response to the B-parameter is 0.5. But the slope is equal to 0.8 when the radius of maximum wind is 40 km. This evidence shows that the surge from a tropical cyclone with a larger radius of maximum wind is more sensitive to larger B-values.

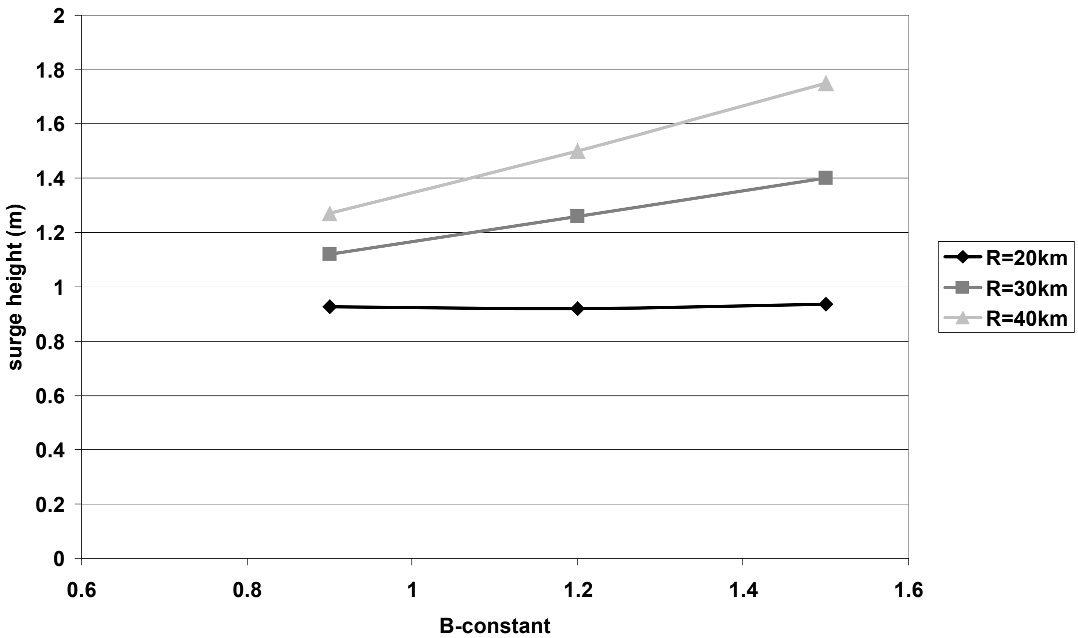

Figure 4.19 Comparing the effect of different B-parameters on surge height for different radii of maximum wind.

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For the negative surge visible in Figures 4.16 to 4.18, no clear response on the amplitude of surge was found (results not presented here).

The effect of cyclone track position on the modelled storm surge

The tropical cyclone track position has an influence on the height of surge at a fixed station because that changes the direction and intensity of the wind field relative to the shore there. The surge height of course everywhere also depends on the shape of shore and the bathymetry too. This section tested the sensitivity of surge height to the tropical cyclone track position in the Gulf of Thailand. Here, we used the wind and pressure field created by Holland's equation with the radius of maximum wind 40 km and B-parameter=1.53 as meteorological input to the storm surge model. The minimum depth here is set to 5 m. We run 6 scenarios, 3 by moving the track of tropical cyclone Linda to the North of the original track (by 40 km, 80 km and 120 km) and another 3 by moving it to the South of the original track (also by 40 km, 80 km and 120 km). A representation of this is shown below.

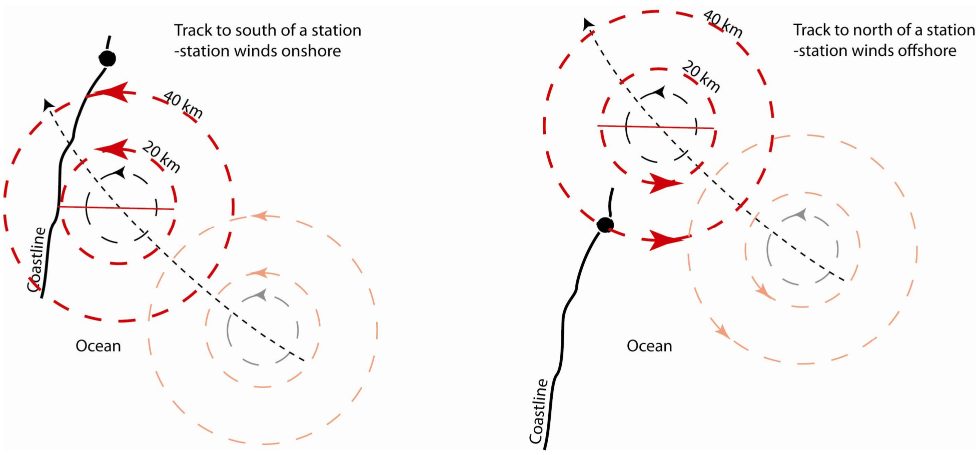


Figure 4.20 The direction of station wind when the track of tropical cyclone pass south and north of a station

For Linda on its actual track at one modelled time, see the figure shown below, along with the surface wind patterns and contours that follow.

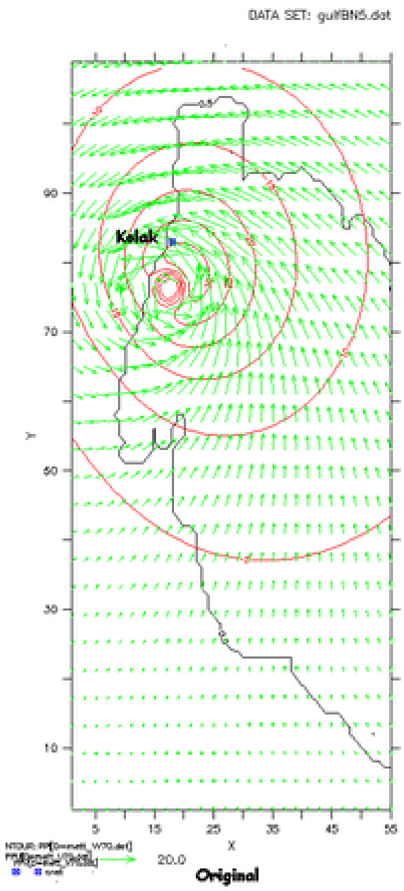


Figure 4.21 The calculated wind patterns and speed contours of tropical cyclone Linda at 17:00UT 03 Nov 1997, interpolated from the JTWC track position near that time.

Following are the modelled wind patterns for different displacements of the tropical cyclone southwards and northwards, and an examination of the surges that result from these displacements.

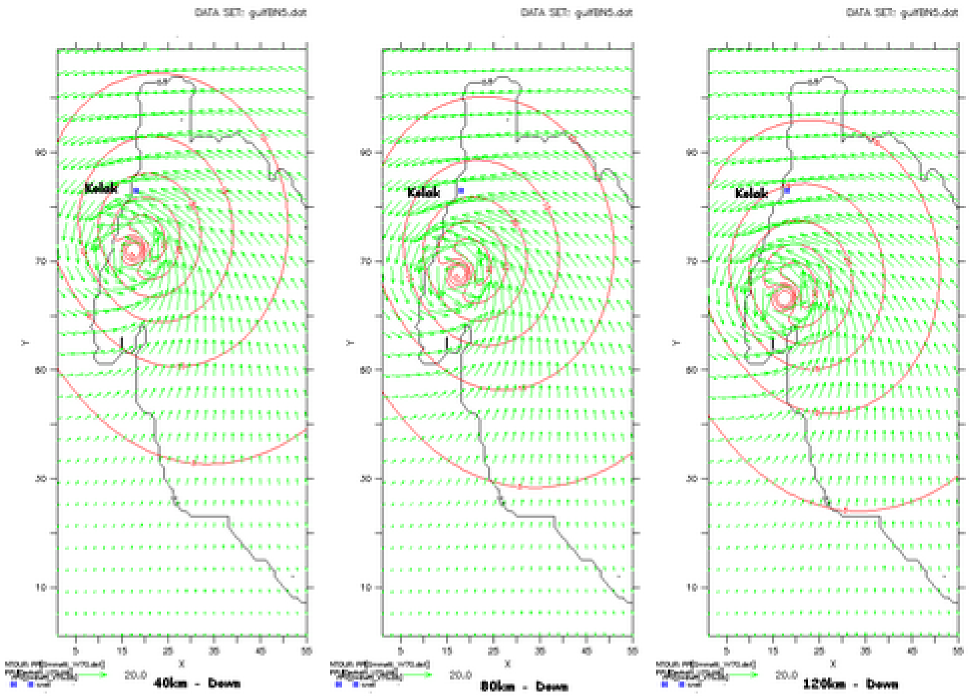


Figure 4.22 The wind patterns of Linda at the same time as in the previous figure, but with the track moved southwards of the original track by 40 km, 80m, and 120m

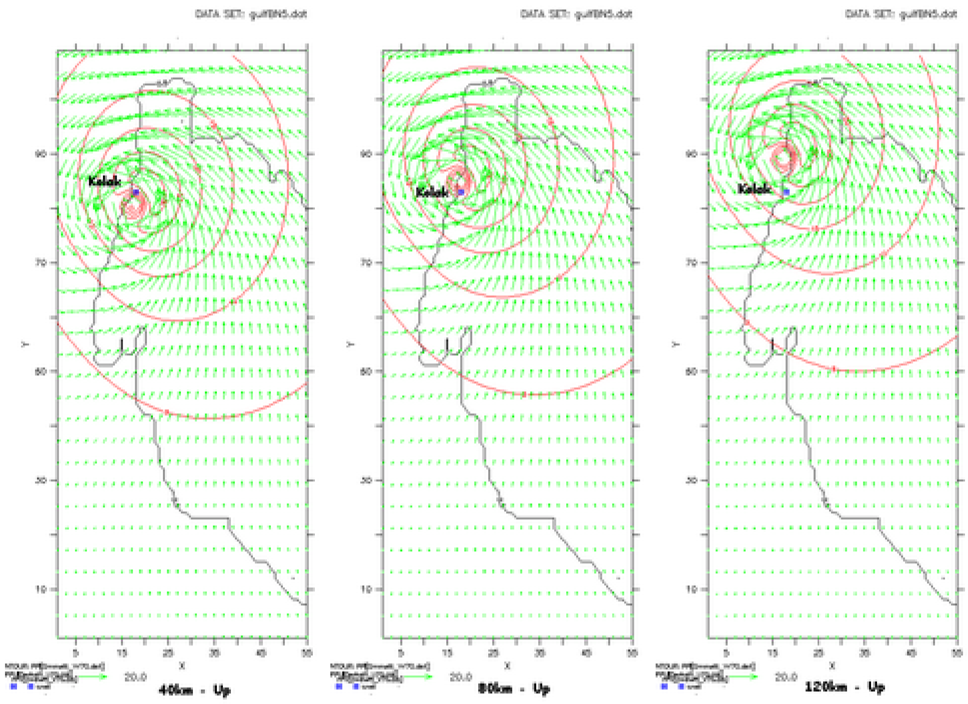


Figure 4.23 As for the previous figure, but Linda's track moved to the North of the original one by 40 km, 80 km and 120 km.

The modelled surge results are presented in Figure 4.24-4.25

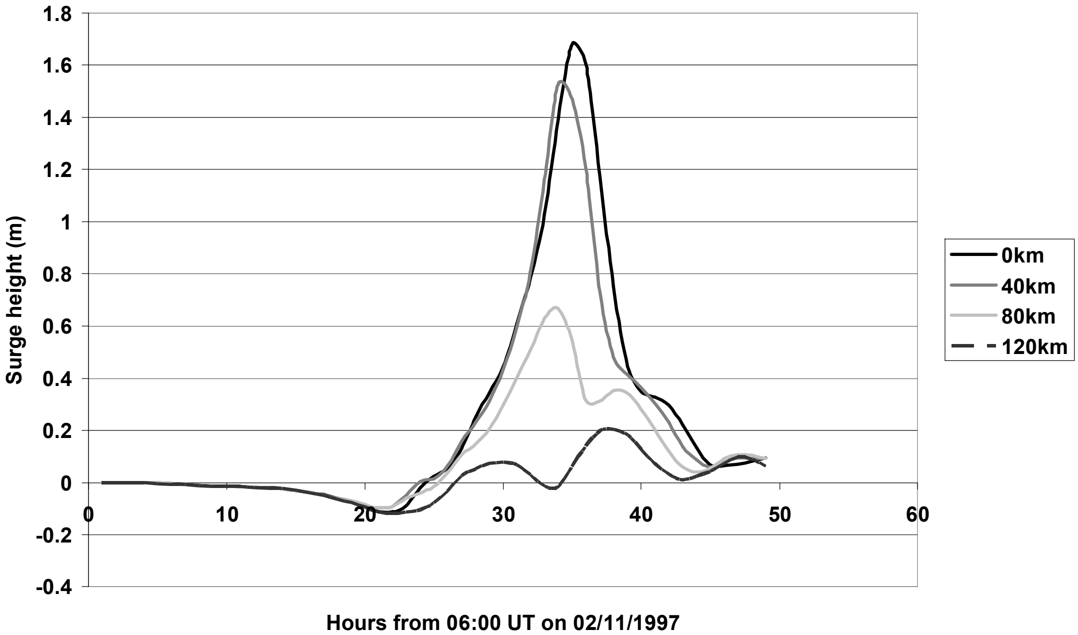


Figure 4.24 Model results for the storm surge with the original track, and when it is moved northwards by 40 km, 80 km and, 150 km. (radius of maximum wind = 40 km)

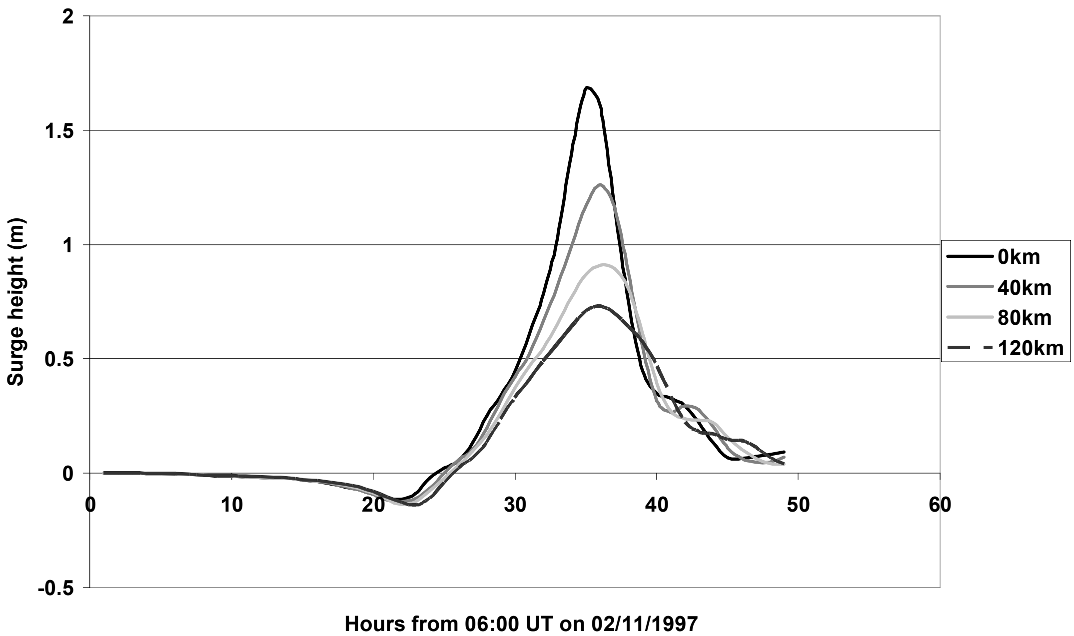


Figure 4.25 Model surge results for southwards displacement of the track position (radius of maximum wind = 40 km)

The original JTWC track of Linda crossed the coast about 34 km south of Kolak, on 3/11/1997, around 16:30 UT. For a wind field with a radius of maximum wind equal to 40 km, the maximum wind should thus be close to Kolak station and directed toward the coastline. That should create the highest surge.

The results are not quite as expected for this experiment. When we used the wind radial profiles with Rmax=40 km, on the original track, the maximum surge is presented. When we move the track 40 km northward, the centre of Linda is very close to Kolak when it came onshore. The maximum wind at the right front is moved higher than Kolak so the peak surge decreased as in Figure 4.24. But when we move the track to 80 km north from original track, we expect a significant negative surge, because the strong off-shore wind should pass Kolak when Linda was onshore. But the negative surge does not become more negative, rather there is only a decrease of the positive surge. For a track that is 120 km north of the original track, there is a negative surge but it is not a strong one. Rather, it just shows a much smaller positive surge down to 0.2 m above mean sea level. The wind fields are then too far north to have any strong effect at Kolak.

We ran the model to check the effect of the storm translation speed (that was added to the circulating speed as in chapter 2), on the negative surge. The result is shown in figure 4.26.

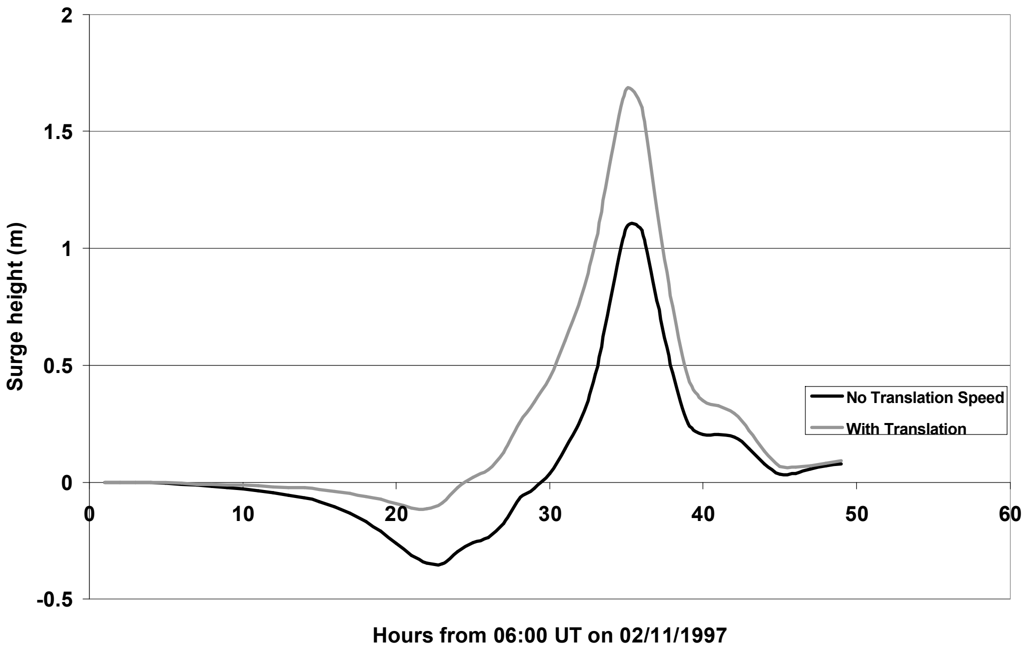


Figure 4.26 Model surge results with the original track of Linda with and without the storm translation speed, B=1.53 and Rmax = 40 km.

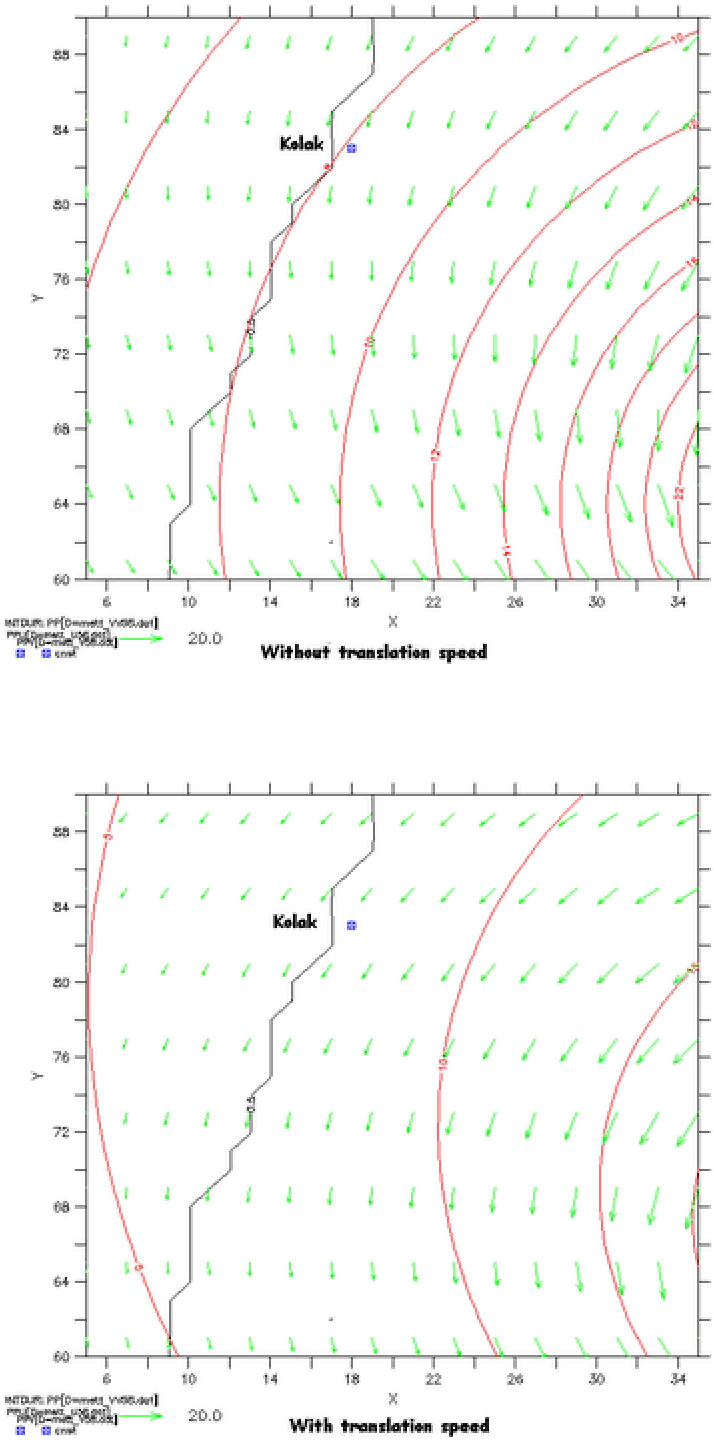


Figure 4.27 Comparing the wind profile created with and without the storm translation speed on 03:00 UT 03/11/1997 when the negative surge was created in Figure 4.26

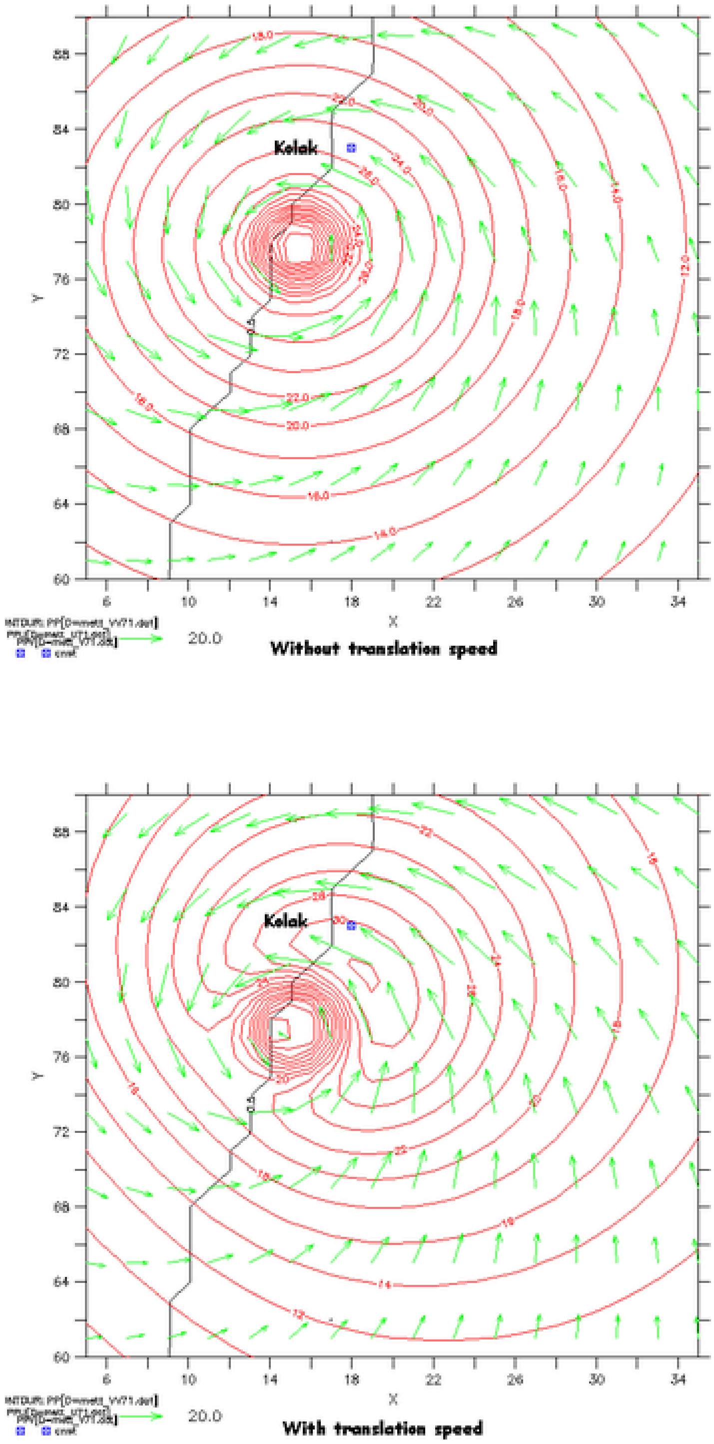


Figure 4.28 Comparing the wind profile created with and without translation speed on 16:00 UT 03/11/1997 when the positive surge was created in Figure 4.26

The Figure 4.26 shows that the translation speed we added to the wind model significantly affects both negative and positive surges. The amplitude of the negative surge is decreased from 0.43 to 0.11 m and the positive surge is increased from 1.01 to 1.68 m when we add the translation speed to the model. The decreased negative surge can be explained with Figure 4.27, that shows the modelled wind fields that acted on Kolak at the time of 1 hour before the negative surge had happened in the model. Without the translation speed, the wind blows nearly parallel to the coastline at Kolak and then slightly off-shore, and that created the obvious negative surge in Figure 4.26. But after we added the translation speed to the wind model, the direction of the wind bends slightly onshore by the affect of the translation speed. So, this resulted in the smaller amplitude of negative surge.

Figure 4.28 presents the wind fields over Kolak at the time of 1 hour before the positive surge had happened in the model. It is obvious that the wind is stronger when the translation speed has been added. The right-front quadrant of the wind fields hit Kolak with a velocity of 30 m/s for the asymmetric case, compared with about 24 m/s wind speed for Holland's wind without the translation speed. This made the difference in the positive surge heights.

In these wind fields, the distortion to the shape of radius of maximum wind was such that no strong off-shore wind was present at Kolak when we moved the track 80 km north of the original, or even 120 km. After the translation speed is added to Holland's symmetric wind profile, the wind fields change to be more realistically asymmetric, with the highest wind at the right-front of the tropical cyclone. But because an understanding of the way that tropical cyclone flow is distorted by its translation speed is still not fully understood, adding it to the wind fields also causes errors in the surge result here.

The results of moving the track southwards are presented on Figure 4.25. Nothing is unexpected in this case, the highest peak decreases as the distance between the centre of tropical cyclone Linda and Kolak increases. The peak surge occurs a bit earlier than it does for the original track.

In addition, we did one more experiment to study the effect of the translation speed by reducing the factor R_G, the length scale of the environmental scale processes, in equation 2.7. It has been taken until now as 500 km (the same as Jakobsen and Madsen). In this experiment, we make the decay distance much smaller by setting R_G = 150 km. This means that the track speed is reduced to about 37% by 150 km, which reduces its influence to an area that is only about 1% of the area with the larger R_G. This wind field produces the surge which is not as high as that with the RG=500 km, nor the negative surge as deep. (Figure 4.29). This parameter may need more study in order to improve the wind field model with translation speed. Obviously, surface wind data would help clarify that aspect.

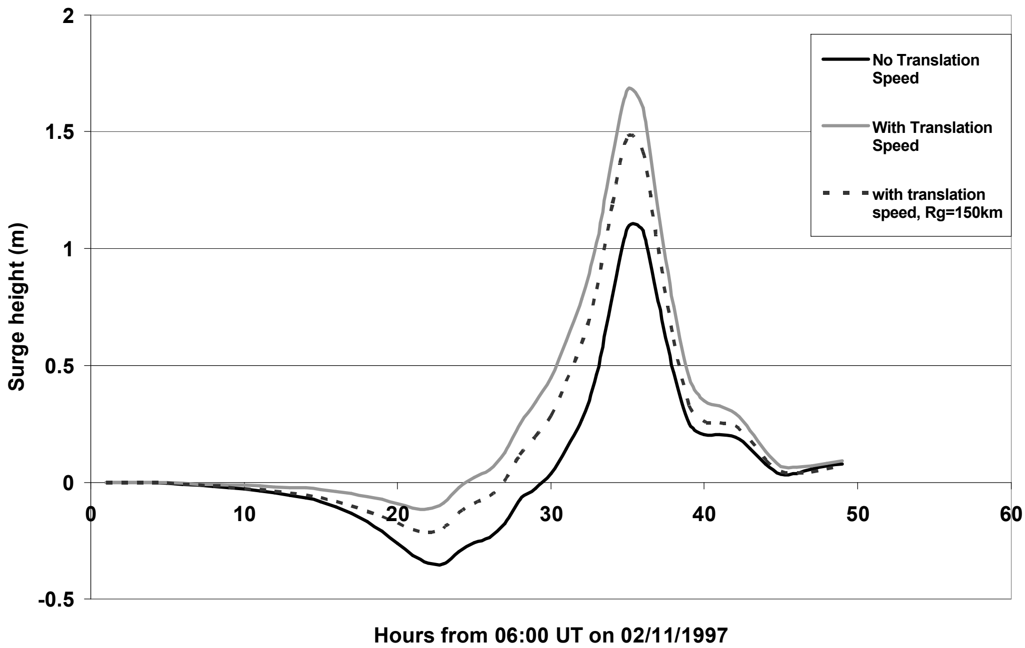


Figure 4.29 Model surge results with the original track of Linda without and with storm translation speed (for Rg = 500 km and 150 km), B=1.53 and Rmax = 40 km.

Comparing the model results with station data from Kolak

Now we use the COHERENS model to hindcast the storm surge caused by tropical cyclone Linda at Kolak station. As before, we created the wind fields and pressure field by Holland's equation, using the data from JTWC, but now with the radius of maximum wind of 40 km. B-parameters of 1.4 and 1.53 are used here. Then, we add the surge from the model on top of the tides from the earlier part of this chapter. The result is shown below.

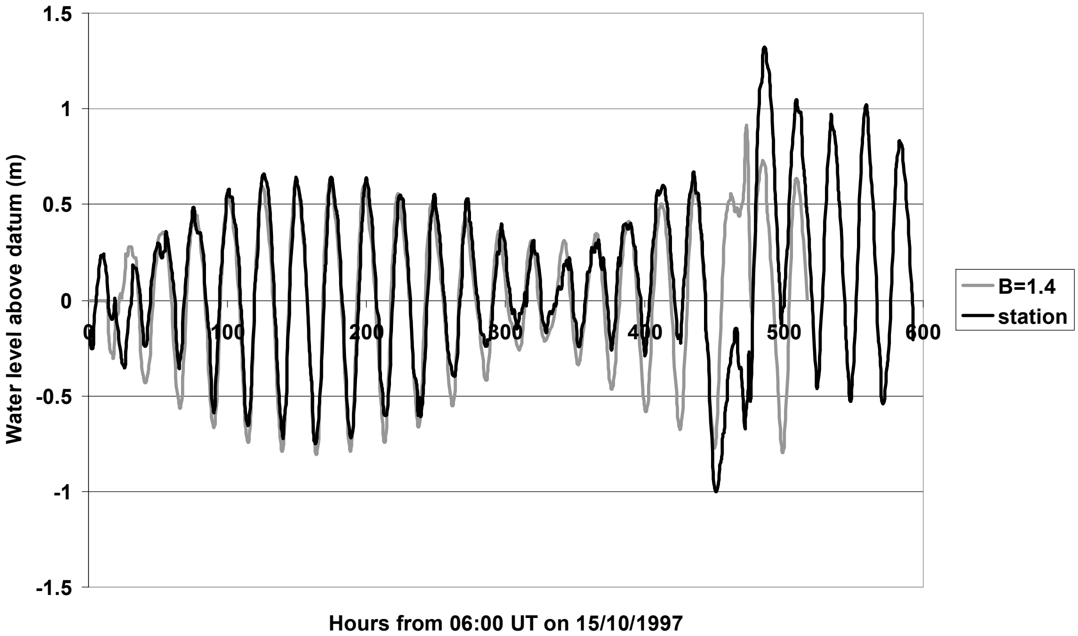


Figure 4.30 The results from the model hindcasting the sea water elevation compared to station data from Kolak, for B=1.4 and Rmax=40 km

In the station record, the highest peak happened at 05.00UT 04/11/1997 and the amplitude was 1.32 m. For the model result, the highest peak occurred at 16.00UT 03/11/1997 with the amplitude equal to 0.91 m. The times of the peak in reality and in the model are different by 13 hours, with the peak surge in the model happening before the station data. The fractional difference in amplitude is 31.1%. No negative surge is present in the model result.

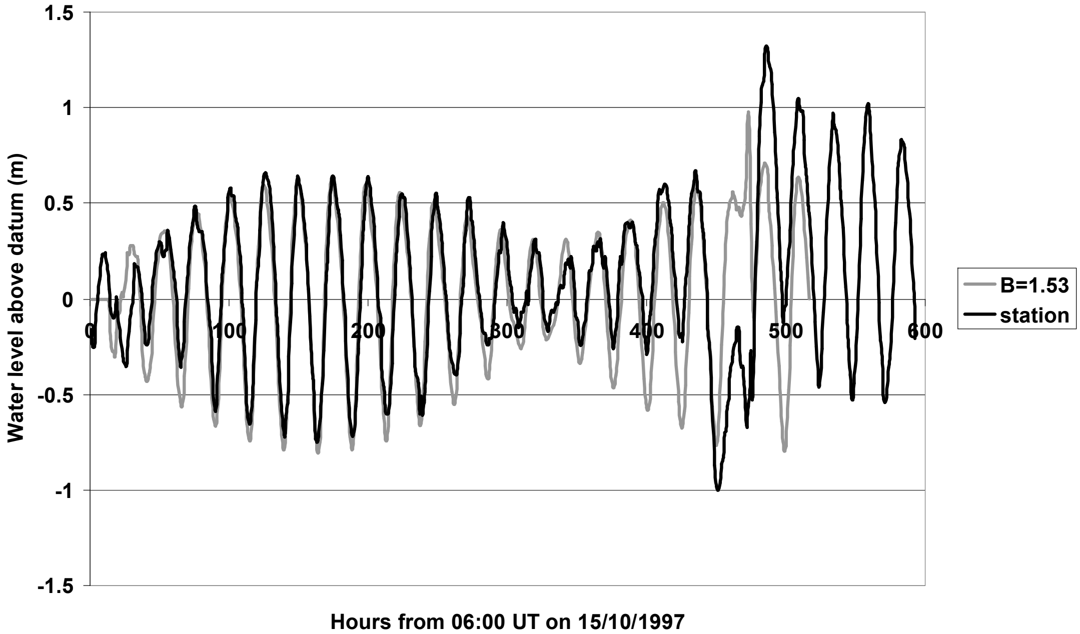


Figure 4.31 The results from the model hindcasting the sea water elevation compared to station data from Kolak when B=1.53.

Using a B-parameter equal to 1.53 (from eq. 2.4), the model result gave the highest peak at 16.00UT 03/11/1997 with the amplitude equal to 0.98 m. The fractional difference in amplitude is 26%. The time difference between the station data and the model is still 13 hours, with the peak surge in the model happening before the station data.

Both of them do not give good agreement with the station data for the amplitude of positive surge. Moreover, the time difference in the peak surge is large. We need to take a look closely to find out the cause of this time difference. The table below shows part of the JTWC best track data for Linda.

Time/Date (UTC)	Latitude (deg N)	Longitude (deg E)	wind speed (knot)	Distance from Kolak (km)
0600 03/11/1997	10.5	101.6	65	246.7
1200 03/11/1997	11	100.5	65	118.1
1800 03/11/1997	11.6	99.3	50	59.8
0000 04/11/1997	12.1	98	45	202.8

Table 4.1 Best track data of tropical cyclone Linda from JTWC in the period 06:00UT 03/11/1997 to 00:00UT 04/11/1997

The location of Kolak station is 11.8N 99.8E referred to Thai Navy data. From table 4.1, we can estimate from the latitude and longitude that tropical cyclone Linda was onshore in the period between 12:00UT and 18:00UT 03/11/1997, based on the 6 hours time interval of the JTWC data. The distance from the TC's centre to Kolak was only 59.8 km at 18:00UT 03/11/1997. Interpolating from the 6 hours time interval data from JTWC in the period 12:00UT-18:00UT 03/11/1997 to 1 hour time interval gives the detail as presented in table 4.2

Time/Date (UTC)	Latitude (deg N)	Longitude (deg E)	wind speed (knot)	Distance from Kolak (km)
1200 03/11/1997	11	100.5	65	118.1
1300 03/11/1997	11.1	100.3	62.5	95.6
1400 03/11/1997	11.2	100.1	60	74.5
1500 03/11/1997	11.3	99.9	57.5	56.7
1600 03/11/1997	11.4	99.7	55	45.8
1700 03/11/1997	11.5	99.5	52.5	47.1
1800 03/11/1997	11.6	99.3	50	59.8

Table 4.2 The positions and distances interpolated to 1 hour time interval of Linda in the period 12:00UT 03/11/1997 to 18:00UT 03/11/1997, from the JTWC's best track

By comparing latitude and longitude of the interpolated data from table 4.2 with the coastline of the gulf of Thailand, Linda came onshore between 15:00UT and 16:00UT 03/11/1997 while the closest distance from Kolak in this data set is at 16:00UT 03/11/1997, 45.8 km. At this time, Linda was apparently onshore with the maximum wind speed at the right-front quadrant over Kolak (Figure 4.28). So, with this set of data that was interpolated from the JTWC set and used to run the storm surge model, it is obvious that the highest peak should present around 16:00UT 03/11/1997. Compared with the surge results from the model, the peak surge happened at the right time expected from the data set.

This means the timing error may came from the data sets we used, the sea level data from Kolak or the best-track data from JTWC. The Kolak station data seems more reliable since it was measured directly from the tide gauge. The time basis for the tidal record has been properly checked, and is in UTC. But, for the case of the JTWC data, Chu et al (2002) report that the maximum wind and position of the tropical cyclone from that data set are estimates and JTWC accepts that the confidence in the quality of estimates is low. They also stated that the error in position and intensity of a tropical cyclone can cause a significant affect on the height of sea water at any location.

The best track of Linda provided by the Hong Kong Observatory (HKO) and by the Japan Meteorological agency (JMA) give somewhat different tracks and hence times and locations of the coastal crossing point The data from JMA shows that Linda came on shore around 20:00UT 03/11/1997 while the HKO data shows the onshore time is at 00:00UT 4/11/1997. The location where Linda came onshore was north of Kolak in both these data sets, whereas JTWC was south.

The 13 hour lead of the modelled surge cannot be explained by differences in TC position arising from the different sources of track information. But some comparisons can still be made between modelled and actual surge peak height by shifting the surge forward in time by 13 hours relative to the tide –i.e. we assume there is no time lag in the modelled surge and consider only the amplitude forced by meteorological input in the model and the station data at Kolak. The results without any time lag are presented below.

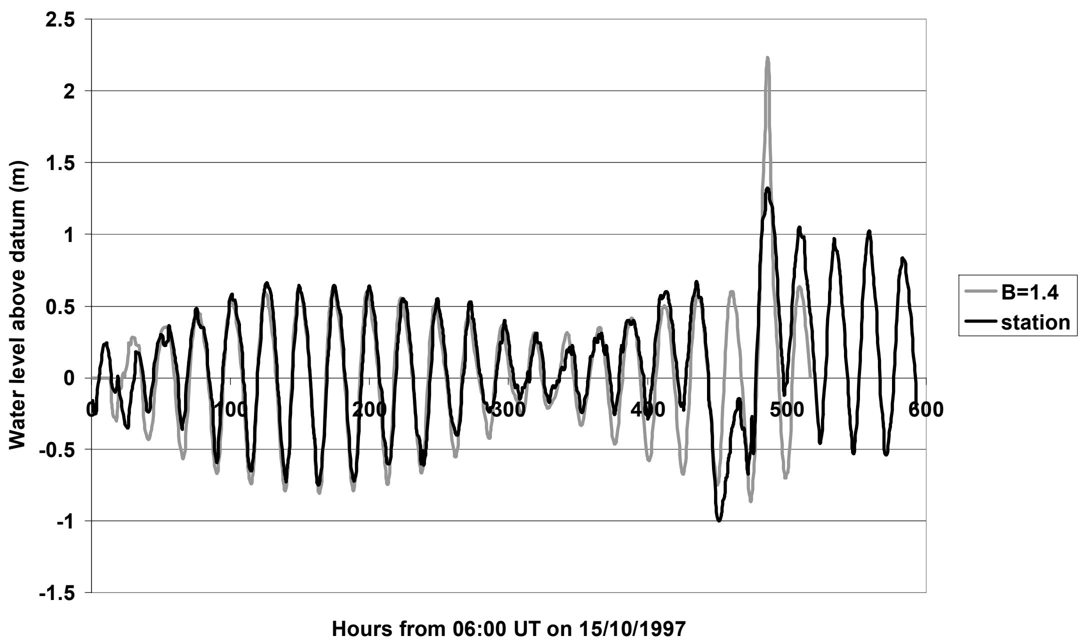


Figure 4.32 The results from the model hindcasting the sea water elevation compared to station data from Kolak, B=1.4, and with no time lag.

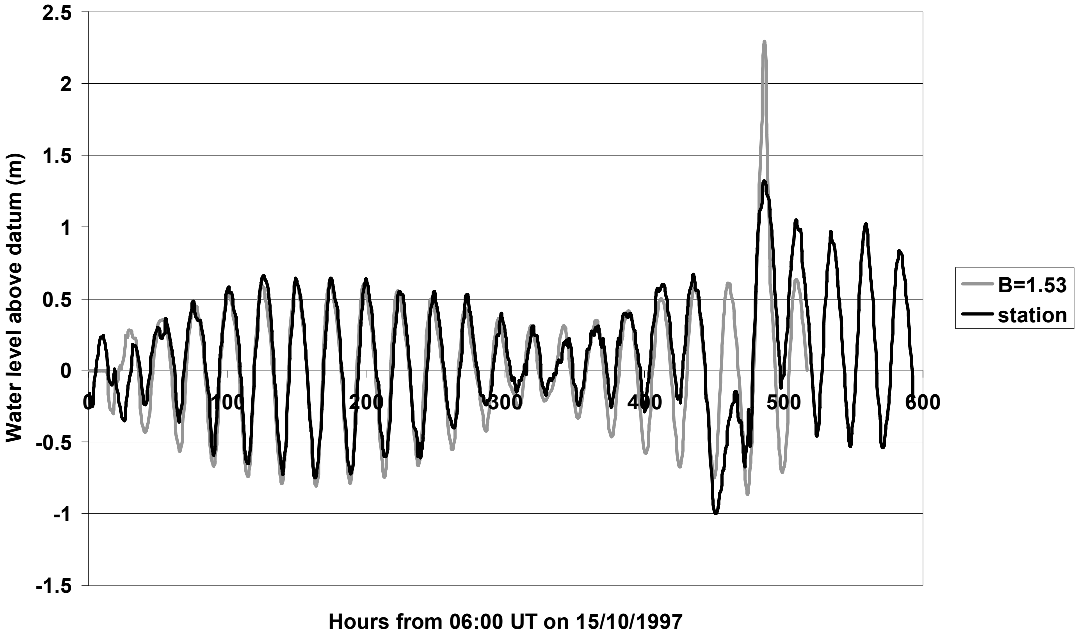
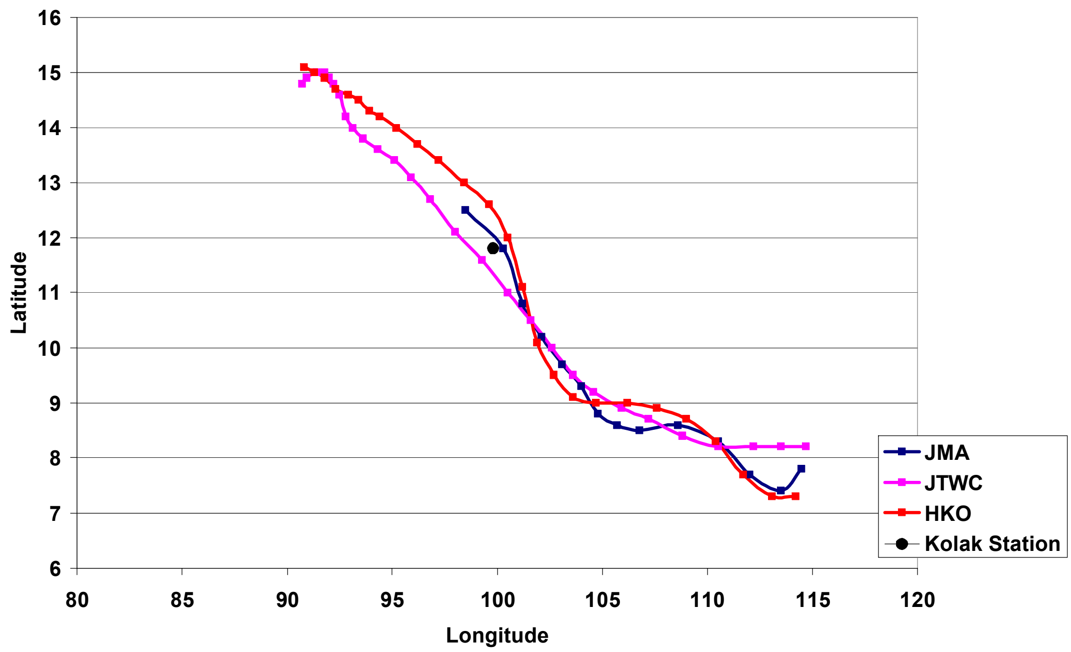


Figure 4.33 The results from the model hindcasting the sea water elevation compared to station data from Kolak, B=1.53, and with no time lag.

The Figure 4.32 and 4.33 show that the amplitude of the modelled surge is too high compared to the station data when there is no time lag. It is 0.94 m higher when B=1.4 and 1.0 m higher when B=1.53. From the preceding work, this error can came from many sources. One that we should consider is the radius of maximum wind. Since we do not know the radius of maximum wind of Linda, we set it to 40 km as a typical Rmax as suggested by Anthes (1982). If the radius of maximum wind of Linda was less than 40 km, the surge results from the model will be smaller. As presented in Figure 4.12, for B=1.5, the surge will be smaller by 0.35 m when the radius of maximum wind decreases from 40 km to 30 km. And if Linda has a radius of maximum wind of 20 km, the surge will be smaller by about 0.8 m than the result in Figure 4.33. But as long as we do not know the radius of maximum wind of Linda, this may or may not cause the error in peak surge.

Another source of error may come from the location where Linda came onshore. Because Kolak is close to the onshore location whichever data set is used, its record is sensitive to changes in the wind radial profile. According to the JTWC data, Linda crossed the shore about 34 km south of Kolak so on that basis, the cyclone would hit Kolak station with its maximum wind at the right front. But the track of Linda provided by HKO and JMA is different. Both these sources located the onshore point of Linda north of Kolak (Figure 4.34). This makes a difference to the amplitude of the peak surge. The surge will decrease the further the track shifted to the north, as the model results in Figure 4.24 show. If we used the onshore location presented by HKO (12.6N, 99.6E) at 00:00UT 04/11/1997, roughly estimated to be about 90 km north of Kolak, the peak surge would be reduced more than 50% with the same cyclone's intensity as used to get the results in Figure 4.24.



.**Figure 4.34** The track position of tropical cyclone Linda provided by JMA, JTWC and HKO compared to the location of Kolak (JMA and JTWC data are taken from their website, HKO data is taken from their annual report for tropical cyclone in 1997)

All these storm surge model scenarios have failed to create the depth of the negative surge. They show only a small lowering of level, whereas the station data shows a clear negative peak. An obvious reason would be that the modelled offshore winds are not sufficiently strong when the typhoon arrived in near shore waters because their direction is bent to a more onshore direction once the storm translation speed is added. The narrower peak surge from the model also shows that the wind distribution in the wind fields still needs to be improved. Although the winds appear reasonable, the absence of any field checks is a big weakness, given the complicated interactions we discussed in chapter 3, and problems revealed in this chapter in specifying storm parameters and track position.

Chapter 5 - Discussion and Conclusions

Summary results from the model

This thesis compared the sea water elevation at Kolak station in the Gulf of Thailand at the time that typhoon Linda (1997) came to the gulf, with the COHERENS model. The response of modeled sea water elevation to typhoon Linda was analyzed in numerical experiments by varying factors that effect the water elevation: (1) Minimum depth (2) Radius of maximum wind (3) B-parameter and (4). Track position. The wind field of typhoon Linda was simulated using the equation that Holland (1980) suggested in his paper as a core. The inflow angle and cyclone translation speed were also added to the wind model. Relevant data of typhoon Linda that helped define the wind field were taken from the Joint Typhoon Warning Center (JTWC). The surface pressure field was also added to the storm surge model in this thesis.

The real sea water level data that is compared to the model is taken from a tide gauge at Kolak station, provided by the Royal Thai Navy.

Kolak station is located at latitude 11° 47′ 42″, longitude 99° 48′ 58″. Typhoon Linda hit the gulf coast south of Kolak station about latitude 11° 34′ 24″, and longitude 99° 36′ 16″, about 34 km south of Kolak, based on the JTWC best track data. That meant the right-front quadrant of typhoon Linda hit Kolak station. After we ran the COHERENS model to investigate the storm surge in this thesis, we can summarize the model results as follows.

The COHERENS model reproduced the tides at Kolak quite well even using only 4 components of the tides in the model. The amplitude of the tides was, however, 19% lower than the observed amplitudes. This arose mostly from the major two diurnal components yielding lower amplitudes in the model. The FFT analysis on station data at Kolak (Figure 4.2) showed at least one missing diurnal tidal component that should also affect the water level. But the most important thing we got from the FFT is that it showed a difference in amplitude of the two major components (K1 and O1) between the model and observations. This is the main reason why the amplitude in the model result is lower than the station data because it cannot reproduced these two main components well enough. Running the model with a minimum depth of 20 m, helped increase the amplitude of the model result to reduce the difference in amplitude from the station data, so we used this depth re-produce tidal levels at Kolak for hindcasting in the storm surge experiment.

The surge results are dominated by the positive surge but do not reproduce well the depth of the negative surge. This may be a result from the wind field created by the method described in chapter 3 not producing a sufficiently strong off-shore wind. The positive surge shows a smooth curve with no multiple peaks as a result of the 1 hour time interval between meteorological data input, except when the radius of the maximum wind is as low as 20 km. The meteorological input time interval of 1 hour is possibly still too large for small fast-moving tropical cyclones.

When we ran the model, we had to set the minimum bathymetry to overcome instability in the model, since it cannot accommodate drying of shorelines. The sensitivity of the storm surge elevation to the minimum depth was tested with the result that changing the minimum water depth did not much effect the surge height, as long as it was not deeper than 10 m. The surge height decreased 14 cm when the minimum depth was increased from 5 m to 15 m, and by 28 cm when the minimum depth was down to 20 m. Changes in the areas between bathymetry contours was the cause of the lowering in surge height.

The surge height was also influenced by the radius of maximum wind. We know that a larger radius of maximum wind makes the maximum wind speed, which circulates around the eye, blow over a greater ocean distance. This means that the surge height should increase when the radius of maximum wind increases. The results in Figure 4.12 confirmed this. But the dependence on the radius of maximum wind was also dependent on the B-parameter in the wind radial profile. The higher B gave a more rapid increase in surge height with radius of maximum wind. However, when the radius of maximum wind was approximately equal to 20 km, changing B did not affect the surge height at all. It appears that for Rmax=20 km, the influence on the surge height by higher maximum speed is compensated by the smaller area of high winds at radii larger than the radius of maximum wind.

The B-parameter in Holland's equation affects the maximum wind and the radial distribution of the wind, so this factor should relate to the surge height as well. Even though model experiments showed that, when Rmax = 20 km, the surge amplitude did not show any dependence on the B-parameter, but if Rmax = 30 and 40 km, an increasing surge height followed an increasing of B-parameter. We can estimate from Figure 4.19 that, for the radius of maximum wind equal to 30 km, the surge increases 0.5 m when the B-value increases 1. This gets higher, to 0.8, when Rmax = 40 km.

The conclusion is made that, if the radius of maximum wind of this tropical cyclone was smaller than about 20 km, the radial distribution of tangential winds affects the surge from the maximum wind, but this is compensated by the small area of high winds at radii larger than Rmax. However, the maximum wind speed would dominate in changing the surge height over the radial distribution pattern, if the radius of maximum wind were more than about 20 km.

The effect of track position of the tropical cyclone on surge height was also investigated. The track of Linda was moved to 40, 80 and 120 km, northward and southward, with its accompanying modelled wind fields. Conclusion from the model results is the surge height depended on the distance and position of the tropical cyclone center from the location that we interested in. The results in Figure 4.24 and 4.25 showed how the position of the tropical cyclone was related to surge height. In the northern hemisphere, the surge that is created at the right side of the track of a tropical cyclone is higher than at the left side because the direction of the wind on the right blows onshore. Linda was onshore at 34 km south of Kolak based on JTWC data so it hit Kolak with its front-right quadrant and created the high surge. When the track shifted southward, the right front of Linda withdrew from Kolak station so the amplitude of the surge decreased with the increase in the distance. Moving the track northward gave the same results but the decrease in surge height was more rapid. The negative surge failed to be re-produced in every experiment, even when the track was shifted 80 km northward, and so when a strong off-shore wind was expected to blow over Kolak as Linda came onshore. This result was caused by the storm translation speed that we added to the wind model, which bent the wind direction to be more onshore. Improving the method of adding translation speed should improve the surge result.

The hindcast of the storm surge caused by tropical cyclone Linda at Kolak station was demonstrated in Figure 4.30 and 4.31. The modelled positive peak differed in both time and amplitude compared to the station data. The time of the modelled peak surge is 13 hours before the station data and the amplitude is 0.94 m higher than station data when B= 1.4 and 1.0 m higher when B=1.53.

Even though the results did not agree well with the station data, the model otherwise seems to work fine. The modelled positive surge at Kolak occurred at a time which corresponds to when the JTWC data indicates Linda reached shore south of Kolak. However, the actual time of the peak surge was 13 hours later. This strongly suggests that the JTWC data does not have correct timing. Note that the best track data from JMA and HKO gave different onshore times for Linda. JMA's track gave a time of coast crossing that was 4 hours later than JTWC, while HKO data indicated it was 10 hours later than JTWC. In no case is there clear evidence which data set is more accurate, but the different sets demonstrate how big the error in best track data might be.

While the station data from Kolak shows an obvious negative surge, the model did not reproduce it at all well. The reason for that may be that the modelled offshore winds were not adequately strong as Linda arrived at near shore waters. This was caused by the character of the storm translation speed that we added to Holland's wind model. It bent the off-shore wind to be more onshore and resulted in a smaller negative surge as discussed under the topic "The effect of cyclone track position on the modelled storm surge" in chapter 4. Decreasing the effect of the translation speed over a large area by decreasing the length scale of the environmental scale processes (R_G) helped in reproducing the negative surge better.

For an amplitude of the peak surge that is much higher than the station data, we found two things that possibly cause this big difference. One is the radius of maximum wind of Linda which we do not know. In this thesis we use a typical Rmax = 40 km, but if the Rmax of Linda actually was smaller or bigger than that, it would cause a significant change in the amplitude of the peak surge. For instant, if the Rmax of Linda = 30 km instead of 40 km, the surge height will decrease about 0.35 m, referring to the results in Figure 4.11. Another aspect that would strongly affect the surge height is the precise location where the cyclone comes onshore. The JTWC data showed that Linda came onshore about 34 km south of Kolak, so the area of maximum wind was at the right front quadrant of TC as it hit Kolak and created the highest peak. But the data from JMA and HKO suggested that Linda arrived onshore north of Kolak as in Figure 4.34. These different tracks decrease the surge height. The roughly estimated onshore location for the HKO track is about 90 km north of Kolak, so the peak surge would be reduced more than 50% with the same cyclone's intensity. This shows that the onshore location is one of the critical factors for surge height, especially when the location we interested in close to the onshore point. The radius of maximum wind and more accurate onshore location are thus needed to be known for more accuracy in storm surge prediction of Linda.

Issues to be resolved

The wind field created for tropical cyclone Linda is one problem area that would cause errors in the modelled sea water elevation in this thesis. The storm surge model results were sensitive to wind data. The maximum wind and position of the tropical cyclone that we took from JTWC are estimates and JTWC accepts that the confidence in the quality of estimates is low (Chu et al, 2002). The error in position and intensity of a tropical cyclone can cause a significant effect on the height of sea water at any location. (Chapter 4). The accuracy of the centre translation speed that we added to the wind field may also cause errors in the results. That speed comes directly from the centre positions of the storm.

More accurate data and improved techniques in verifying the wind field than was able to be used in this thesis are needed. The Holland equation is being improved by modellers and Holland himself. Updating the new techniques on that equation may be required for better storm surge hindcasting. A better method for calculating the B-parameter needs to be applied to the model since it is the critical parameter that affects the maximum wind and the radial distribution of the wind profile. Using a B-parameter that changes with radius of maximum wind and central pressure as suggested by Holland (2008) should be considered as well. The method of applying the storm translation speed to Holland's wind field needs to be re-examined. And different data sets of wind fields should be tested. The 1 degree NOGAPS data had a resolution too low for the project, but with interpolation, it might be worth trying in COHERENS. The data from Hong Kong Observatory (HKO) could also be used as a substitute of the JTWC best track even though it is not as widely used as JTWC for storm surge modelling. Unfortunately, the Japanese Meteorological Agency (JMA) data that we got from their website was too short to run the full model for tropical cyclone Linda.

In this thesis, the different best track data provided by different agencies make a significant change in time and amplitude of the peak surge. Comparing the differences and carefully using the data from several sources may help in lowering the error. The station data near the onshore location could be used as a tool to help determines the best track data as well.

Because the radius of maximum wind of tropical cyclone Linda was unknown, it would help to improve a surge result when we are able to use data from more recent TC's that included surface wind observations and Rmax values from radar. Such data would resolve a number of issues in this thesis.

Small improvements to the tide modelling could be achieved by using more tidal components. However, the greater improvements may come from improving the excitation at the mouth of the gulf in the major diurnal components.

Another limit for the results of this thesis is a problem in COHERENS when dealing with shallow water. To run the COHERENS model on shallow water, we had to set the minimum bathymetry to 5 m to prevent the model from crashing. And this made a difference to the shallow coastline of the Gulf of Thailand. This 5 m limit made the modelled water levels change somewhat, but its effect on the surge also depends on the bathymetry at the point we are interested in. At Kolak, if the minimum depth is set to 5 or 10 m, it does not have much effect on bathymetry (as in Figure 4.7). But if the minimum depth is changed to

15 or 20 m, the bathymetry is significantly different. Anyway, some locations are more sensitive to minimum bathymetry, where only a 5 or 10 m change can re-shape a wide area. An improvement in technique to solve this limitation should be investigated. A model with wet-dry grid-points could be tested with Linda wind fields to compare the performance.

This thesis shows how hard it is to hindcast the storm surge caused by the tropical cyclone Linda at Kolak station when provided with limited data. But using this model for forecasting a storm surge on the Gulf of Thailand is more complicated than this. There would have to be real time wind data for forecasting the storm surge. The wind speed, central pressure, radius of maximum wind and tropical cyclone forecast position would be needed for the prediction. The improvements in storm surge forecasting thus depend on improving storm forecasting as well. The sensitivity of various parameter parameters on storm surge which we have tested in this thesis would help in understanding the complexity of the forecast problem and have to be specified carefully in any forecast model.

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