Analysis on storm surges

Bachelor Thesis In Oceanography

UNIVERSITY OF GOTHENBURG

Johannes Johansson, gusjjoha25@student.gu.se

Supervisor:
Torsten Linders, torsten.linders@gvc.gu.se

June 3, 2013

Abstract

Storm Gudrun, January 2005, was one of the worst storms in modern history over the northeast Atlantic ocean. The purpose of this paper is to analyze the storm surge created by Gudrun and look at what might have been the major contributer to sea level raise along the west coast of Sweden. For this an approach of a one equation model has been set up and the results were compared with observational data from the period of Gudrun. Interesting facts when analyzing data is how observations show a peak in water elevation before the speed of wind peaks. Model results did not correspond well with observations in Skagerrak but better in Kattegat. The conclusion is that maybe local wind, which the model is built on, does not influence the sea level as much as what happened a few hours earlier over the North Sea.

Contents

1 Introduction

(a) (b)

Figure 1: Storm Gudrun left some subnational marks. (a) shows a house that has been traveling over the sea and been washed up on a coastal rock. (b) shows where the boardwalk used to be, to the right of the wall. (Photos: Kerstin Ericson)

Extremely high water level has always been a great issue for low-laying coastal areas. The combination of low barometric pressure, strong onshore winds and spring tides may cause extreme sea level raises. With a powerful storm high wind speed towards the shore always arrives with high wind waves. For low laying areas these waves can be catastrophic when the sea level already might be several meters above normal due to the storm surge.

One of the worst examples during the 20th century happened in The Bay of Bengal year 1970. The region was hit by a storm surge that created a sea level raise of locally 10.7meters above normal and took the life of 250,000 people (Murty et al., 1986). The North Sea storm surge in 1953 gave a sea level raise of 3 meters which led to the death of 1800 people in the Netherlands and 300 in England (Wolf and Flather, 2005). These kinds of occurrences does not particularly relate to the west coast of Sweden but in the event of the great storm Gudrun in January 2005 the damage was severe due to a storm surge and high wind speeds (Suursaar et al., 2006).

When attempting to forecast a storm surge there is a lot of factors that has big enough impact on the system for one to take these into account. There are plenty of different models, some more complex than others. One example of a complex model is the Unstructured Grid Hurricane Storm Surge Model applied in southern Louisiana. This area is highly complex and the sea level is then affected by wind, tides, atmospheric pressure gradients, river flow, wind waves and rainfall. The model for an area like this also need to have accurate information about topography, bathymetry, predominant physical features and flow dynamics. The standard deviation when validating this model were 0.31m if two out of twenty stations were removed. These two stations had missing subgrid-scale features. Hurricanes Betsy (1965) and Andrew (1992) were used when validating this model (Westerink et al., 2008). One less advanced model were made in Estonia, a 2D hydrodynamic model with a 1-km grid step were used when modeling sea level raise under the period of storm Gudrun. Simulations from this model gave an 10-40cm error (Suursaar et al., 2006). The approach taken for this essay is based on one equation with observational wind and atmospheric pressure data. The forcing parameters are wind stress and change in atmospheric pressure, these are assumed to be horizontally uniform and time independent. The sea level is hence assumed to adjust instantaneously to the forcing. This makes the one equation approach to a huge simplification compared to multi-equation models used in Louisiana and Estonia.

The contents within this paper starts in Section 2 with background theory of storm surges and the method used to create the one-equation model. In Section 3 results from observational data and from the model is presented. Section 4 takes up discussion and then summarize the acquired results and why it may not be as accurate as a multi-equation model.

2 Method

2.1 Equations and Theory

In this paper a one-equation model has been made and the equation used originates from ((Cushman-Roisin and Beckers, 2011) Eq. 9.78),

$$\frac{\partial \eta}{\partial x} = \frac{\tau_w}{\rho_0 g h}, \tag{1}$$

where $\partial \eta / \partial x$ stands for the slope in x-direction, perpendicular to the coast line. τ_w is wind stress, ρ_0 is the density of water, g is the gravitational force and h represents the mean height of the water column. Eq.(1) represents the balance between the wind stress and the pressure gradient which has been created from the piling up of water due to the wind stress ((Cushman-Roisin and Beckers, 2011), Eq. 9.77),

$$\tau_w = C_d \rho_{air} U_{10} u_{10}. \tag{2}$$

From Eq.(1), τ_w, the wind stress acting on the sea surface is described with a drag coefficient C_d, ρ_{air}, the density of air, U_{10}, the wind speed at height 10 meters above sea level and u_{10}, the wind speed perpendicular to the shore line. Calculation for u_{10} were made by,

$$u_{10} = \cos(|253 - w_d|)U_{10}, \tag{3}$$

where w_d is the wind direction and the number 253 derives from the approximation that the west coast of Sweden tilts 17 degrees away from the north axis. The drag coefficient, C_d, varies with U_{10} (Garrett, 1977),

$$C_d = (0,75 + 0,067U_{10})10^{-3}. \tag{4}$$

Eq.(1) can show how the amplitude of the storm surge depends on the length over witch the wind is blowing (fetch). From integrating Eq.(1) over the fetch the result becomes,

$$\eta_w = \frac{L\tau_w}{\rho_0 gh}, \tag{5}$$

where η_w stands for sea-level elevation caused by wind and L is the fetch of the wind (over the sea surface). Influence on the sea level elevation from the atmospheric pressure can be looked at as,

$$\eta_p = \frac{p_{atm} - p_{ref}}{\rho_0 g} = \frac{\Delta p}{\rho_0 g}. \tag{6}$$

In Eq.(6) η_p represent the raise of water column that balance the pressure difference between the atmospheric pressure, p_{atm} and its reference point, p_{ref}. Δp, the change in atmospheric pressure compared to p_{ref}, gives the final equation used in this paper to calculate sea level:

$$\eta_w + \eta_p = \eta_{tot} = \frac{1}{\rho_0 g}\left(\frac{L\tau_w}{h} + \Delta p\right) \tag{7}$$

Table 1: Constants.

Constant	ρ_0	ρ_{air}	g	p_{ref}
Value	1000 kgm^{-3}	1.2 kgm^{-3}	9.82 ms^{-2}	1013 hPa

2.2 Stations and Data

There are three stations along the Swedish west coast were Eq.(7) has been used. These stations belong to Station Groups in which air pressure-, sea level- and wind-data are included. The Station Groups are presented in Table 2 and Figure 2. When applying Eq.(7) each of the three Station Groups has different properties when it comes to fetch and depth, this can be seen in Table 3. At Nordkoster (Station Group 1) which has its location close to the Norwegian border and at station Måseskär (Station Group 2) the fetch has been set with two different lengths because of comparative purposes, one from the area between Norway and Denmark and one from the mid parts of the North Sea. At the southern most station, Nidingen (Station Group 3), the fetch only stretches to the coast of Denmark.

Table 2: Stations for observations.

Station Group	Wind data	Air pressure data	Sea level data
1	Nordkoster	Nordkoster	Kungsvik
2	Måseskär	Göteborg	Smögen
3	Nidingen	Göteborg	Ringhals

Table 3: Fetch lengths and depths thats been used with Eq.(7) is presented for each Station Group.

	Example A		Example B	
Station Group	Fetch A	Depth A	Fetch B	Depth B
1	150 km	200 m	500 km	100 m
2	150 km	100 m	300 km	80 m
3	80 km	24 m	-	-

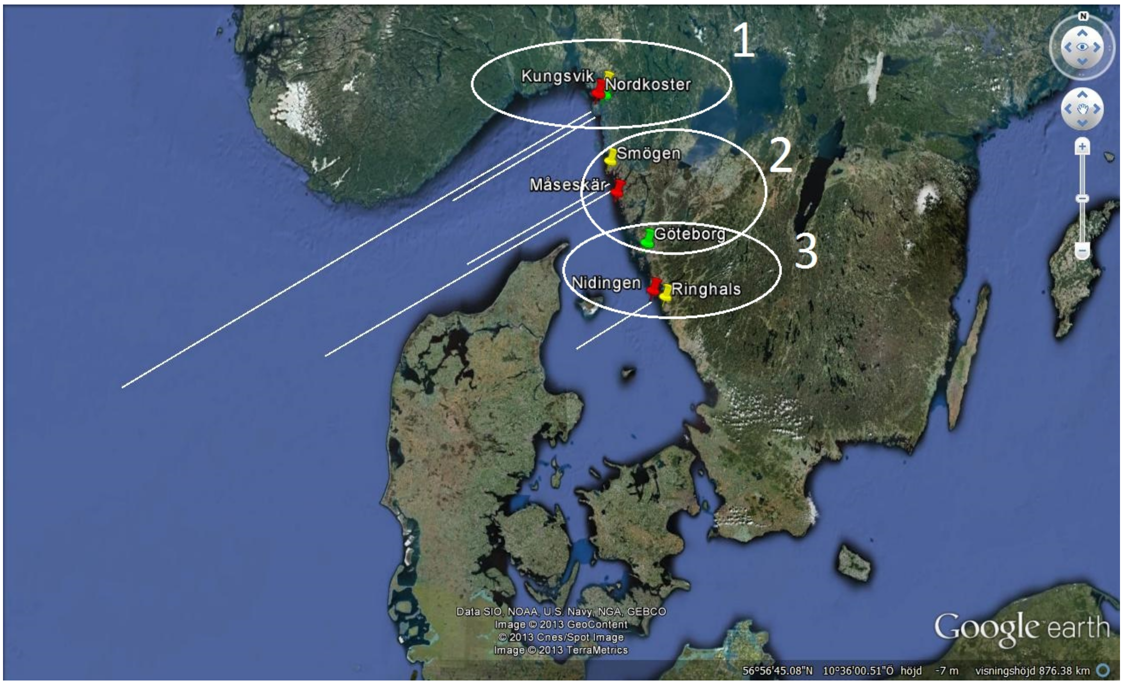


Figure 2: Yellow markings represent stations with observational sea-level data; Red markings represent stations with observational wind data; Green markings represent stations with observational air pressure data. All data has been supplied by SMHI (Swedish Meteorological and Hydrological Institute). The five lines represent fetch lengths for each Station Group, see Table 3 .

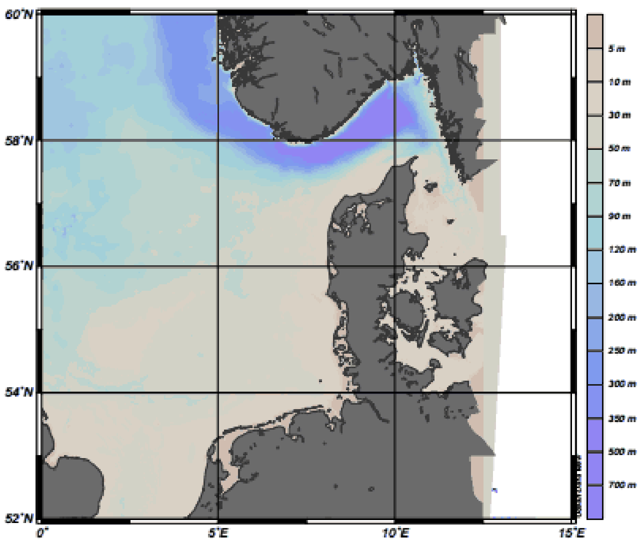
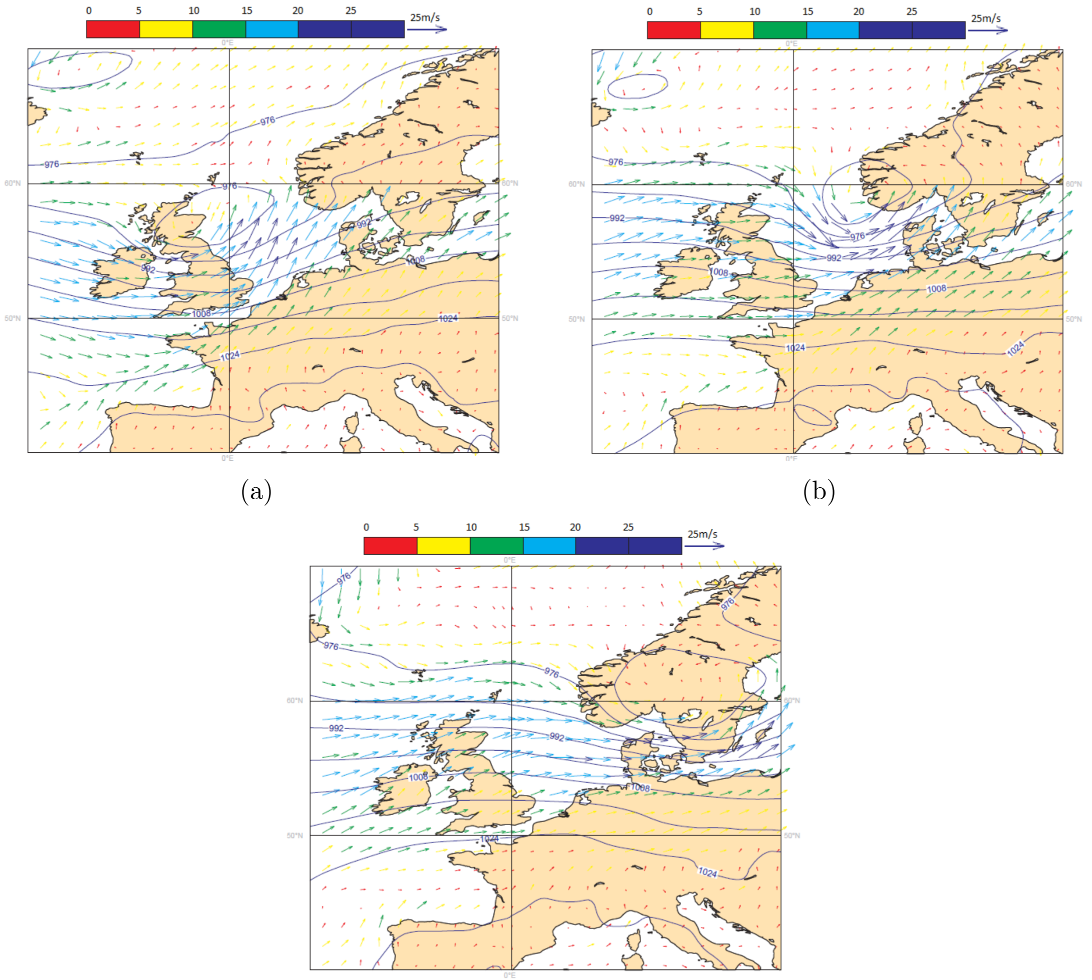


Figure 3: Bathymetric map. (By: Johanna Linders)

3 Results

3.1 Development of Storm Gudrun



(a) (b) (c)

Figure 4: Sea level pressure (hPa) and wind (see legend) for western Europe January 8, 2005. Time development (UTC): (a) 06.00, (b) 12:00, (c) 18:00, local time in Sweden is one hour before UTC. Data for these figures are re-analysis (ERA-Interim) from ECMWF (European Centre for Medium-Range Weather Forecasts).

Figure 2 presents the development of storm Gudrun. The storm first formed over the northern parts of the Atlantic Ocean and then came in over the British Isles were it really started to gather its force. In Figure 4(b) one should note the strong wind over the North Sea pushing water towards the Skagerak Sea. This is important since it will be discussed later on in section 4. The wind is strongest on the Swedish west coast In Figure 4(c).

3.2 Observations and Calculations

In this subsection Station Groups 1,2 and 3 is presented with observations and calculations. For each of the three Station Groups observations on wind (U_{10}, u_{10}) and air pressure is plotted together as well as observations on sea-level with results from the model. I start by presenting wind and air pressure for each Station Group referenced to Figures (3,4,5). Next I present observed sea level for each Station Group and continues with calculated sea level. I then finish this subsection with results from calculating sea level raise over the North Sea and discuss why this might influence the west coast of Sweden.

In Figure 5(a) one can see that air pressure reaches its lowest point at around 16:00 January 8. There is one peak of wind speed at around 15:00 but it is not until proximately 21:00 that both U_{10} and on shore wind, u_{10} peaks with full power. Figure 6(a) looks pretty much the same as Figure 5(a) with the difference that the dip in air pressure is not as low and that on shore wind speed u_{10} corresponds well with U_{10}. Figure 7(a) does not induce any big surprise either, the wind speed looks similar to that in Figure 6(a) and the atmospheric pressure is observed at the same station, Göteborg (Table 2).

Note the early peak in observed sea level around 19:00 January 8, it shows up before the peak of on shore wind. Another interesting thing when looking at the observed sea level is that the tidal water seems to combine with the two highest peaks. The periodic rhythm of tidal water reveals itself at both Station Group 1 and 2 (Figure 5(b), Figure 6(b)). The two sea level peaks occur at almost exactly the same time. Figure 7(b) on the other hand give us some new things to consider. There is one peak from the observed sea level, higher then any of the other peaks north of this station, it stretches to 160cm compared to the other peaks on 110cm above normal. However the observed sea level still occurs before the powerful on shore wind does. Note though, how wind velocity U_{10} reaches 20ms^{-1} at already 12:00 January 8. One should also be able to see the small tendency of tidal water and how it emerges a little bit later here at Station Group 3 (Figure 7(b)) compared to that of Station Group 1 and 2 (Figure 5(b), Figure 6(b)).

The two different methods of dealing with Eq.(7) is shown in Figure 5(b) and Figure 6(b) were they are compared to observational data. Note the difference between Eq.(7) A and Eq.(7) B and how both of them react to change of on shore wind speed. With Eq.(6) the effect of air pressure on the water elevation is presented with a black line. Eq.(7)A is strongly effected by the impact of Eq.(6)

at Station Group 1 (Figure 5(b)). Because the peak of the sea level corresponds well with the peak of wind-speed data from Figure 7(a) so does the modeled water level. Result from Eq.(6) looks the same as in previews figures(3,4).

Because of the early peak in sea-level raise, Figure (5) and Figure (6), before the strong wind takes command at the west coast of Sweden, the theory of an inertia wave pulse took place. This gave room for the use of the one equation approach even at the west coast of Denmark, the fetch, depth and result can be seen in Table 4. Because the lack of data over the North Sea, wind speed and atmospheric pressure were given values by observing Figure 4(b), the values are presented below in Table 4 as well. The result of modeling over the North Sea, from were an inertia wave pulse might have taken place, gave a sea-level raise of 1.0m. In Section 4 this result is discussed whether or not it is a reasonable theory.

The equation for long waves such as an inertia wave,

$$c = \sqrt{gH} \tag{8}$$

With values from Table 4 and simplified calculations (Eq.(7) and Eq.(8)), results shows that a sea level raise of 1.0 m may have occurred together with a wave pulse that would have arrived to the west coast of Sweden 1.5 hour after its creation over the North Sea, see Table 4. This is off course just an assumption with substantial approximations.

Table 4: Values for calculating storm surge at the coast of Denmark at 12:00 (UTC) January 8 and for long wave pulse. These values have been used together with Eq.(7) and Eq.(8).

Eq. (7)	
Wind	20 ms^{-1}
Air Pressure	970 hPa
Fetch	300 km
Depth	50 m
Sea level raise	1.0 m
Eq. (8)	
H (Skagerrak)	200 m
c	44 ms^{-1}
Distance	250 km
Time	1.5 hour

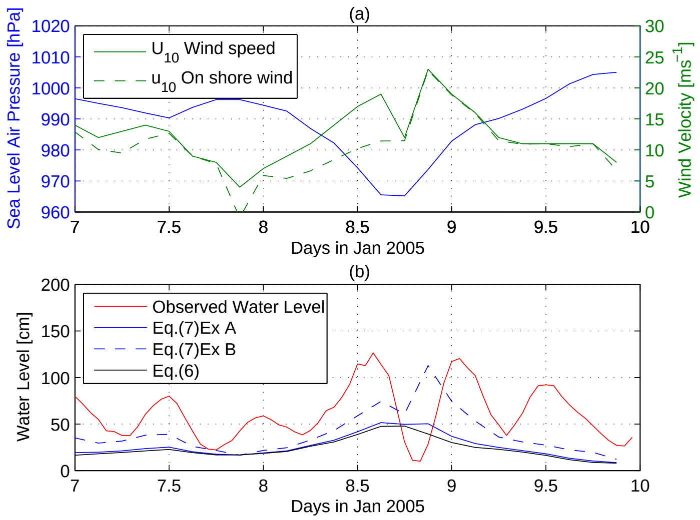


Figure 5: Station Group 1. The upper plot, (a), presents wind velocity and its on shore component together with air pressure at sea level. The lower plot, (b), presents observed water level and two different approaches on Eq.(7). The dashed blue line represents Eq.(7) with a longer fetch length and a smaller depth. The effect from air pressure on sea level is shown with Eq.(6).

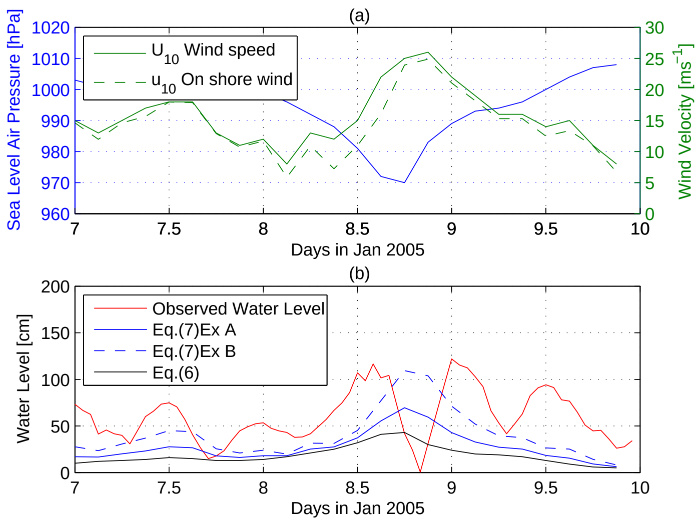


Figure 6: Station Group 2. The upper plot, (a), presents wind velocity and its on shore component together with air pressure at sea level. The lower plot, (b), presents observed water level and two different approaches on Eq.(7). The dashed blue line represents Eq.(7) with a longer fetch length and a smaller depth. The effect from air pressure on sea level is shown with Eq.(6).

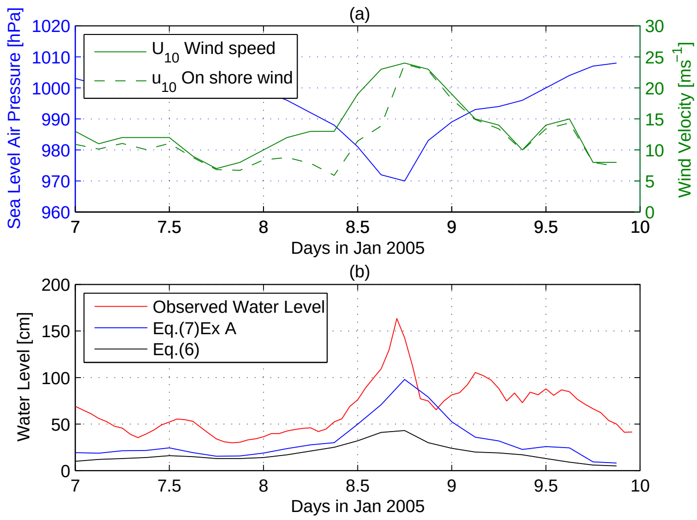


Figure 7: Station Group 3. The upper plot, (a), presents on shore wind together with air pressure at sea level. The lower plot, (b), presents observed water level with a red line and the blue Eq.(7). The effect from air pressure on sea level is shown with Eq.(6).

4 Summary and Discussion

Figures (5, 6, 7) all have a mean water level at around 50cm above normal before 06:00 January 8. One can ponder if this high observed water level only reflects the coast line or if a large part of Skagerrak and Kattegat also have high water level. If so this would probably mean that water have been pushed in from the North Sea and have continued to do so throughout the high wind speed event of January 8.

At 12:00 the wind peaks over the North Sea, see Figure 4(b), which possibly creates a strom surge at the west coast of Denmark as well as pushing water towards the mouth of Skagerrak. This is important to keep in mind during the inspection of observed water level at Station Groups 1 and 2 (Figures 5, 6). The first peaks at both these stations occur at 14:00 January 8 before wind arrives with full force. This gives room for speculations about what actually been the main contributer for high water level at Stations 1 and 2. The answer is presumably that a combination of factors collaborates, some more then others, to fulfill the peaks in water level at the west coast of Sweden. Maybe an inertia wave pulse from the North Sea have been transported into Skagerrak and further in to Kattegat or perhaps air pressure and wind from 12:00 gave rise to the first peak at 14:00. Regardless of the foremost contributing factors, one thing is for sure, they combine in resonance with tidal effects which has a period of 12.42 hours. Between 00:00 January 7 to 06:00 January 8 the tides reveal it self clearly (Figure 5).

At Station Group 3 there is one peak, reaching higher then at any of the other stations, that cumulates at 17:00 January 8(Figure 7). This could be a cause due to both an inertia wave pulse, wind speed as well as air pressure- and tidal effects. The tide show up later here at the southern most station which then consequently arrives to the coast line together with wind speed.

Results from calculating water level with Eq.(7) gave useful insight to when wind affects the sea level and when it does not. At Station Group 1 (Figure 5, Eq.(7)Ex.A) effects from air pressure is the major contributing factor whilst wind stress effect is absent. The explanation for this is the greater depth used in Eq. (7)Ex.A see Table (4). When the fetch length was stretched out and used in Eq. (7) Ex.B the wind stress gave results but it is hardly realistic to consider a fetch of 500km and in addition the depth were reduced. The same conclusions can be made for Eq.(7) Ex. A and B in Station Group 2 (Figure 6). Another proof for the lack of wind and air pressure impact at Station Group 1 and 2 is the distinct dip in water level at the time of wind and air pressure maximum.

The calculated water level at Station Group 1 matches well with observations. The shallower water outside this station group leads to a greater impact on the water column by wind stress. Looking at U_{10} (Figure 7(a)) and how it keeps a wind speed above 20ms^{-}1 it starts a theory about importance of length of time the wind holds up a high speed.

It seems as the tides amplitude are strengthened by the storm (Figure 5, 6). Whether its because of an inertia wave pulse from the North Sea, air pressure and wind or a combination of them all together cannot be answered with just this essay. Hence the main conclusion that can be brought out from the work on this essay is the impeccable fact that a one equation approach is not enough to cover the complex development of a storm surge. One can only speculate about what type of surroundings this model has its best fit, probably in an region much like that around Station Group 3 (Figure (7)) were water is shallow and tidal effects are small.

References

Cushman-Roisin, B. and Beckers, J.-M. (2011). *Introduction to Geophysical Fluid Dynamics: Physical and Numerical Aspects*. Academic Press, Waltham, Massachusetts.

Garrett, J. R. (1977). Review of drag coefficients over oceans and continents. *Monthly Weather Review*, 105(7):915–929.

Murty, T. S., Flather, R. A., and Henry, R. F. (1986). The storm surge problem in the bay of bengal. *Progress in Oceanography*, 16(-):195–233.

Suursaar, U., Kullas, T., Otsmann, M., Saaremäe, I., Kuik, J., and Merilan, M. (2006). Cyclone gudrun in january 2005 in the estonian coastal waters. *Boreal Environment Research*, 11(-):143–159.

Westerink, J. J., Luettich, R. A., Feyen, J. C., Atkinson, J. H., Dawson, C., Roberts, H. J., Powell, M. D., Dunion, J. P., and Kubatko, E. J.and Pourtaheri, H. (2008). A basin- to channel-scale unstructured grid hurricane storm surge model applied to southern louisiana. *Monthly Weather Review*, 136(3):833–864.

Wolf, J. and Flather, R. A. (2005). Modelling waves and surges guring the 1953 storm. *Phil. Trans. R. Soc. A*, 363(1831):1359–1375.