A predictive model for hurricane surge levels in New Orleans

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ROYAL HASKONING

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Preface

The topic of this report is the prediction of maximum surge levels due to hurricanes. It is the result of almost three months of work. This work is done during my internship at the department of Royal Haskoning in New Orleans. The internship is part of the study Civil Engineering at the University of Twente.

It were three exciting and busy months, in which I learned very much. I studied hurricane and storm surge phenomena and the flood protection system of New Orleans before and after Katrina. It has become clear how the city is better protected against hurricanes but also that there still is much room for improvement. I also improved my Matlab skills that will probably be very useful in the future. Hopefully I also learned how to write a good report on my findings about storm surge predictions, but that will become clear in the next chapters. I also realize better than before that it is very difficult to protect a city against hurricanes, most of all because of the extreme circumstances. The American government has a different view on the protection against surges than the Dutch government. Everybody has an opinion over the situation and some people can get very emotional when discussing this.

It was a very nice time in New Orleans because it is an impressive city with a good atmosphere. The city is still influenced by Katrina, some of the areas that were destroyed by the hurricane are not being rebuilt. It is very sad and impressive to still see the destruction from the hurricane. You can see the city is coming back to where it was, but a lot has to be done. It was great to be here and I hope to come back some day.

I would like to thank dr. Mathijs van Ledden and dr. Kathelijne Wijnberg for their supervision and allowing me to do this internship. I would like to thank Mathijs for giving me the opportunity to do this internship at Royal Haskoning in New Orleans. I would also like to thank dr. Bas Jonkman for the best idea ever, ir. Maarten Kluyver for his suggestions and comments and my two colleagues in the New Orleans office, Mats Vosse and Marcel van de Waart for their support. Last but not least I want to thank my parents, Karin and Rene, and my girlfriend, Marieke Sloots for all their support and allowing me to leave them for three months.

Management summary

This report investigates how to predict maximum surge levels based on detailed model data. The surge levels are based on data generated by a numerical computer model named ADCIRC. With this computer model 152 different fictional storms have been simulated. Using only the hurricane parameters as input, a method to calculate the maximum surge levels based on these data is developed. For this purpose the relation between the hurricane parameters and the maximum surge is investigated first. Key hurricane characteristics are the minumum pressure at the center of the hurricane, the radius to maximum winds, the central (forward) speed and the Holland-B parameter. After investigating these parameters, it became clear that the wind speed, the pressure and also the local bathymetry (including obstacles like levees) are the main factors affecting the storm surge. Therefore these parameters were chosen as the input for the prediction model.

After this the optimal representation of these parameters was investigated. The pressure difference between normal atmospheric pressure and current pressure was found to be the best way to take the pressure effect on the storm surge into account. In order to improve the predictions, the wind in a certain direction – for example in the direction of a levee – was taken since wind blowing the water away from a levee will not cause high surge levels. The wind component in the direction of a levee will cause high surge levels. The direction that has the best correlation with maximum surge levels is determined for every point of the prediction model. This direction is called the dominant wind direction and is used to improve the relation of the wind speed and the maximum surge. For some points, the wind over a certain time will cause storm surge levels to be built up. Therefore the wind speed in the dominant direction, averaged over time, was taken as the best predictor of storm surge.

The optimal parameters for the pressure and wind are now known. It can be justified that the wind speed to the square is linearly related to the surge levels. The same is assumed for the setup due to the pressure difference. Therefore the surge levels in the prediction model are a function of these parameters. Location specific parameters in this function are assumed to take the local bathymetry into account, like levees or shallow water in the neighborhood. With this function and the storm surge known for 152 different storm, the optimal values of these coefficients relating the wind speed and pressure to the maximum surge levels, can be determined using multiple linear regression. With these coefficients predictions of the storm surge can be made for the same 152 storms and compared to the known surge levels. From the results can be concluded that it is possible to predict maximum storm surge based on the basic parameters of a hurricane.

Furthermore a selection of points to be used in the Prediction Model was made. An interface has been developed in which the results can be presented and which can be used to enter any random storm track and storm parameters. And finally the results of the storm surge levels predicted by the Prediction Model have been validated to the results of Katrina. All of the results and how the exact coefficients and function has been determined is presented in this report.

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1 Introduction

1.1 Context

At August 29, 2005, Hurricane Katrina struck New Orleans. Because of the large impact of this hurricane, a lot of media attention has been given to it. High storm surge levels, as a consequence of this storm flooded large parts of the city, at some places over 10 feet deep. Huge damage and loss of life was the result.

After Katrina much attention has been given to the Hurricane Protection System of New Orleans. A Dutch delegation visited New Orleans to give advice. Similarities can be found between the Netherlands and Louisiana. Most important similarities are that both are located for a large part below sea level and the existence of polders protected by a system of levees. In both cases many people live in these polders below sea level.

In order to protect the city it is necessary to have insight in the surge levels that can appear during a storm. This information is necessary to make decisions about measures, for example emergency evacuations and placing sandbags. To predict these surge levels the ADCIRC model, is used by the U.S. Army Corps of Engineers (USACE). Surge levels for many different storms have been determined with this model. The ADCIRC model is very detailed but computationally very expensive. The results of this model, in the area near the coast of New Orleans, are the input of this assignment.

Using the data from the model, a relation between the storm surge and the different characteristics of the storms should be determined. With these relations it should be possible to predict the surge levels quickly for different storms, or a certain range of possible storms, that could be threatening New Orleans. These predictions are then to be presented in an easily to be understood way. In this way, very quick insight in the storm surge levels for a wide range of storm tracks and storm characteristics can be made. This is useful because the uncertainties in the predictions of the storm track and characteristics are high. The ADCIRC model takes a long time to compute the predictions, and therefore it is difficult to compute, for example, a worst or best case scenario. With a quick and reliable model for New Orleans the whole range of possible storm tracks and characteristics can be calculated which gives insight in the storm surge levels for the storm arriving. This results in the objective given in the next paragraph.

1.2 Objective

Find the relations between the storm characteristics and the maximum surge levels based on the results of the ADCIRC model for 152 storms. Use these relations and the data to quickly predict the surge levels for user defined hurricanes. Present the results of the predictions in a clear manner.

1.3 Outline

In chapter 2 is explained how a hurricane causes a storm surge, the different parameters of a hurricane will be explained and the effects of these parameters on the maximum surge levels is examined.

In chapter 3 the data used is described, and the model used to collect the data is also described. The data consist of storms surge series for 152 different storms, at almost 3000 different locations.

In chapter 4 is explained how storm surge can be predicted by using the parameters discussed in chapter 2. The predictions are based on pressure and wind speed. It is explained how the wind and pressure are calculated for different locations and how the best relation to storm surge can be found.

In chapter 5 the prediction model equations are discussed. The equation on which the model is based on is given, the model calibration is discussed and the interface is presented. The validation of the model is described and whether the model can be used for real time predictions is discussed.

In the final chapter, chapter 6, the conclusions and recommendation for improvements are given.

2 Hurricanes in New Orleans

2.1 Introduction to the study area

New Orleans is surrounded by the Mississippi river, Lake Pontchartrain to the North, Lake Borgne to the East and the Gulf of Mexico / wetlands to the south. The city is protected against flooding by a system of levees, floodwalls and pumps. This system is now officially called the (Greater New Orleans) Hurricane and Storm Damage Risk Reduction System. This system of levees and floodwalls can be seen in figure 1.

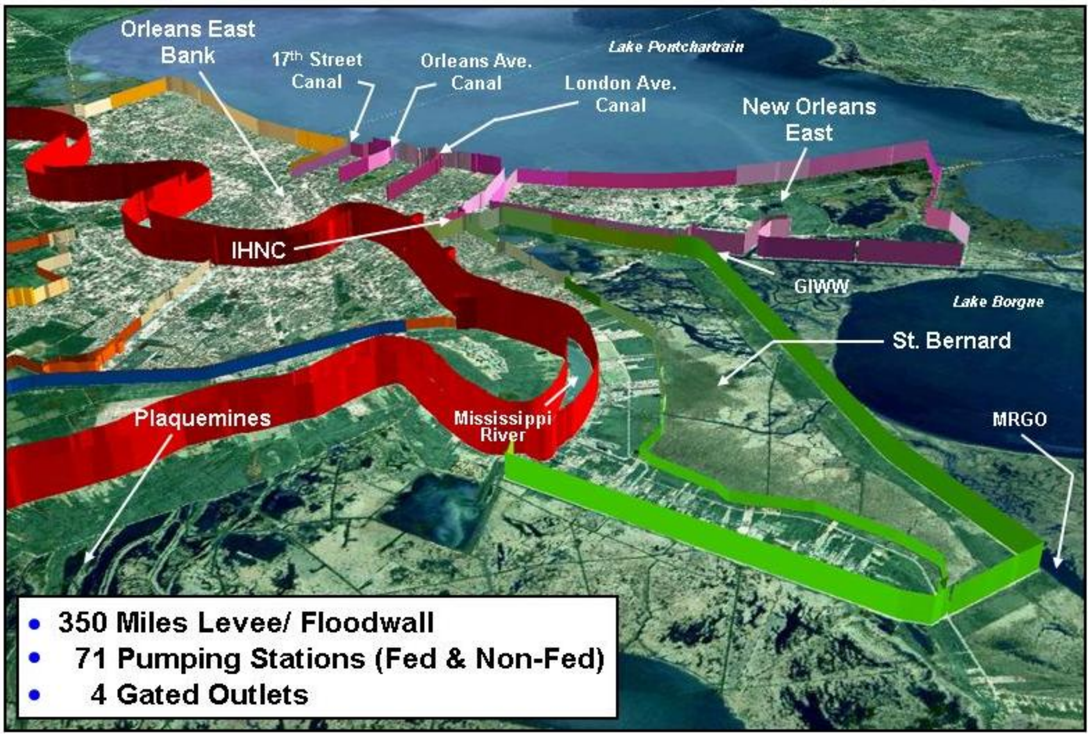

Figure 1: Hurricane and Storm Damage Risk Reduction System of New Orleans (Interagency Performance Evaluation Task Force [IPET], 2007)

During a storm the wetlands south of New Orleans (the Plaquemines area) will inundate. The Mississippi River, with its levees, lies in the middle of these wetlands. The levees of the Mississippi have a great impact on the surge levels occurring because the water piles up against them. The wind drives the surge to New Orleans, where the Hurricane and Storm Damage Risk Reduction System protects the city. The wetlands are of large influence on the storm surge, they protect the city to a certain extent from very high surge levels and waves. In the last decades a lot of wetland loss has been suffered. Apart from their positive impact on the storm surge, these wetlands are ecologically and economically very important.

The wind during a typical hurricane is mostly blowing from the southeast to northwest, so the water is driven into lake Borgne and into lake Pontchartrain. At the most western end of lake Borgne the system has a V-shape. In this area, where a new surge barrier is planned to be built, some of the highest surge levels occurred during Katrina in the New Orleans area because of this V-shape.

North of New Orleans Lake Pontchartrain is situated. A large bridge that crosses this lake was damaged during hurricane Katrina. This made it difficult to reach the city when help was needed the most. The infrastructural damage was one of the reasons why it took long before a lot of people, that haven't evacuated the city, were helped.

The city of New Orleans is protected by levees on the south side of the lake. But as can be seen a lot of canals enter the New Orleans and Metairie area, since these canals were not closed during Katrina, high water levels occurred in these canals. Overtopping or failing of the floodwalls along these canals caused a lot of problems. These canals are closed at this moment.

Figure 2: Erosion from overtopping which caused floodwalls to collapse.

Other canals in the area are the IHNC (Inner Harbor Navigation Canal) and the MRGO (Mississippi River Gulf Outlet - authorized in 1956 to allow commercial shipping to enter the port of New Orleans from the Gulf of Mexico). The MRGO allows the water to enter the New Orleans area and is a connection between lake Borgne and Lake Pontchartrain. The high water level differences create large high velocity flows of water, threatening the levees along the IHNC and MRGO. The high water levels on lake Borgne, threaten the New Orleans East and St. Bernard Polder levees. Overtopping of these levees occurred during hurricane Katrina, which caused erosion on the back side of the levees, which can be seen in figure 2. This weakened the levees. The same happened to the floodwalls along the canals causing them to collapse. The overtopping and failing of the levees and floodwalls along lake Borgne and the MRGO, IHNC and GIWW (the Gulf Intracoastal Waterway, which is a recreational and commercial waterway that extends all the way to Florida), was the main reason for the flooding of the New Orleans East area and the St Bernard Parish. The Lower Ninth Ward, where the largest inundations occurred was flooded because of the IHNC floodwall breaches.

2.2 Hurricanes

Category	Wind Speed (mph)	Damage at Landfall
1	74-95	Minimal
2	96-110	Moderate
3	111-130	Extensive
4	131-155	Extreme
5	Over 155	Catastrophic

Figure 3: Hurricane category's (How does a hurricane form? n.d.)

Hurricanes, or tropical cyclones, have a center of low pressure and are accompanied by strong winds and thunderstorms. The formation of hurricanes is not fully understood, but the following factors are of importance. A high enough sea water temperature, rapid cooling of the air with height is required to release enough heat of condensation. A high humidity and low wind shear are also favorable circumstances for the formation of hurricanes. The location where the hurricane is formed should be a certain distance from the equator and also there already has to be a disturbed weather system. (Tropical Cyclone, n.d.).

Hurricanes on the northern hemisphere rotate counterclockwise, wind is driven to the low pressure center of hurricane, and from all directions this wind is directed to the right (on the northern hemisphere) because of the Coriolis force . This causes hurricanes to rotate counterclockwise, because the wind that is attracted to the low pressure center of the hurricane is directed to the right because of the Coriolis force.

Hurricanes are divided into 5 categories, where a category 5 hurricane is the most extreme hurricane (figure 3). Before a storm becomes a hurricane (or tropical cyclone) it can take the following forms: tropical disturbance, tropical depression, tropical storm and then it becomes a tropical cyclone. Warm ocean water and winds are needed to create a tropical disturbance, when the warm ocean water vapor condenses to clouds, heat is released (heat of condensation). This heat warms the air and makes it rise, where further condensation and evaporation makes the clouds even larger. A system develops where the warm moist air keeps on rising, forming clouds along a moving column of air, which keeps on collecting clouds that form thunderstorm. The unstable cool air of the thunderstorms release a lot of heat from the water vapor, causing high and low pressure areas generating wind. This wind is affected by the coriolis force causing the circular motion. The larger the pressure differences, the larger the wind speeds. At speeds of 25mph the tropical disturbance becomes a depression, at 39mph it becomes a tropical storm and at 74mph it becomes a category 1 hurricane. (How does a Hurricane form? n.d.) See figure 4.

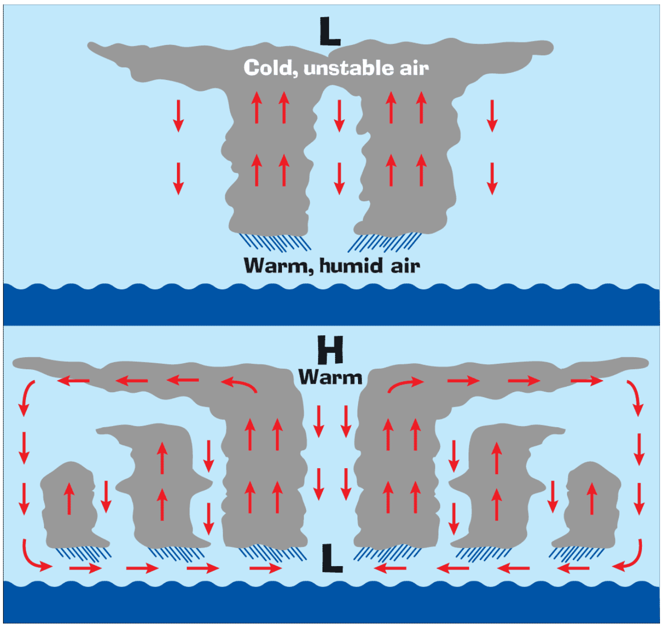

Figure 4: Formation of a hurricane (How does a hurricane form? n.d.)

2.3 Storm Surge

The strong wind and low atmospheric pressure of a hurricane causes storm surges. Storm surges typically cause the most damage near the coast, whereas winds cause the most damage inland.

The main contributor to storm surge is the wind. Wind drags over the ocean's surface and pushes the water in one direction. This wind also causes waves and these waves add height to the storm surge. During a typical hurricane situation, the wind will be blowing from the east - easterly wind - most of the time. Depending on the track this is causing water to pile up against the east banks of the Mississippi River.

What becomes clear from figure 5, is that storm surge on the deep sea might be small, for even the biggest of hurricanes. The water is being pushed in a circular motion along the center of a hurricane because of the winds. In the deep sea the wave energy below the water level does not reach the bed level, therefore the water can dissipate in the deeper waters. When the sea becomes more shallow, the water cannot dissipate anymore because the wind stresses and wave energy put momentum in the movement of the water body. Therefore the water is pushed up as the sea becomes more shallow, see figure 5. Typical wind effects in shallow water range from 10-20ft.

Another factor contributing to storm surge height is the reduced pressure, in the center of a hurricane pressure can be as low as 900mbar. The normal atmospheric pressure at sea level is about 1013mbar. The typical contribution of the pressure is about 2-3ft.

The tide is of importance too, because it contributes to the maximum water levels. Storm surge is the difference in height in water level over the level expected from the normal tide. The tide can further increase the maximum water levels as the storm surge is added to the tide to reach the maximum water levels. But the tidal difference at the coast of Louisiana is relatively low (IPET 2004) so this effect will be relatively small.

Another factor is the local bathymetry. The local bathymetry has a large effect on the storm surge levels. The wind pushing the water up against a levee or a surge at sea entering the coastal zone. In figure 5 it can be seen how a surge entering a shallow coast will become larger. The coast of Louisiana is very shallow, because of the sediment deposited by the Mississippi River.

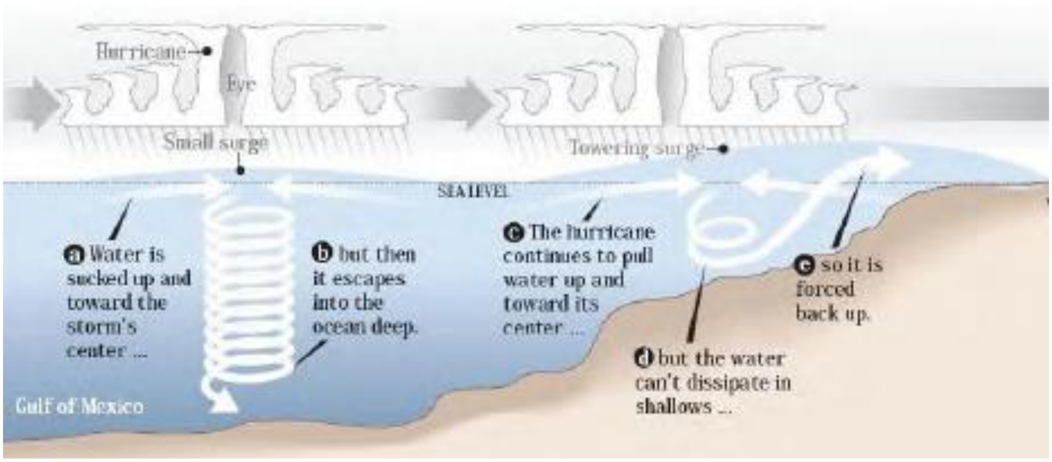

Figure 5: storm surge build-up near the coast. (Dijkman 2007)

2.4 Parameters affecting maximum surge levels

The different parameters affecting surge levels and their relation with the maximum surge levels will be discussed in this chapter.

2.4.1 Radius of maximum winds

The radius of maximum winds is the distance between the central low pressure point of a hurricane and the location where the maximum wind speeds occur. Figure 6 shows Storms the maximum surge levels at 5 different locations of three different storms (7, 8 and 9) modeled by ADCIRC. These storms only differ in terms of their radius of maximum winds. Points 45, 71 and 593 are offshore locations. The location of point 157 is in the middle of Lake Pontchartrain and one point 316 is in the middle of Lake Borgne. The water levels in the lakes are higher than the offshore points because of the western winds that are pushing the water towards the lakes which the water cannot leave. The surge in points 71 and 45 are very low because of the great distance from the storm track of storms 7, 8 and 9. From this figure it can be seen that there is a non-linear relation between the radius and maximum surge.

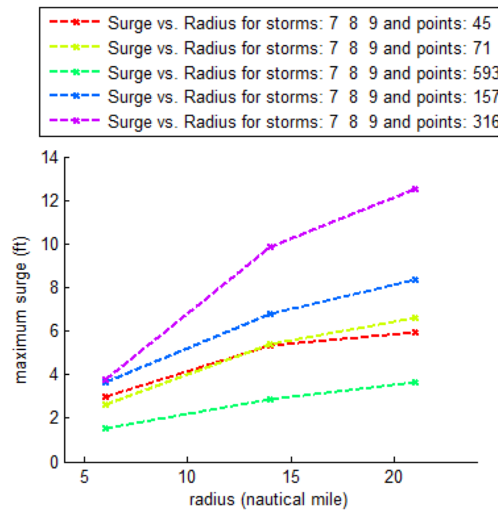

Figure 6: Effect of radius on the maximum surge for storms 7, 8 and 9 for 5 different points of the Q835 data set. These storms have a minimum pressure of 900mbar, a central speed of 21mph and a Holland-B parameter of 1,27. The radius of storms 7,8 and 9 is 6, 14 and 21nm (nautical mile) respectively.

A larger radius will result in the highest wind speeds at a distance further from the centre of the storm. The highest storm surge will normally coincide with the highest wind speeds when local effects are not taken into account. In figure 7, where offshore points are chosen to eliminate these local effects, it can be seen that there is a peak of the storm surge at the eastern side of the storm track at a distance of about the radius of maximum winds. A larger radius of maximum winds does not necessarily result in larger wind speeds, but an increase of radius of maximum winds result in a higher storm surge (all other factors constant). When this effect is examined more closely, in particular the maximum wind speeds at the moment of landfall, it can be seen that storm 7, 8 and 9 have a maximum wind speed of 55.3, 48.4, and 46.6 m/s respectively (Appendix 2). While the wind speeds are lower since a larger radius of maximum winds results in

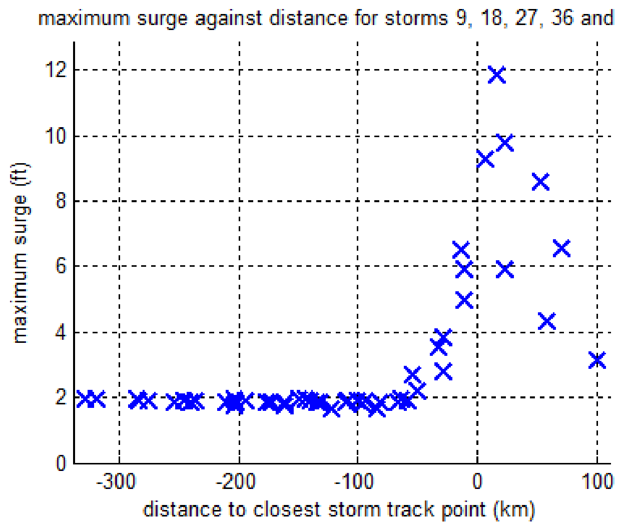

Figure 7: Maximum surge for storms 9, 18, 27, 36 and 45 against the distance from the storm track, a negative distance is a distance to the west. The points where the surge is measured are offshore points. Notice the peak in surge levels at a distance about the radius of the storms. (all storms have a radius of 21 nautical mile, about 40km)

smaller differences in pressure (Appendix 2), the storm surge is higher. The reason for this is that a larger body of water is put into motion because the wind speeds are affecting a larger area. When the water body that is put in motion reaches the shore it has an exit path at a certain distance away from the storm center related to the radius of maximum winds. When the exit path lies further away more water is pushed up against the shore because it cannot reach the exit path as easily. The formulas and a more detailed description on this effect will be given in paragraph 2.4.3 and 2.4.4.

2.4.2 Central speed

The central speed has little influence on the maximum surge levels. The surge series in figure 8 illustrate this. To show the effect of central speed the storms 101 and 5 are compared, just as storms 103 and 23 are compared since these only differ in central speed.

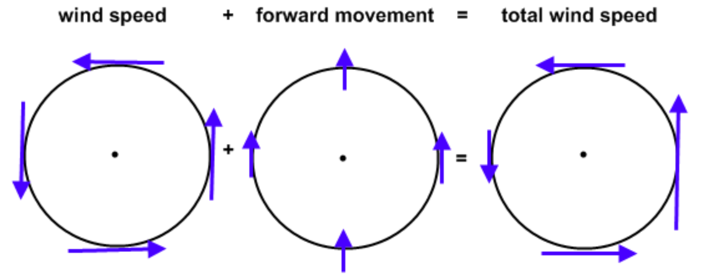

Figure 8: Difference in maximum wind speeds east or left from a hurricane.

The difference that is observed is a shift in time. The storm passes more quickly with a higher central speed. The difference in surge height is relatively small, and most of the times an increase in central speed will result in a larger maximum surge. In figure 9 can be seen that a higher central speed results in higher wind speeds at the east side of a hurricane (for a hurricane moving north, and on the northern hemisphere). The west side of a hurricane will experience smaller wind speeds. This is the effect of the superposition of the two different wind speeds, the wind speed along a hurricane, and the forward speed along the track of hurricane. Therefore the effect of the central speed on storm surge is mostly dependent on the location of the surge point with respect to the storm track.

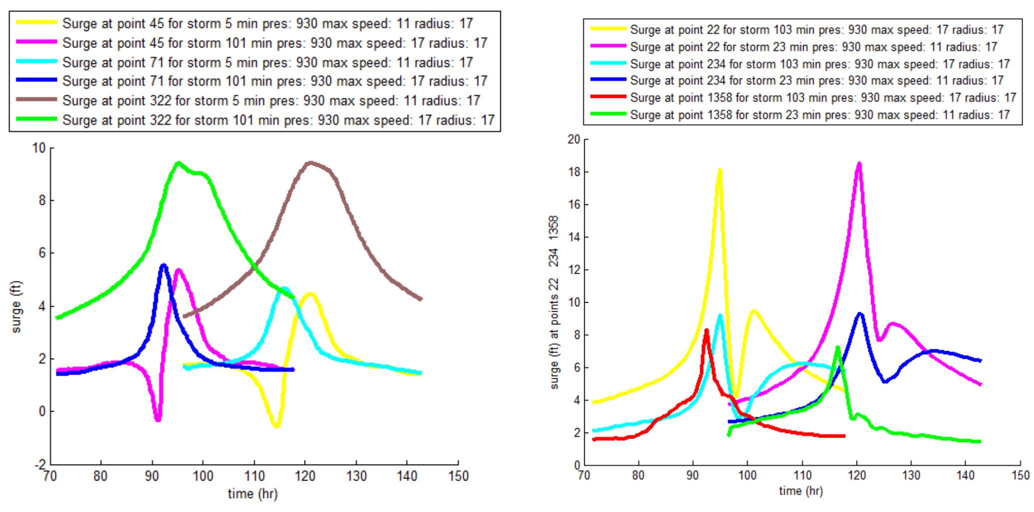

Figure 9: Surge for different central speeds, as expected the central speed has a very small effect on the maximum surge. Points are from the Q835 dta set. The radius and minimum pressure can be read from the graphs.

2.4.3 Pressure

relation between the pressure difference and surge level is theoretically linear, at the open sea, a 100mbar drop in pressure results in a 1m rise of the water level. The pressure effect on storm surge is smaller at a distance further from the center of a hurricane. At the maximum radius of winds the pressure gradient is largest. The pressure differences are highest at the radius of maximum winds, beyond this radius the pressure differences will become smaller. At the center of a hurricane the highest pressure surge will occur.

The pressure at a certain distance r from the center of a hurricane is given by equation 1:

$$p(r) = p_0 + \Delta p \cdot e^{\left[-\left(\frac{r_m}{r}\right)^B\right]} \qquad (1)$$

With p_0 the pressure at the center of the hurricane, Δp the pressure difference between the normal pressure (1013mbar at sea level) and p_0, r_m is the radius of maximum winds, r is the distance to the center of the hurricane. B is the Holland-B parameter. Like the other parameters, the Holland-B parameter is not constant during the lifetime of a hurricane, but it affects the pressure profile and the wind speeds (Vickery & Skerlj, 2006).

The Holland B parameter determines the shape of the pressure profile, a lower Holland B parameter results in a wider pressure profile and smaller pressure differences. For values of the Holland B parameter of 1.0, 1.27 and 1.8 the profiles are shown in figure 10. All the lines in this figure have the maximum gradient at the distance of the radius (in this case 40km), where the wind speeds are highest.

The difference between the pressure at the center of the hurricanes with tracks and surge series shown in appendix 1 is 60mbar. For this pressure difference a decrease in total surge from about 15 feet (about 4,6m) to 7 feet (about 2,1m) can be seen for respectively storm 18 and 11 at point 316. The normal difference in storm surge, for an offshore location would be about 2 feet (60cm) for a pressure difference of 60mbar. Therefore it can be concluded that due to the local bathymetry the effect on storm surge is increased compared to the expected linear effect on storm surge, this phenomena will be discussed in the next paragraph.

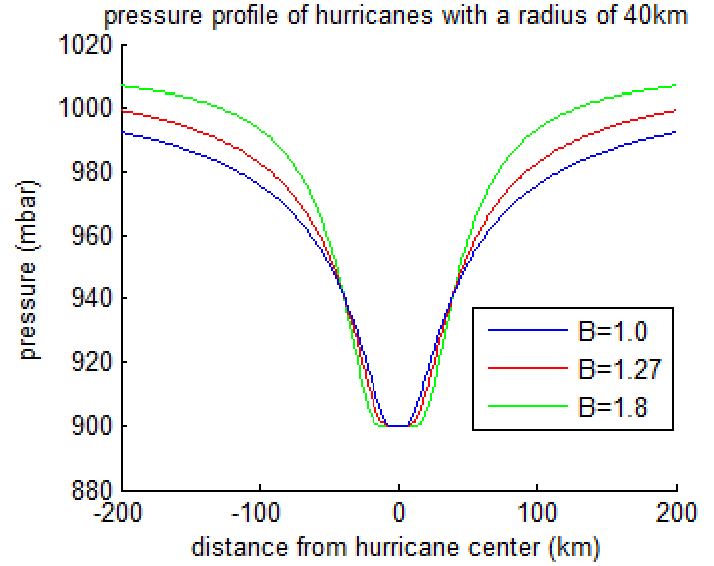

Figure 10: pressure profiles for different values of Holland B parameter. (p_0=900mbar, dp=113 mbar, r_m=40km)

2.4.4 Location specific parameters

When the maximum surge levels of the storms are examined more closely, it becomes clear that there is a large difference between the points west from the Mississippi and east from the Mississippi (see figure 14 at the next page). This will make it very difficult to predict the surge levels with a global model in which the surge levels for all locations have the same relation with wind speed and pressure. Consider a location in a global model which has almost the same distance to the storm track, the wind speed and pressure difference is thus almost the same. But the storm surge levels for these locations can show large differences. For this reason location specific information about, for example, the local bathymetry has to be taken into account.

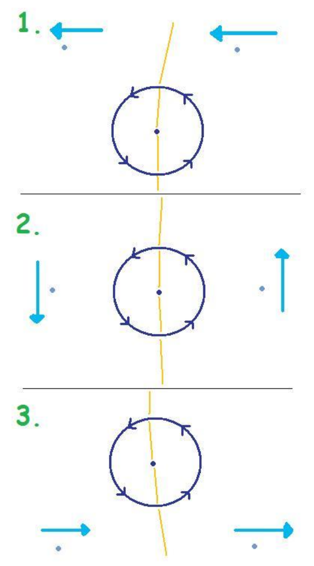

Figure 11: Changing direction of the winds for storms passing a location to the east or to the west. Because of this difference a difference in maximum surge levels are expected for storms passing a location to the east or to the left. The dots are the locations where the wind direction is given. The direction is shown by the arrows. The track is the orange line. The blue circle represent the hurricane.

First of all, there is a difference between a storm track passing east or west, see figure 11. Points east and west from the storm track will mainly have westerly winds before the storm passes. At the moment the storm passes wind will change direction to the north for points to the east of the storm track and to the south for points to the west of the storm track. When the storm has passed wind will blow mainly to the east.

So storms passing to the west of a certain location have a relatively larger net wind to the north. Since the coast of Louisiana and New Orleans has the sea to the south, the wind will create larger surges when it is directed to the north. A wind to the south will mainly push the water into the open ocean, it will not contribute to a larger storm surge. Therefore a difference in maximum surge levels should be seen for points east or west from the storm track. Points east of the hurricane track overall experience a larger maximum surge.

When storms 9 and 111, with a comparable maximum surge, are more closely examined, important differences come to attention. The point and the tracks of storms 9 and 111 can be seen in figure 13. The surge series for these storms at point 601, an offshore point, can be seen in figure 12.

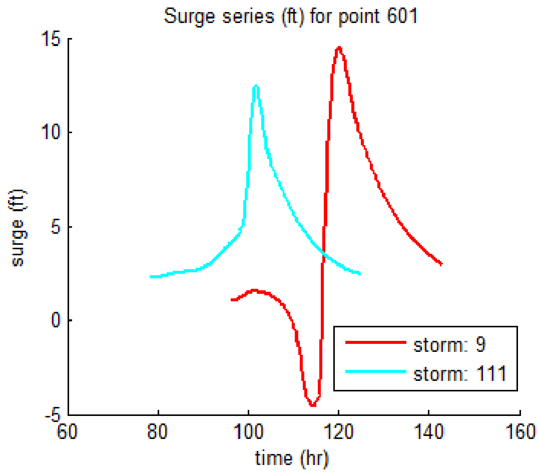

Figure 12: Surge for storms 9 and 111

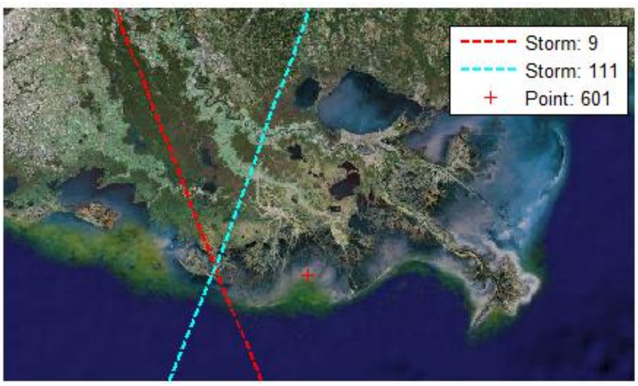

Figure 13: Tracks of storms 9 and 111, and location of point 601 from the Q835 data set.

What causes this large difference with respect to the storm track? The direction of the wind is the main reason for this. The surge series show that for storm 9 the wind will change direction, firstly the surge will become smaller (even negative) because the wind has a positive component directed to the south (the wind is directed to the southwest before the storm makes landfall). This is causing the first dip in the storm surge levels. After that the wind will change direction to the north when the storm is passing the location to the west. This will cause a large storm setup, since the wind is now directed to the coast. The peak of storm 111 is a earlier because this storm has a higher central speed than storm 9. It is noted that the peak of storm 111 is significantly lower because the direction of the wind is not optimal for a large surge.

Normally the maximum surge would be found at a distance equal to the radius of maximum wind, but due to local effects this cannot be seen in practice. As can be seen in figure 14, the points where the surge is highest are on the east side of the Mississippi levees. The water will be pushed up against these levees. This is why certain location specific parameters have to be used when predicting storm surge. These location specific parameters take into account the local bathymetry and obstacles nearby.

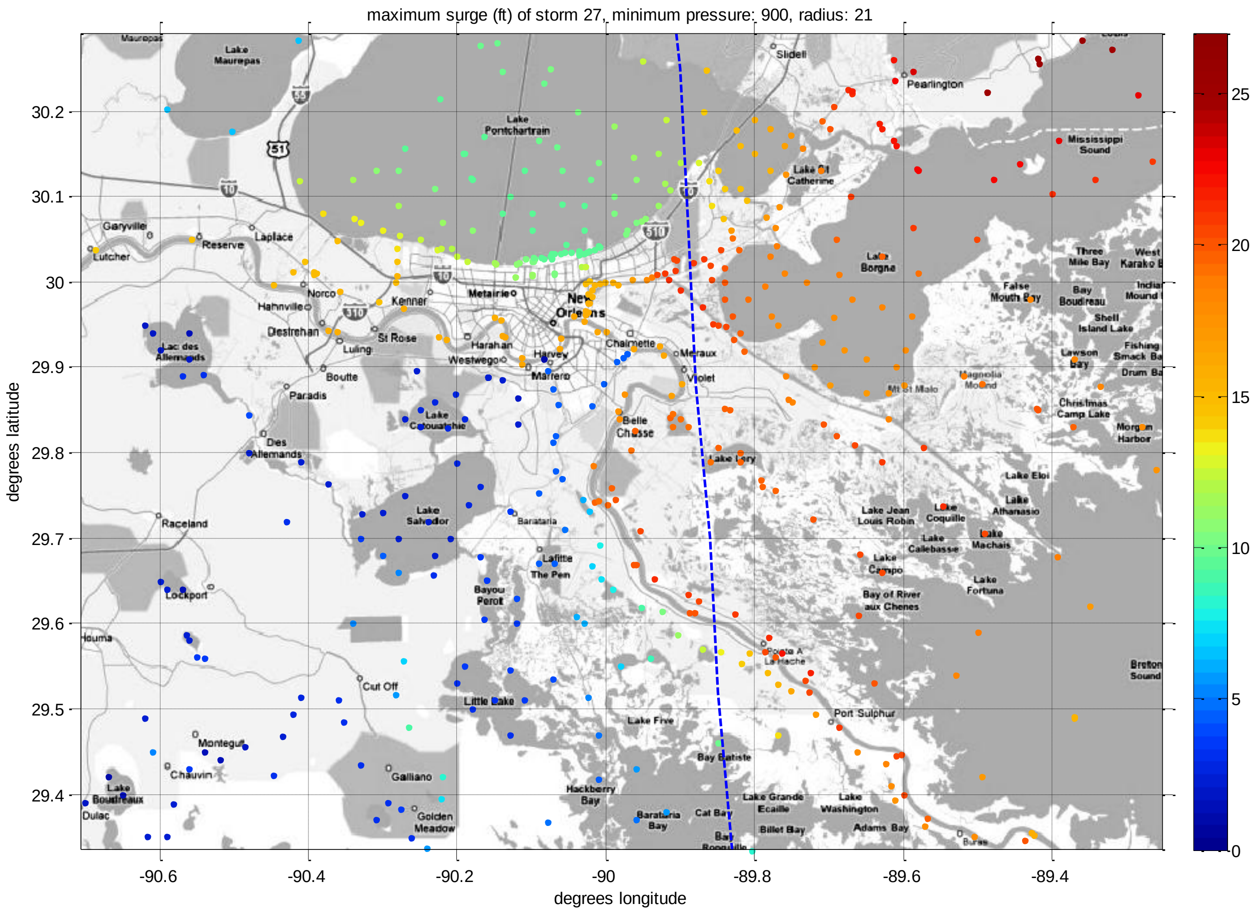

Figure 14: Maximum surge levels for storm 27, for reference, New Orleans is located at -90,30. The large red line is the east bank of the Mississippi River. Large differences between the east and west bank can be seen.

3 Data and ADCIRC model description

3.1 ADCIRC Model

ADCIRC is a computer program that calculates the free surface elevation of a water body due to tides, storms, river discharges and more. To compute the free surface elevation, ADCIRC uses the depth integrated shallow water equations. It is a numerical model, calculating the water level elevation over small time steps and small distances using finite element and finite difference techniques. (Luettich & Westerink, 2006)

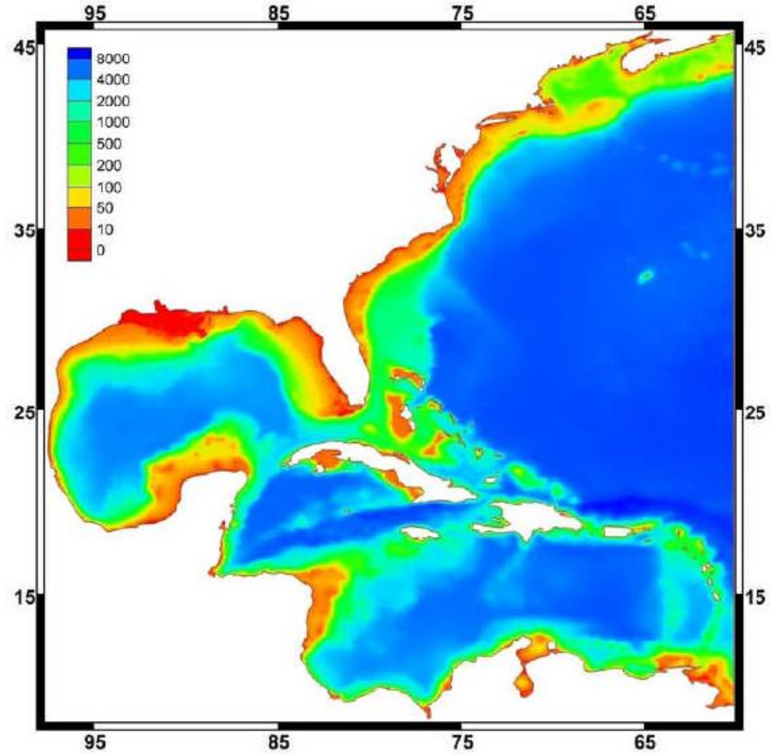

Figure 15: bathymetry of the domain of the grid used for the 152 storms (Federal Emergency Management Agency [FEMA], 2008)

The high detail of the grid in the Louisiana and Mississippi region is very useful for application in the New Orleans area. Sometimes the nodes are less than 100 feet apart and 90% of the nodes are in this region. This allows very accurate predictions, while the lower detail of the grid in the other regions that are not of particular interest save a lot of computational effort. The model grid covers the entire Gulf of Mexico and has boundary conditions in the Atlantic Ocean. Because the boundary conditions are set in the Atlantic Ocean, it is not necessary to have ad-hoc boundary conditions. The large size of the grid with the boundary conditions set far away allow accurate calculation for the states of Louisiana and Mississippi. An overview of the entire domain, with its bathymetry is given in figure 15. (FEMA, 2008)

All the levees, lakes, canals and other structures that are hydraulically important (that enhance storm surge) are incorporated in ADCIRC. The wetlands and rivers that affect storm surge are also modeled. Levees and other structures that have a certain height (such as road or railroads that are heightened) are modeled as weirs. Otherwise it would require a much higher spatial resolution. (FEMA, 2008)

The water surface elevation is referenced to NAVD88, the North American Vertical Datum of 1988. Which is a sound reference for the calculation when corrected for LMSL (Local Mean Sea Level). The difference between LMSL and NAVD88 is on average 0,44 ft for Southern Louisiana. At a longer term, the thermal heating of the ocean can cause the water to expand in the summers, while it cools down in the winters. Other factors like the salinity, riverine runoff, and pressure are also taken into account. For this reason the 152 fictional storms get another 0,66 ft extra above the NAVD88 level. The tide, which has a very low amplitude with a maximum of about 3ft, is also taken into account in the modeling (FEMA, 2008).

In order to validate the ADCIRC model, a Katrina hindcast was done and a selection of high water marks (maximum water levels) were compared to the ADCIRC model results. The R^2 of the results was over 0,93 for different high water marks data sets. The model predicted the maximum water levels within ±1.5 feet at about 69% of the location and within ±3.0 feet at 97 percent of the high water mark locations. (FEMA, 2008)

3.2 Storm and surge series

3.2.1 Storm series

152 hypothetical storms are calculated with the ADCIRC model. These storms are chosen in order to cover the full range of expected storms that could affect the Louisiana / New Orleans area. The tracks of the 152 fictional storms with their corresponding tracks are shown in figure 16.

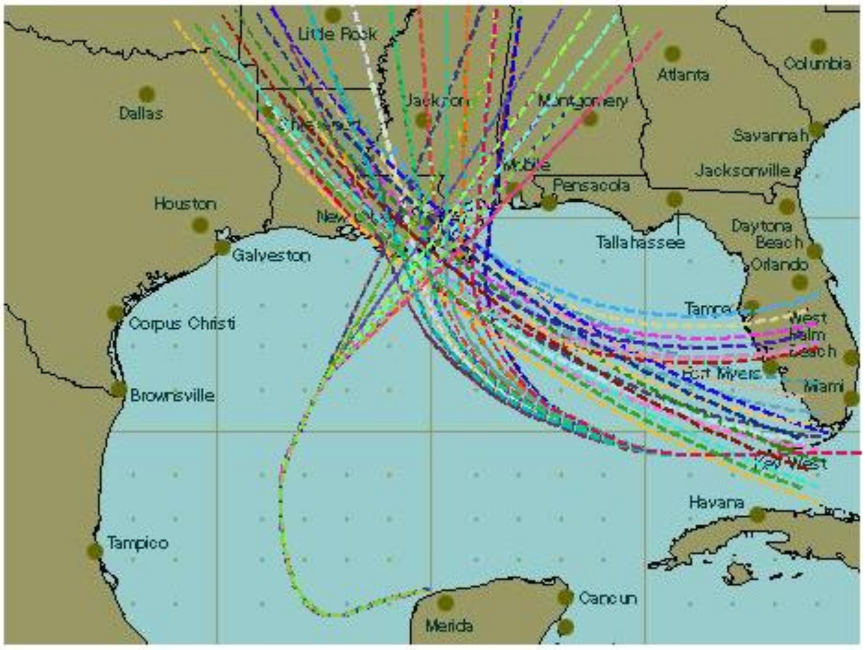

Figure 16: Storm tracks of the storms in the data set. They are chosen to cover the whole range of expected storms that could pass New Orleans.

The hurricane characteristics are provided in a table with data about the storm number, the track number, the minimum pressure, the central speed and the radius of maximum winds. The Holland-B parameter for the storms is also given. The storms are numbered from 1 to 162. This means ten storms have no data. In the table with the storm information the minimum pressure, radius and all other parameters are given the value of -999 for these 10 storms.

The storm tracks of these 152 storms are defined in another file. The pressure and radius, just like the central speed and Holland-B parameter can vary very quickly over the storm track, for every time step the data of these parameters is given. The storms are defined over a number of locations, this number lies between 55 and 156, with an average of about 100 time steps. The track of the storm is given in longitude and latitude coordinates.

3.2.2 Surge data

The data of the surge series is given for various locations. The locations are divided into three sets, the D1479 set, the Q835 set and the L274 set. For these sets data about the surge level over time and the maximum surge levels are given. The first set is the D1479 set, with 1479 points near the levees of the Mississippi River and the levees of Lake Borgne and Lake Pontchartrain. The second set is the Q835 set, used as a quality control set containing 835 points located in the wetlands to the south of New Orleans, points near the coast and points close to or in New Orleans and Lake Pontchartrain and

Lake Borgne. The third set is the LACPR (Louisiana Coastal Protection and Restoration) set, or L274 set, with 274 points near the coast and the lakes and in the wetlands.

For every storm, a file with the surge over time is given for all the points of 1 data set. In total 456 files with the surge series for the 152 storms for the 3 data sets. For the Q835 data set the series are given in quarters of an hour and for the other sets the data is given in half hours. Not for all points is information available at all times, for some points no information at all is given. The surge at those times is equal to -999ft. And for some points the surge is always -999ft, these points remain dry. The points can be identified by a number, or by the longitude and latitude coordinates of the points.

3.2.3 Other data

Other data that is included are maps with data about the storm tracks (see figure 17), files with maps of the wind speed and direction at landfall (see appendix 2) and maps of the maximum wind speeds around the track of the hurricane over time of the 152 different fictional storms. Also maps of the points of the different data sets are given, with the same numbers used in the surge series. These can be used to easily locate and identify important points.

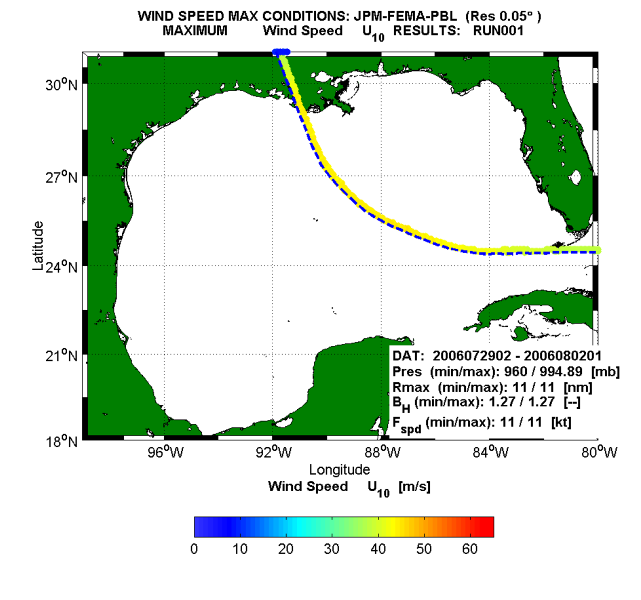

Figure 17: Example of figure of the storm track information, in this case for storm 1. The minimum and maximum pressure, radius, Holland-B and central speed are also shown. The wind speed (U_{10}) is the colored line next to the dashed line of the storm track.

4 Storm Surge Prediction

In order to be able to give reliable predictions, it is necessary to find the best parameters that can be used to predict storm surge. The use of the basic hurricane characteristics (radius, central speed and minimum pressure) by themselves did not give satisfying results (See Appendix). Therefore a different approach has been chosen in which different parameters have been used. In this chapter the parameters that will be used in the prediction model for hurricane storm surge in New Orleans will be introduced.

4.1 Prediction model definition

Globally the storm surge of a hurricane consists of a surge due to the pressure effect (pressure surge) and a surge due to the wind forcing the water in one direction (wind surge). These two parameters will be used to predict the total storm surge. The model is thus based on the following equation:

$$\Delta h_{model} = H_0 + \Delta h_{wind} + \Delta h_{pressure} \qquad (2)$$

Equation 2 states that the total model storm surge ($\Delta h_{mode\,l}$) is the sum of a minimum surge level, H_0, a pressure surge ($\Delta h_{pressure}$) and a wind surge (Δh_{wind}). Most of the time a minimum surge level of about two feet is found, this phenomenon is described in paragraph 3.1 and is the reason for the parameter H_0. Due to local circumstances this parameter value can vary. The parameter used to calculate the pressure surge, $\Delta h_{pressure}$, is based on equation (1) at a certain distance r from the center of the hurricane, is explained below.

The basic hurricane characteristics; the minimum pressure, radius of maximum winds, central speed and Holland-B parameter can be used to calculate the wind speeds around a hurricane. This will introduce one single parameter, the wind speed, that has all the other parameters in it. How the wind speed is calculated, used to calculate the wind surge and how the correlation with the storm surge can be improved is also explained below and in paragraph 4.2 and 4.3.

The pressure and the wind speed are correlated, higher wind speeds are caused by a lower pressure, but this correlation will be neglected for this research. This could also be solved by only using the wind speed as a prediction parameter, but linear regression gives better results when more (not perfectly correlated) parameters are used (Davis, 2002, p469). Therefore both the pressure and the wind speed are chosen as the parameters to use for the prediction model.

The difference in pressure between the center of the hurricane and the pressure at a certain location can be calculated using equation (1):

$$p(r) = p_0 + \Delta p \cdot e^{\left[-\left(\frac{r_m}{r}\right)^B\right]} \qquad (1)$$

A lower pressure will result in a higher storm surge. The relation between the pressure and maximum surge level is assumed to be linear. The difference between the normal pressure at sea level (p_{normal} = 1013mbar) and the pressure calculated at the location of interest is taken as the parameter to predict the storm surge. Δp is the difference in pressure between p_0, the minimum pressure at the center of the hurricane, and the normal pressure at the sea level. The difference between the normal pressure and the pressure at a location a certain distance r away from the center of the hurricane then becomes:

$$dp(r) = p_{normal} - p(r) = p_0 + \Delta p - \left(p_0 + \Delta p \cdot e^{\left[-\left(\frac{r_m}{r}\right)^B\right]}\right) = \Delta p - \Delta p \cdot e^{\left[-\left(\frac{r_m}{r}\right)^B\right]} \qquad (3)$$

The pressure taken to predict the surge will be the pressure at the moment the wind speeds are the highest. This is chosen because of the assumption that the wind driven surge is higher than the pressure surge (see paragraph 2.3). When the maximum pressure would have been used the setup could be overestimated. The pressure at the moment the wind setup is highest could be lower than the maximal pressure since these two do not have to coincide in time. Therefore if the maximum pressure would be taken as a predictor, the storm surge could be estimated higher than it in fact is.

When the wind driven surge is relatively low, the above approach could result in an underestimation of the storm surge. In this case the pressure surge can be higher than the wind driven surge. The maximum pressure will then be taken instead of the pressure at the moment the wind speeds are highest. A threshold for this has been determined. This threshold is based on the wind speed, if the wind speed is relatively low the maximum pressure is taken, if it is relatively higher, the pressure at the moment the wind speed is maximum is taken. The threshold is determined during the calibration of the prediction model, described in paragraph 5.2.

The effect of the wind on storm surge at a certain location can also be calculated. It is assumed that the wind setup is a quadratic function of the wind speed, see equation (4) below. Thus by taking the calculated wind speed to the square, a linear relation between the storm surge due to the wind and the maximum wind speed squared should be present under the assumption that for every point of the three data sets, a single basin with constant length and depth exist.

$$\Delta h_{wind} = F_{set-up} \cdot c \cdot \frac{V_s^2}{gd} \qquad (4)$$

Here, Δh_w is the wind setup, F_{set-up} is the basin length, *c* is a constant, V_s is the surface wind speed, *g* the gravity constant and *d* the average basin depth (Klaver, 2005).

Because the surface wind speed does result in high correlation between the maximum surge and the calculated pressure and wind setup, the 'dominant wind speed' and 'time-averaged wind speed' concepts will be introduced. These require the wind speeds around the center of a hurricane, called the gradient wind field, which is explained in paragraph 4.2.

The use of equation (4) is important because this implies that a linear relation between the wind speed squared and the storm surge exists. The relation between the pressure difference and the storm surge is also assumed to be linear. Therefore it is possible to use multiple linear regression to determine the relation between these two parameters and the total storm surge.

4.2 Gradient wind field

The equations to calculate the gradient wind field are the following:

$$\frac{1}{\rho}\frac{\partial p(r)}{\partial r} = \frac{V^2}{r} + fV \qquad (5)$$

With ρ the air density [kg/m^3], $\frac{\partial p(r)}{\partial r}$ the slope of the pressure profile, V the wind speed (m/s), r the distance to the center of the hurricane (m) and f the coriolis parameter (Vickery, 2000).

The equation of Blaton describes the radius of a moving air 'particle' . The trajectory of such a moving air particle is not circular because of the forward speed of a hurricane (Klaver, 2005) & (Vickery, 2000).

$$r_t = \frac{r}{1 - \frac{c}{V}\sin(\emptyset)} \qquad (6)$$

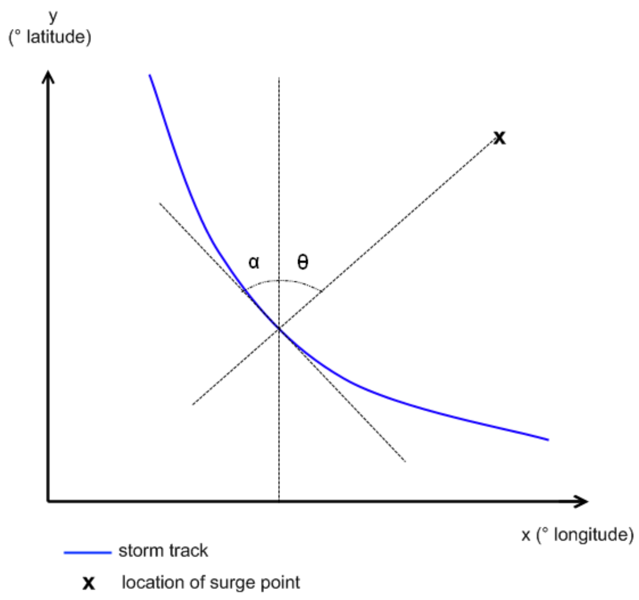

Figure 18: determinination of the angle $\emptyset$ used in equation 6. In the Matlab scripts used the angle is defined as $\emptyset$ = θ – α. These angles are defined positive clockwise.

With r_t the Blaton adjusted radius of curvature and Ø the angle between the hurricane movement vector and the radius vector, c is the central speed.

Combining equations (1) and (5) and using the Blaton adjusted radius r_t for r, and substitution r (as in equation (6)) results in the following equation for the wind speed (Vickery, 2000):

$$V = \frac{1}{2}\cdot(c\sin(\emptyset) - fr) + \sqrt{\frac{1}{4}(c\sin(\emptyset) - fr)^2 + \frac{B\Delta p}{\rho}\cdot\left(\frac{r_m}{r}\right)^B \cdot e^{\left[-\left(\frac{r_m}{r}\right)^B\right]}} \qquad (7)$$

The angle Ø = θ – α, with θ and α both positive clockwise, is shown in figure 18. Again, p_0 is the pressure at the center of the hurricane [Pa]. Δp the pressure difference between the normal pressure (1013mbar at sea level) and the minimum pressure [Pa], r_m is the radius of maximum winds [m], r is the distance [m] to the center of the hurricane (not the blaton adjusted radius). B is the Holland-B parameter [-]. ρ is the air density [kg/m^3], V the wind speed (m/s), f is the coriolis parameter [-] and c is the central speed [m/s]. Note: [Pa] = [kg m/s^2]

Since the locations of the points of the storm track and the locations of the points of the data sets are given in longitude and latitude coordinates, an equation to find the distance between two points is needed. The following equation allows the calculation of the distance between two points with coordinates in latitude and longitude (Great Circle Distance, n.d.):

$$R\Delta\hat{\sigma} = arctan\left(\frac{\sqrt{\left(\cos\emptyset_f \sin\Delta\lambda\right)^2 + \left(\cos\emptyset_s \sin\emptyset_f - sin\emptyset_s cos\emptyset_f cos\Delta\lambda\right)^2}}{sin\emptyset_s sin\emptyset_f + \cos\emptyset_s \, cos\emptyset_f cos\Delta\lambda}\right) \qquad (8)$$

In which $\emptyset_s, \lambda_s;\ \emptyset_f, \lambda_f$ are the latitude and longitude of points *s* and *f* (or "standpoint" and "forepoint"), respectively. $\Delta\lambda$ is the longitude difference and $\Delta\hat{\sigma}$ the angular distance. Multiply this last one by the radius of the earth (R = 6372.795km) and the distance between two points will be found.

The angles θ and α are calculated with the following equation:

$$\theta = \tan^{-1}\left(\frac{d(x)}{d(y)}\right) \qquad (9)$$

Where d(x) is the distance calculated with equation (8) between the location in degrees longitude of the storm track and surge point, d(y) is the distance over latitude. A positive and negative distance can be used, the origin of the axes is at the location of the storm track point.

$$\alpha = \tan^{-1}\left(\frac{d(x_{t+1} - x_{t-1})}{d(y_{t+1} - y_{t-1})}\right) \qquad (10)$$

$d(x_{t+1} - x_{t-1})$ is the distance between the x coordinate of the storm track point at time t+1 and time t-1. This distance is also calculated with equation (8). The same holds for the distance in the y direction, $d(y_{t+1} - y_{t-1})$. With these angles and the data about the pressure, radius and central speed, for the different storms the gradient wind field can be calculated.

In figure 20 the angles θ and α for storm 9, with the track shown in figure 19, are given for point 144, which is also shown in figure 19. The location of point 144 is given by the white marker. The angle α of the track should start at -90 degrees, because the track is heading west, after a while when the track is not heading west anymore, it should slowly go to another angle of about -20 / -30 degrees. This can be seen in figure 21. The angle θ, the angle between the track location and point 144, should start at about -60 degrees, it should be zero when the track is exactly south of this point. After this the angle should become more positive very fast since the track crosses the point quite fast. This can also be seen in figure 20. The line of α is not smooth because of rounding errors in theinterpolation of the storm track locations.

Figure 19: path of storm 9 and location of surge point 144

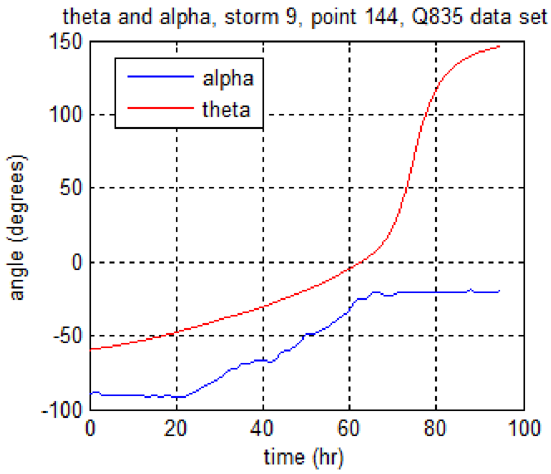

Figure 20: angles alpha and theta for storm and surge point of figure 23.

In equation (7) the speed calculated is the gradient wind speed. In order to translate this to a surface wind speed a multiplication factor 2/3 is normally used (Klaver, 2005). This will result in wind speeds that compare well with the wind speeds calculated with the ADCIRC model. The shape of the field is also in good comparison with the ADCIRC wind data. In appendix 3 these wind fields from ADCIRC are shown.

In figures 21 and 22, showing the surface wind fields of two storms, the angles used are equal to the angles at the moment the storm reaches the "shore". The shore is defined as a straight line at 29.5 degrees latitude. The maximum surface wind (the gradient wind multiplied by 2/3) calculated with formulas above is equal to 41,3 m/s for storm 162 and 47.2 m/s for storm 49. ADCIRC calculated 43,9 m/s for storm 162 and 46,3 m/s for storm 49.

The differences can be explained because the ADCIRC values are not given for the moment the storm track crosses the "shore". Another reason for this could be that the factor 2/3 that is taken to calculate the surface wind is an average value. This factor will be higher over sea (storm 162 has the maximum winds over sea) and slightly lower over land (storm 49 has the maximum winds over land). This could be why the maximum wind of storm 49 gives a slight over estimation and why the maximum wind of storm 162 gives a slight under estimation. At a distance of about 200km to the east of the storm track location the wind speed calculated for storm 49 is about 22,3 m/s, for storm 162 the calculated wind speed is about 19 m/s. From the figures in appendix 3 can be seen that at a distance of 200km east of the storm track location (where 100km is just over 1 degree longitude) the ADCIRC wind speeds for storm 49 is about 23 or 24 m/s, for storm 162 the ADCIRC wind speed is about 19 – 20 m/s. These comparisons make clear that the estimations of the surface wind speeds are quite well.

The relation between the gradient wind field and the two concepts of the dominant wind speed and the time-averaged wind speed will be introduced in the next two paragraphs.

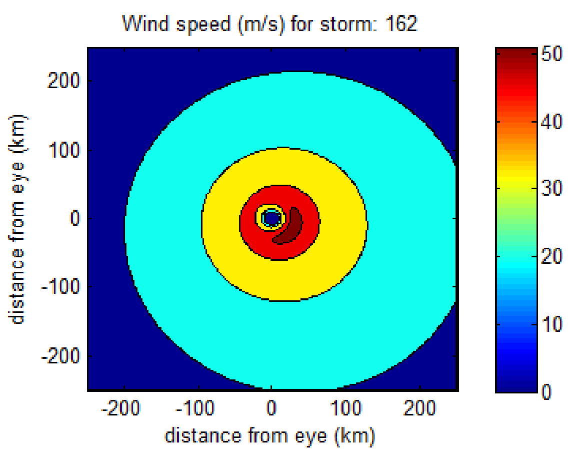

Figure 21: wind field for storm 162

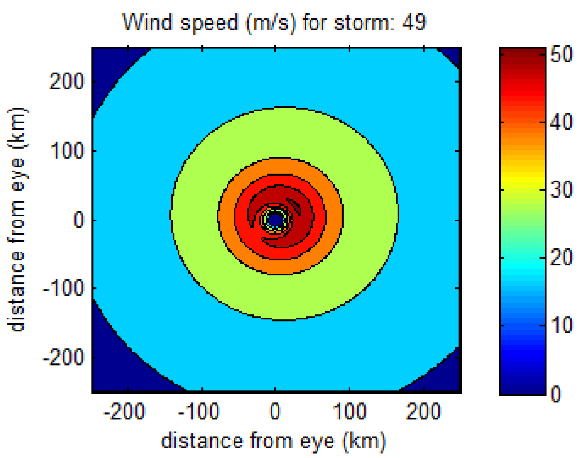

Figure 22: wind field for storm 49

4.3 Dominant time-averaged wind speed

Since local bathymetry is of big influence on the maximum surge levels, for example the presence of the Mississippi levees, the surge built-up can be relatively large *when the wind is in the right direction.* Therefore the concept of the dominant wind direction is introduced. For an offshore point, it is expected that the wind in the northern direction is causing the largest surge levels, since the wind in the direction of the shore will cause the highest surge levels. For a point on the west bank of the Mississippi levees a wind blowing to the east causes the highest surge levels. The component of the wind in a direction that is expected to be dominant, or **the dominant wind speed V_d** can be calculated. For this the direction of the dominant wind, or as it will be called from now on, the *dominant wind direction* β, is needed. This direction has to be defined for every location where predictions of the surge need to be made. The values will be determined during the calibration of the prediction model in paragraph 5.2.

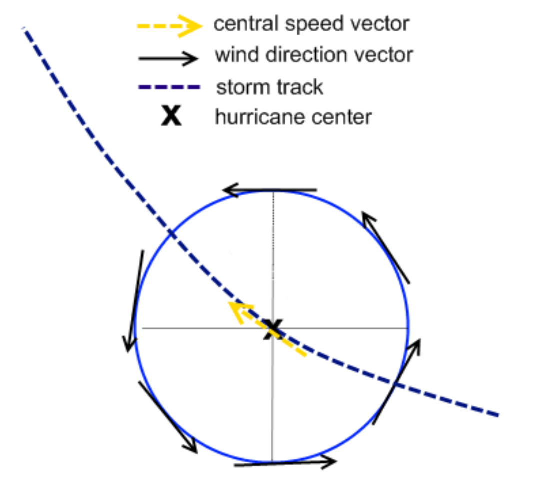

Figure 23: Wind direction vector of 'stable' hurricane and central speed vector. With these two vectors the wind direction can be calculated

The component of the dominant wind direction is calculated from the surface wind at that location. The direction of the wind in the gradient wind field has not been determined yet. For this, some assumptions are made. The wind direction to the north of a hurricane is assumed to be to the west. The wind direction to the west of a hurricane is thus assumed to be to the south, to the south of a hurricane the wind direction is eastern and to the east of a hurricane the wind is expected to be northern. See figure 23.

The angle of the dominant wind direction is defined as the angle between a vector to the north from the point of interest (the point where the wind is calculated) and the vector of the wind direction, positive counter clockwise. See figure 24. The surface wind direction in the gradient wind field is a function of θ. The angle of the wind direction is equal to $\theta - 90$ degrees. The angle is defined 0 degrees for wind to the north, and 90 degrees for wind to the west etc.

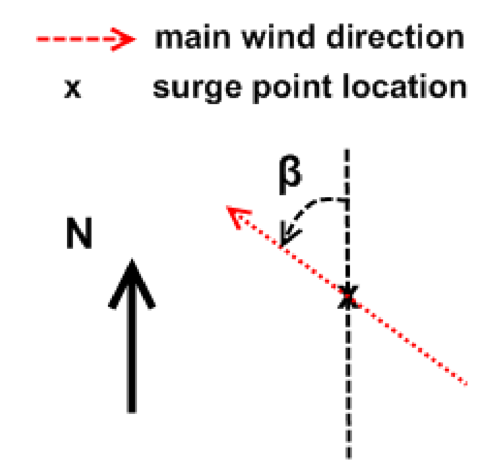

Figure 24: angle of dominant wind direction

The component of the surface wind speed in the direction of the dominant wind, defined as the dominant wind speed V_d is then equal to:

$$V_d = sin(\theta + \beta) \cdot V_s \qquad (11)$$

For θ = 0°, the surge point location is exactly north of the storm track, and the wind direction at that location is to the west, as can be seen in figure 24, for β = 90°, when the dominant wind direction is defined to the west which means that there will probably be a levee or another obstacle west of the surge point location, V_d will be equal to V_s. This is correct since the surface wind is in the same direction as the dominant wind direction. Now consider a point to the east of the storm track (θ = 90°), the direction of the surface wind vector is to the north. And consider that for this location the main wind direction is defined to the northwest (β = 45°). This would result in $V_d = \sin(90+45) \cdot V_s = 0{,}707\ V_s$. This is also correct, the component of vector to the north, in the northwestern direction, is equal to $1/\sqrt{2}$ times the value of the vector to the north. This can for example be derived with the Pythagoras equation.

Since surge levels are built up over time, and the dominant wind speed over a certain time will contribute to this effect, it is useful to integrate the dominant wind speeds over a certain amount of time steps. **The dominant time-averaged wind speed** can then be calculated by dividing the sum of the dominant wind speeds over the amount of time steps. The wind speed will be averaged over the time steps between the time step of the highest dominant wind speed, $t=t_{max}$, and the time step $t=t_{max}-t_{int}$. t_{int} = the number of time steps over which the dominant wind is time-averaged (int stands for integrated). The time steps are defined as t=0 at the location where the first storm track location is given, for every next location where the storm track is defined, t is 1 higher. The storm tracks are given for anything between 55 and 156 locations, with an average of about 100 locations per storm track (see paragraph 3.2.1). This means that t is defined, for a storm track given over 100 location, from t=0 to t=99. The time-averaged dominant wind speed $V_{d,int}$ then becomes:

$$V_{d,int} = \sum_{t=t_{max}-t_{int}}^{t=t_{max}} \frac{V_d(t)}{t_{int}} = \frac{1}{t_{int}} \sum_{t=t_{max}-t_{int}}^{t=t_{max}} V_d(t) \qquad (12)$$

The dominant wind can be calculated for every point of the storm track location, this will give the dominant wind over all of the time steps $V_d(t)$. The maximum dominant wind is found at time step t_{max}. How to determine the optimal number of time steps over which to integrate is explained in paragraph 4.3.

Another reason why the time-averaged dominant wind speed improves the results is that it better captures hurricanes with a larger radius. As stated before, hurricanes with a larger radius have a lower maximum wind speed, but the surge levels are higher. These surge levels are higher because a larger body of water is put into motion over a larger period in time.

A larger radius means higher wind speeds further away from the hurricane center. Therefore an approaching hurricane with a large radius will have high wind speeds earlier than a hurricane with a small radius (given equal central speeds). By averaging the wind speeds over time, the effect of a larger radius is thus taken into account because the (higher) wind speeds at some time before the maximum wind speed occurs, are contributing to a higher dominant time-averaged wind speed. Thus resulting in a higher maximum surge than a hurricane with a smaller radius but higher maximum wind speeds.

In this chapter the parameters used for the prediction model were defined. In the next chapter the Prediction model itself will be introduced, the calibration of the model will be explained and the interface will be presented.

5 Prediction model

5.1 Description

Using the surge predictors from the previous chapter, the total setup can be calculated for every different point. The local bathymetry, which has a large influence on the storm surge levels has not been taken into account, except in the dominant wind speed. The maximum surge level at location X is assumed to be linearly related to the maximum of the dominant time-averaged wind speed to the square for that location at t=t_{max} ($V_{d,int}^2$ (t_{max})) and the pressure difference at that time for location X ($dp(r)\ at\ t = t_{max}$). If the dominant time-averaged wind speed is relatively low the maximum pressure difference will be taken instead of the pressure difference at t=t_{max}. The total storm setup was defined as the sum of a minimum surge level H_0, the wind setup and the pressure setup. Using the parameters described in the previous chapter the model setup can be defined as follows:

$$\Delta h_{model} = H_0 + \Delta h_{wind} + \Delta h_{pressure} = H_0 + A \cdot V_{d,int}^2 + B \cdot dp(r) \tag{13}$$

It is assumed that the local bathymetry can be described by the parameters A and B in the prediction model formula (equation 13). A and B are coefficients containing information about how the maximum surge and the pressure difference and surface wind speed (to the square) relate. For coefficient A this is evident because it replaces the parameters in equation 4, these parameters defined a certain basin length and a certain basin depth. Because these are different for every single point they have to be determined individually for every single point in the data set. These coefficient thus contain information about the local bathymetry, and other obstacles present locally. The coefficients H_0, A and B can be found using multiple linear regression.

To calculate the pressure difference and wind speeds at the locations of the prediction model (defined by a longitude coordinate (x) and latitude coordinate (y)) the following input is needed: the storm track, the minimum pressure at the center of the hurricane, the radius of maximum winds, the central speed and the Holland-B parameter (which will be most of the time equal to 1,27).

For every output point (x,y) of the prediction model, the dominant time-averaged wind speed and the pressure difference are then calculated, for every position of the storm along its track. This will result in series for the wind speed over time (as the storm propagates along its storm track locations) and a series for the pressure difference over time. The maximum dominant time-averaged wind speed at t equal to t_{max} is taken, together with the pressure difference at t=$t_{max.}$ The maximum pressure difference is taken if the wind speed calculated is lower than the wind threshold specified (see next paragraph). Together with the H_0, A and B values found during the calibration of the model, which also will be explained in the next paragraph, the storm surge can be calculated for every single location.

In appendix 5, a scheme is presented in which the steps taken to calculate the surge levels are shown. In the next paragraph the calibration of the model will be discussed.

5.2 Calibration

5.2.1 Dominant wind direction

The calibration of the model parameters, H_0, A, B, β (dominant wind direction), t_{int} (integration time) and the wind speed threshold (from now on called V_{limit}) is an iterative process. Since the dominant wind direction in general gives the best improvements of the R^2 value of the predictions, the points will be calibrated for this parameter first.

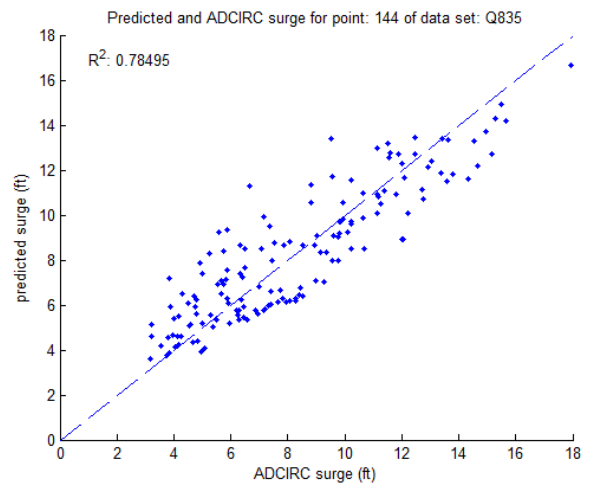

Figure 25: ADCIRC surge versus predicted surge, when the surface wind to the square and the pressure difference from normal pressure (see paragraph 4.1.2) are taken as the predictors of the maximum storm surge.

This has been done as follows. For every location of the prediction model, all possible "dominant" wind directions are tried. This will result in 360 different series for the dominant wind speed over time, since every possible angle (with an integer value) has been tried. From all these series, the maximum dominant wind speed can be found. The time $t=t_{max}$ of the maximum is stored and the pressure difference at that time is also stored. With these values for the dominant wind speed and pressure difference – still for every possible direction – a multiple linear regression can be used to determine the optimal values for the coefficients A, B and H_0. For this calculation values of t_{int} and V_{limit} equal to 0 are used. With these coefficients predictions can be made of the surge for the 152 different storms, these can be compared with the ADCIRC surge. When they are compared the R^2 value of the predicted surge and the ADCIRC surge can be calculated. This will result in 360 different R^2 values. The dominant wind direction is chosen as the direction in which the R^2 value is the highest. This direction is stored for further use. In appendix 6 these steps are schematically presented.

How much does the dominant wind direction improve the predictions? The graph in figure 25 is obtained when using the maximum surface wind speed occurring at the specific output location as derived from the gradient wind field. This value is the highest value that can be found for the dominant wind speed because a component of the wind speed in a direction that is not exactly equal to the dominant wind direction will always be smaller than the surface wind speed. The graph is obtained for point 144 of the Q835 dataset.

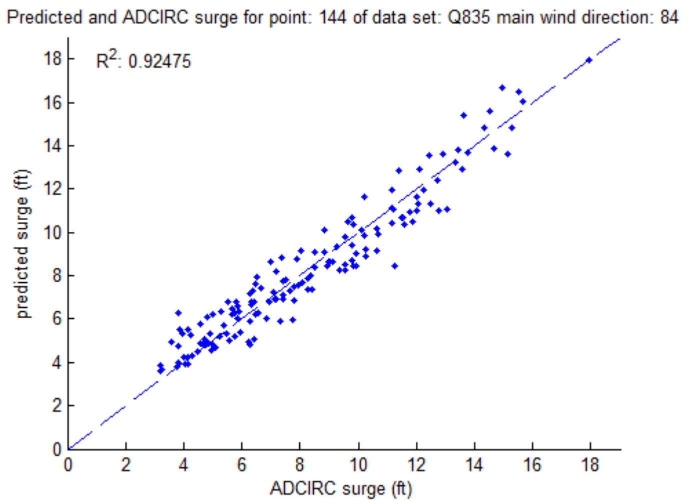

Figure 26: comparison of predicted and ADCIRC surge using the dominant wind direction found.

When the surface wind speed in the dominant wind direction is used (not the dominant time-averaged wind speed) the graph in figure 26 is the result. The main wind direction found is 84 degrees, which means a wind almost completely to the west. This is logical considering the situation at the western shore of Lake Pontchartrain of this point (point 144 of the Q835 data set). Most importantly, it can be seen that there is a large improvement of the R^2 value and the predictions.

5.2.2 Other parameters

The other parameters (t_{int} and the wind speed threshold V_{limit}) also need calibration, this is where the calibration process becomes an iterative process. The next parameter that is calibrated is t_{int}, the integration time. When the dominant wind direction is known for a certain surge point, different integration times can be tried and the R^2 values can be compared. Note that the optimal dominant wind direction can change slightly when using different values for the integration time.

The concept of the time-averaged dominant wind speed does not improve the predictions for every point. Point 144 of the Q835 data set already has a relatively high R^2 value when only using the dominant wind speed, for this point no improvement can be seen by taking the time-averaged dominant wind speed. For other points a large improvement can be seen, especially points where the R^2 value is relatively lower. For example, points near the southern shore of Lake Pontchartrain were very hard to predict well using the dominant wind speeds. Point 644 of the Q835 data set is a good example of this. The R^2 value of this point, with a main wind direction of 94 degrees is just below 0,60. When the time-averaged dominant wind speed is taken as a predictor, instead of the dominant wind speed, the R^2 value can become as high 0,89. An optimal number of steps over which to integrate the wind speeds is found to be 24 for this point (which in case of the 152 fictional storms is the same as 24 hours).

The wind speed threshold (V_{limit}) is estimated to be 24 m/s for all points (Note that this value is not optimized, different values have been tried and this value is estimated to give the best results). When also taking this wind speed threshold into account the R^2 value of the predictions for the 152 hypothetical storms can even become 0,91 for point 644 of the Q835 data set. The graphs of the improvements of these predictions in surge levels can be seen in Appendix 4.

In order to be able to try the different values fast, a Matlab script is developed where a surge point can be selected, a certain value for t_{int} can be entered together with the dominant wind direction found and the value for the wind limit estimated. The R^2 value for the point selected and for the chosen parameters is the output of the script, together with graphs like in figure 25 and 26. Trying different values, in the wind direction found earlier, will result in higher or lower R^2 values. When the values found don't seem to get any higher, the iterative process stops and the optimal parameter values are stored.

5.2.3 Interpolation of storm tracks

In order to optimize the predictions of the maximum surge, the storm tracks are interpolated. They are interpolated to have about 400 different locations (instead of the 56 to 152 locations where the tracks were defined). This will especially improve the predictions for points close to the storm track. Thus for every 1 of the 400 locations of the storm tracks, for every storm track of the 152 fictional storms, in every dominant wind direction, the pressure difference and dominant wind speed are calculated. In total the wind speed and pressure difference will thus be calculated over 20 million times for every individual point.

When this is done for a certain number of surge points, the values of H_0, A, B, R^2, β_{opt}, t_{int} and V_{limit} for these surge points are stored in a table. It took a laptop almost two days to calculate the coefficient for the Q835 data set points (835 points). Once having obtained these coefficients the predictions of the storm surge levels are relatively fast, within about 10 seconds on an average laptop. For some interesting points the results are shown in table 1.

point	644	590	655	303	350	452	448	462
wind_dir	94	72	70	92	86	94	96	24
int_time	24	12	12	12	6	6	8	6
wind_limit	24	24	24	24	24	24	24	24
H0	2,3629	2,0118	3,8925	3,3159	3,1124	4,6176	3,5686	-0,14947
A	0,008429	0,008517	0,008664	0,009428	0,007172	0,008246	0,011337	0,006299
B	0,043829	0,082203	0,14157	0,075792	0,020753	0,019433	-0,02503	0,081298
R2	0,91624	0,78917	0,79866	0,88445	0,90676	0,91388	0,90665	0,81822

Table 1: Parameters and coefficients found for the predicition model

Note the negative value of B for point 448, which physically would mean that the pressure difference is negatively correlated with the maximum storm surge. The values of H_0 found are also quite different for different surge points. Some of them are close to the value of about 2 foot that would have been expected – since the ADCIRC spin up run will result in a surge of about two foot – but some of them are higher or even negative.

The error of predictions for the different points can also be calculated, when assumed that the errors are normally distributed. Using the standard deviation of the predicted surge minus the ADCIRC surge, the 90% confidence bounds are found by multiplying this standard deviation with 1.64, or 1.96 for the 95% confidence bounds. The values of the 90% or 95% confidence bounds can be found in the Student t-table.

5.3 Prediction Model interface

For the Prediction Model 27 surge points of particular interest were selected. For lake Pontchartrain, points near the southern shore were chosen, a point in the middle of the lake and a point near the 'entrance' of the lake. For Lake Borgne and the V-shaped entrance of the MRGO points near entrance of the MRGO were chosen, some points near the levees of the St. Bernard Polder and New Orleans East polder were chosen and a point in the middle of Lake Borgne was chosen. Furthermore some points offshore, near the wetlands of southern Louisiana were chosen. Some points near the Mississippi levees at the East bank, which always experience high surge levels are also selected. And some points west of the Mississippi levees were chosen, although surge levels usually remain relatively low in these areas.

In order to be able enter an arbitrary storm track and storm parameters a graphical user interface (GUI) was developed. A storm track can be entered by clicking with the mouse on a map. A storm track can also be loaded from a file, or one of the 152 hypothetical storm tracks can be loaded. For the 152 storm tracks the parameters are instantly entered in the model.

When entering a storm track with the mouse (see figure 28), the track will be automatically interpolated to about 400 points, evenly spaced over the track, to have the same amount of storm track locations as the (interpolated) hypothetical storm tracks. This will ensure that the time steps over which the wind speed is time-averaged are equal. This time step is adjusted for the number of times the storm track locations are interpolated. If they are interpolated to have 4 times as much storm track locations, the number of steps over which the integration takes place is also multiplied by 4.

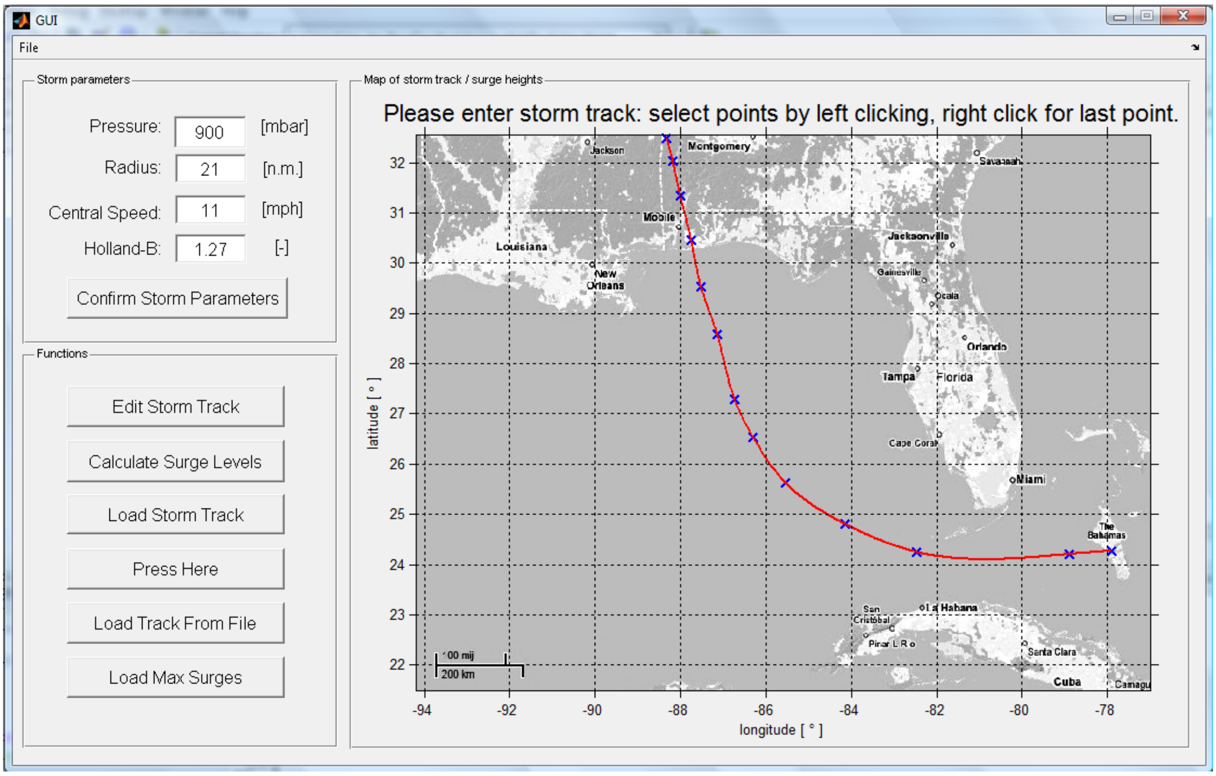

Figure 27: example of how a storm track can be entered into the model

When the storm track has been entered, the storm parameters can be adjusted, after every adjustment the button confirm storm parameters should be pressed. A pressure between 850 and 1013mbar is accepted, a radius of maximum winds between 5 and 50 nautical mile, a central speed between 1 and 30 mile per hour and a Holland B parameter between 0.7 and 1.5 is accepted.

After this the button Calculate surge levels can be pressed, which will present the surge levels of the 27 points of interest chosen. The maximum surge levels, as calculated by ADCIRC, for the 152 fictional storms can also be loaded in order to be able to compare them to the predictions of the model. This can be used to compare the results to the data, although it would be better to compare the results to the surge levels of different storms which are not used in the calibration process.

5.4 Prediction model validation

The prediction model is validated against an ADCIRC simulation of hurricane Katrina, for these predictions a minimum pressure of 902mbar, a central speed of 7mph and a radius of 25nm with a Holland-B parameter of 1.1 were used.

The results are surge levels of about 10-11 foot at the southern shore of Lake Pontchartrain, Just under 20 foot in Lake Borgne near the funnel and at the levees of the St. Bernard Polder. The levees at the east bank of the Mississippi River experience surge levels over 22 foot. The west bank experiences very low surge levels.

When these predictions are compared to the calculated surge levels with the ADCIRC model, the results compare quite well. For the southern shore of Lake Pontchartrain surge levels of about 10 to 12 foot are calculated with the ADCIRC model. The funnel and Lake Borgne have a surge of just under 20 foot. Along the East bank of the Mississippi levees the surge is higher than 20 foot. Note that in figure 29 lake Pontchartrain looks larger than it looks on the map in figure 28.

For the model to be valid, the storm tracks entered should be within the range of the 152 fictional storm tracks. The tracks of these storm make landfall between -92 degrees longitude and the Mississippi / Alabama border. The quality of the predictions for storm tracks entered outside of these ranges is unclear. For tracks making landfall at a distance far away from these borders, the surge levels will be small, and not too important to calculate for the New Orleans area. The surge levels will likely be too high because some of the points start with a minimum surge of 4 foot. For storm close to these boundaries but not within them the surge levels could provide unreliable results because the coefficients A and B might be out of balance for these parameters. The validation for the storms tracks that not lie within these boundaries cannot be done without reliable data.

The parameters entered into the model are calibrated for pressures between 900mbar and 960mbar, a radius of between 6 and 35nm, a central speed between 6 and 17mph and for a Holland-B parameter of about 1.27. The data of the storm tracks contain values for these parameters over the storm track, the values lie within the ranges given here.

For the 152 storms, the difference between the predictions and the ADCIRC predictions, for the points of the prediction model, are in 95% of the cases within 3 foot, in 85% within 2 foot and in 61% of the cases they are within 1 foot from the ADCIRC predictions. The prediction model can thus reproduce the surge levels for the 152 fictional storms quite accurately.

The accuracy of the predictions of the surge levels for an actual hurricane has not been assessed. Accuracy could be different because there are a lot of uncertainties entering a storm track or entering the parameters for the storm. Furthermore the predictions of the ADCIRC model have uncertainty too, and the prediction model itself adds to the uncertainty. A high R^2 does not guarantee reliable results for real storm surge levels. A high R^2 means that the predicted results are close to the ADCIRC predicted results, using the exact same parameters (over time) and track as entered in the model.

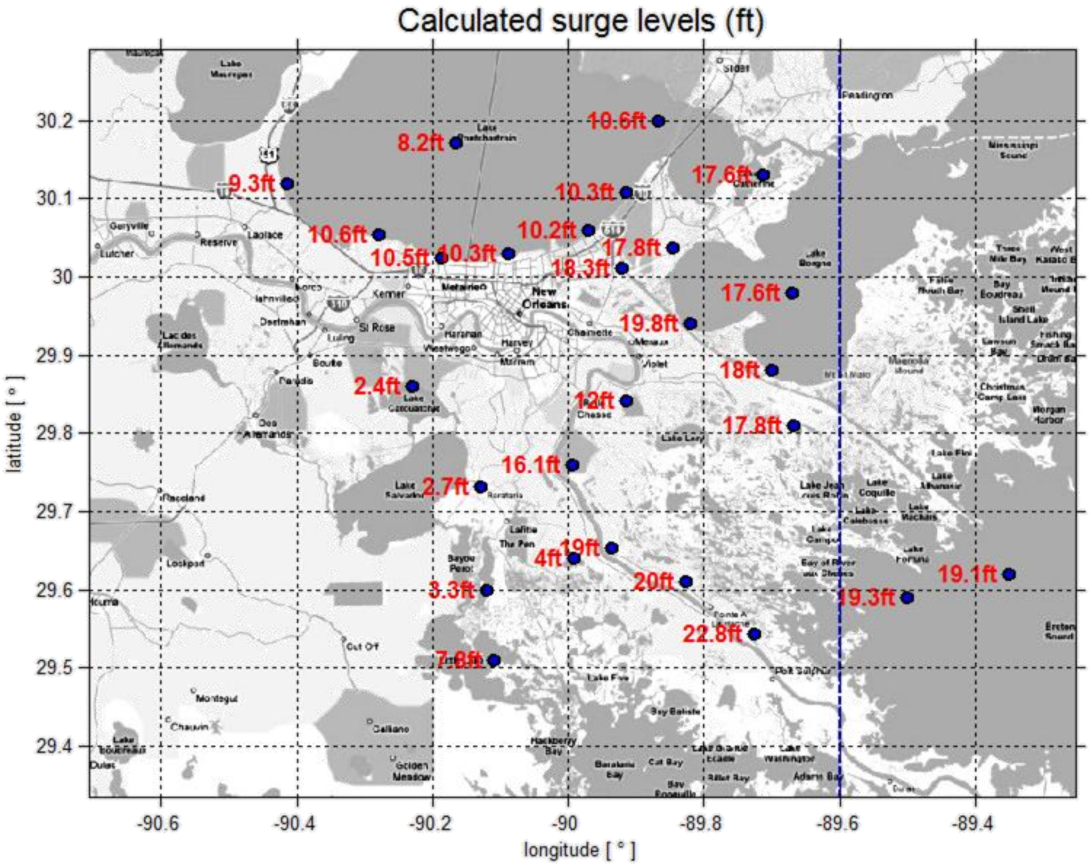

Figure 28: Calculated surge levels with the prediction model, surge levels are given in foot.

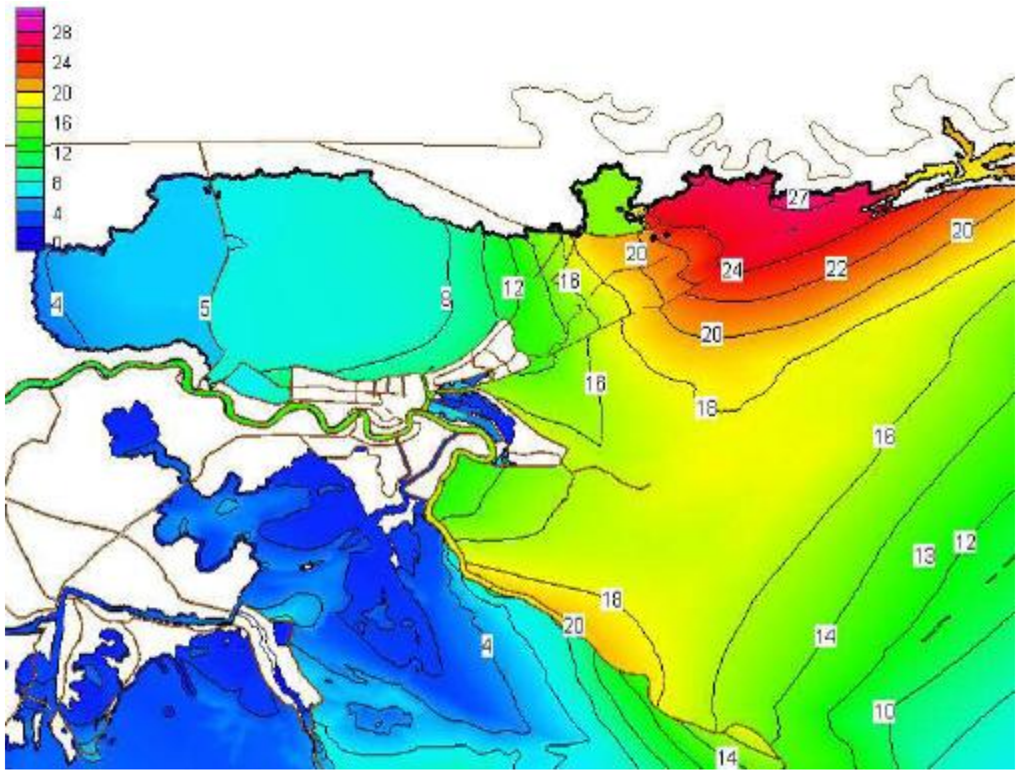

Figure 29: surge calculated with the ADCIRC model for Katrina. (IPET 2007)

5.4.1 High Water Marks

After Katrina a collection of High Water Marks (HWM) was documented by the Federal Emergency Management Agency (FEMA, 2006). The High Water Marks were collected by the URS Group and the United States Geological Survey (USGS). These marks are visible signs of the surge levels that occurred during Katrina. For example a mud line on the exterior of a building can be used as a HWM, see figure 30. The HWMs are collected by flaggers who used their best judgment to estimate the exact height of the surge and the type of the surge. The three basic types of storm surge HWMs are coastal, riverine or levee-related. Off course the flooding in New Orleans was mostly caused by coastal flooding or levee-related flooding.

Figure 30: High Water Mark found on the exterior of a house (FEMA, 2006).

Using these High Water Marks the surge predicted by the Prediction Model (and the ADCIRC Model) can be validated to the real storm surge of Katrina. For this some of the points of the Prediction Model will be compared to the HWMs from the FEMA (2006) report. This report contains maps of the High Water Marks found. The locations of the High Water Marks found are shown in figure 31, not all High Water Marks are found at locations where the Prediction Model gives results but most points of the Prediction Model can be validated using these High Water Marks.

For Lake Pontchartrain the prediction model found surge levels of about 11ft at the eastern end, and about 9 ft at the western end. The High Water Marks vary between almost 14ft at the eastern end, 9-10ft at the southern side of the lake and about 5ft at the most western end of the lake. The points close to the city, at the southern and western side of the lake compare very well with the High Water Marks, the differences remain within 2ft for most of the points. The most western point of the prediction model shows the largest difference. The HWM found close to this point is a coastal surge only HWM, no HWM for the coastal surge taking into account the wave height is found. This could be a cause for the difference. But on the other hand, the Prediction Model is found to overestimate the storm surge at this location sometimes.

For Lake Borgne there are a limited amount of HWMs available, one HWM is found close to where the MRGO channel enters the lake near the V-shape . The location of the HWM is in the MRGO channel at some distance from the V-shape. It shows a surge height of 15ft. This is close to the 18ft predicted at the point where the MRGO enters lake Borgne. Other High Water Marks found are close to where the Prediction Model predicted a surge of 18ft, the HWMs show a surge between 17,7ft and 19ft. This suggests good results for Lake Borgne.

Along the Mississippi levees also very good results are found, the points at the eastern side of the levees are validated first. The point where the Prediction Model predicted 12ft near the large bend in the Mississippi River a HWM of 12,1ft is found. More to the south the Prediction Model showed a surge of 16ft, HWMs found show a surge of 16ft. More to the south no HWMs on the eastern side of the levees are found to validate the results. At the western side of the levees the Prediction Model shows surge levels between 2-8ft. The HWMs near the levees at the western side of the Mississippi River typically show surge levels in this range, which indicates that the predicted surge levels are very well.

When the results of the Prediction Model are compared to the results of the ADCIRC model and the HWMs found it can be concluded that the surge levels calculated are very accurate. The errors for Katrina are usually very low. The results are within 3ft of the HWMs and the ADCIRC surge, except for one point in Lake Pontchartrain. This is why it can be concluded that the Prediction Model is valid for storms that hit the coast of Louisiana and Mississippi.

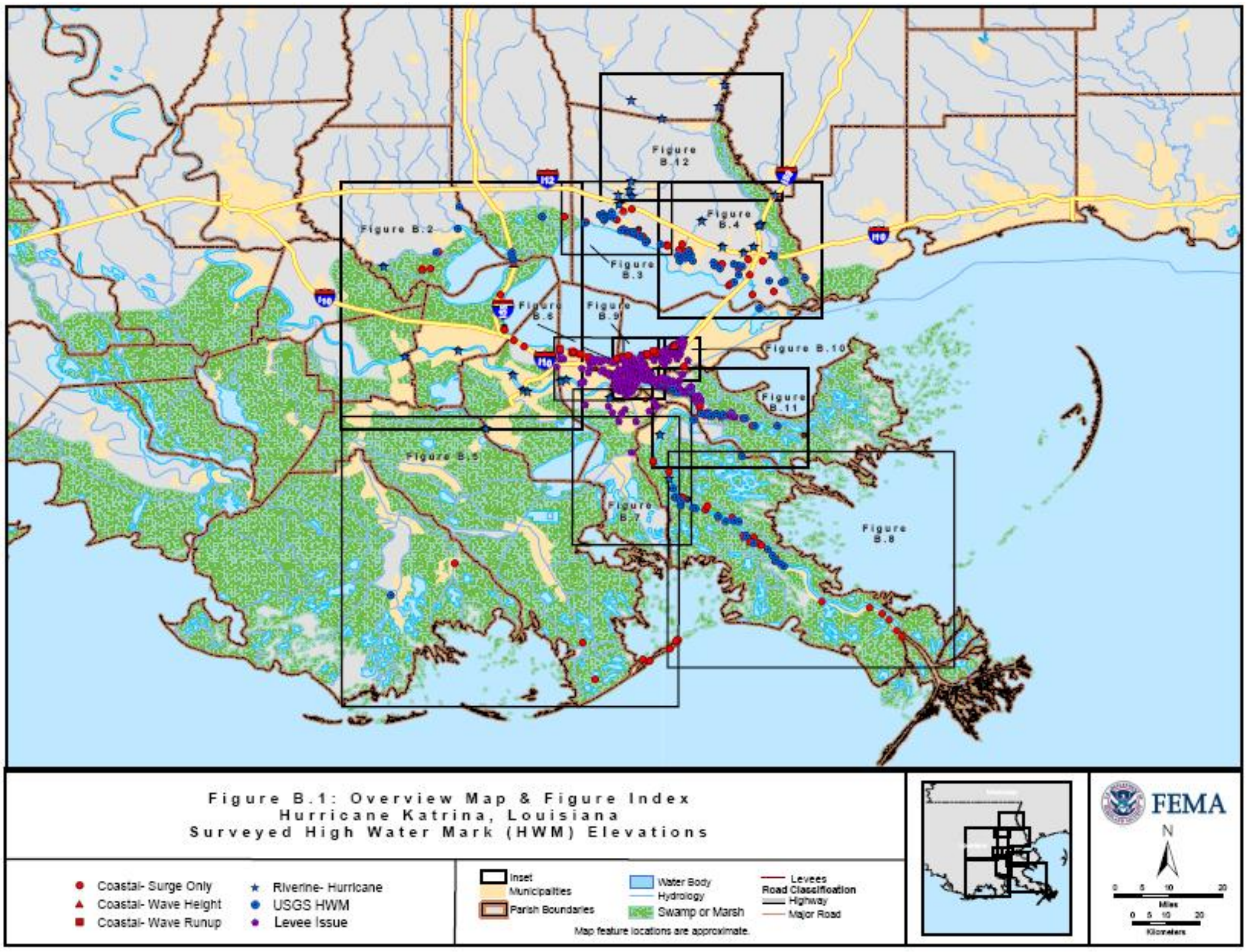

Figure 31: Locations of the HWMs collected by the URS Group and the USGS and USACE. (FEMA, 2006)

5.5 Real time predictions

The predictions of a track of a hurricane are very uncertain. For example, the National Hurricane center predicted the track of Katrina four times a day. On Friday August 26, 2005, 11 AM the track was still predicted in the direction of the coast of Florida, while on the same day at 5 PM the track that was predicted would hit the coast of Mississippi, and on Saturday 5AM the track was heading for the coast of Louisiana. The prediction of the track of Saturday 5AM was within acceptable limits of how the track would eventually be, which allows more accurate predictions of the storm surge levels. (2005 Storm Archive, Hurricane Katrina, n.d., Hurricane Katrina Graphics Archive, n.d.)

Katrina hit the shore of Louisiana early in the morning Monday, August 29, 2005. What becomes clear from this is that the track of hurricane is very hard to predict. It is therefore advised to take caution in trying to predict the storm surges for a hurricane with a track predicted for more than two days in advance. In order to illustrate this the weather forecasts of Hurricane Katrina are discussed. Two days in advance, at Saturday August 27, 2005 9PM, the storm parameters that could have been entered in the prediction model were: a minimum pressure of 945mbar, a central speed of 6 knot (= 6 n.m. per hour = 6 * 1,15mph, which is 6,90mph) and a radius of maximum winds of 10 nautical mile (Hurricane Katrina Archive, n.d.). The Holland-B parameter is not measured but leaving the value at 1.27 is suggested when no information is present. These values differ completely from the storm parameters on Sunday August 28, 2005, 21PM, one and a half day later, the parameters were: a minimum pressure of 902mbar, a central speed of 11 knot (12,7mph) and a radius of maximum winds of 25 nautical mile. Another very illustrative story about the unpredictability of the track and hurricane parameters is found at the WeatherUnderground website, Hurricane Katrina's Surge, Introduction (n.d.). Although the circumstances for Katrina were quite extreme, it is a very insightful and at the same time shocking summary of the days of forecasting before Katrina made landfall.

The predictions for a hurricane being forecasted have a lot of uncertainties. Not only the prediction model, which is based on the predictions of the ADCIRC model, has its own uncertainties. Also the uncertainties in track of the forecasted hurricane, and the parameters of the forecasted hurricane need to be considered. It is therefore very uncertain whether the model will be able to be used for accurate real time predictions. In the case of Katrina, the parameters of the hurricane, like the pressure and the radius, changed very fast while the storm was moving over the Gulf of Mexico. The amount over which the intensity of this storm increased before making landfall could not have been forecasted. And since the model depends on accurate estimations of these parameters the results would have varied greatly with the changing forecasts of Katrina. This is not a disadvantage of the prediction model, the ADCIRC model also has to cope with these uncertainties. The prediction model has an advantage dealing with these uncertainties when compared to the ADCIRC model.

The advantage of using the prediction model is that you can easily do a lot of storm surge predictions for different storm tracks and parameters. That is something that is not possible with the ADCIRC model. With all the different predictions it is easy to get a view on the uncertainties that occur because of the uncertainties in the weather forecasts. Therefore you can also get insight in the best and worst case scenarios of the surge levels. This is a big advantage compared to the ADCIRC model.

6 Conclusions and Recommendations

6.1 Conclusions

This research shows that it is possible to predict storm surge based on a data driven approach with reasonable accuracy. The best surge predictors for a single point are the wind speed and the pressure difference at that point. The wind speed and pressure difference at a certain location can be calculated from the minimum pressure, radius of maximum winds, central speed and Holland-B parameter.

The surge predictions are better if the component of the surface wind speed in the dominant wind direction is taken. The dominant wind direction found is usually directed towards obstacles like a levee, or otherwise a logical explanation for the dominant wind direction found can be given. The pressure at the moment the dominant wind speed is at maximum, is the best predictor of the storm surge. If the dominant wind speed is low (less than 24 m/s) it is best to use the maximum pressure as a surge predictor. For most points, the predictions can be improved by taking the time-averaged dominant wind speed. In this case the dominant wind speed is time-averaged over a number of time steps, since the surge needs time to be built up.

The Prediction Model, can capture the effect of local bathymetry of the location of interest quite well. This can be concluded from the R^2 values found. For almost all points in the Prediction Model itself the R^2 value found is above 0.85. The errors of the predicted surge levels remain within 2 to 3ft in 90% of the cases, looking at the hypothetical storm tracks.

The Prediction Model can calculate the surge levels very fast, the model calculates the surge levels in and around New Orleans in about 10 seconds on an average laptop. The ADCIRC model is run on a supercomputer that takes almost a complete day to finish one run. This is a large improvement in calculation time. This allows for much more runs to be made. Therefore the prediction model can give quicker insight in the best and worst case scenarios that can occur as a hurricane approaches. And also, many different tracks can be entered in the model, dealing with the uncertainty in the forecasted track of a coming hurricane. Also different parameters of the hurricane can be entered in the model. All this gives insight in the uncertainties in surge levels due to the (relatively high) uncertainties that are present in the hurricane forecasts.

6.2 Recommendations

Points at the south side of Lake Pontchartrain can experience 2 peaks in the surge levels, these are due to different wind directions. The first peak will occur because of wind directed to the west, filling Lake Pontchartrain. Since the lake can be considered as a closed basin with an entrance at the east side, the filling of the lake is of importance when the wind is directed to the west. The other wind direction of importance is directed more to the south, or south-east. When the wind is in this direction the water in the 'filled' Lake Pontchartrain will be pushed against the south (or south-east) shore of the lake. It is difficult to capture this effect, although the dominant wind directions found indicate that the filling of the lake caused by the wind to the west is of the most importance. For other points it could be logical the wind directed to the southeast is more important, or for some points even a combination of both wind directions could be used. This could happen when the wind to the west could first add to the surge levels for the points in Lake Pontchartrain and after that the wind with a direction approximately to the south-east could add to the surge levels. It is recommended to do extra research about how this effect can be captured better.

For some surge prediction points, it could be logical to use the wind speed at another point. It can be imagined that the winds at a location near the 'entrance' of the lake Pontchartrain are more important than the wind at the location of interest itself. Especially considering that the filling of the lake is the most important factor in determining the maximum storm surge in the lake itself. This could be implemented in the model to improve the predictions.

The surge predictions found for points very close to the storm track are usually less accurate than for points at relatively larger distance away from the storm track. To improve this, the prediction of the exact wind direction along the center of a hurricane can be improved. The wind direction is now assumed to be perpendicular to the vector of the radius (see figure 23). This is not an exact representation of the wind direction along a hurricane, compare this direction with the direction found, for example, in the wind fields in appendix 2 and 3. Improvements might result in better predictions of the storm surge. Especially points close to the storm tracks, where the direction of the wind assumed differs most from the direction found in the wind fields of ADCIRC, could show much improvement in the surge predictions.

For some points, the number of time steps found over which to time-average, is found to be quite large, especially for points in lake Pontchartrain. This could be true if the lake could be considered as a closed basin, a closed basin takes time to fill. The time over which the wind is time-averaged is, for these points, 24 hours. Research could be done to verify whether the time over which is averaged is realistic, and if Lake Pontchartrain could be considered as a closed basin for the purpose of storm surge prediction.

7 Afterword

When finishing this report, Hurricane Gustav was heading for New Orleans. This was the first time the Prediction Model could be used for a real Hurricane that was threatening New Orleans. During the days before the hurricane made landfall, the model has been used to predict the storm surge levels. This was a very exciting time for me to see how well the model could predict storm surge taking into account the changing weather reports and varying storm conditions.

From a few days in advance, when became clear the hurricane was threatening New Orleans, different predictions have been made. The first results could be given very fast after the first weather report. Together with my colleagues from Royal Haskoning different storm tracks have been used in the prediction model. Therefore the range of the storm surge levels of the coming hurricane became visible. For every day different predictions have been made when a new weather report became available. The results showed that the surge levels could come close to levels that could be very dangerous. For the most extreme storm track the results showed that the storm could produce very high storm surge levels. People were already talking about the evacuation of New Orleans at this moment.

When the first results of the storm surge predicted by the ADCIRC model became available it was clear that the prediction model results were quite reliable. When the same track as used in the ADCIRC model was used in the Prediction Model, the results showed good similarities. This was a very nice moment for me because this was the first time the model had been used for a real coming hurricane. This gave confidence in the reliability of the Prediction Model.

At first the results seemed to underestimate the surge levels at the west side of the Mississippi levees. But in the meanwhile the model results were also validated to the results of ADCIRC of other hurricanes, and to the ADCIRC results for hurricane Gustav. Again the confidence in the reliability became bigger. For the final storm track the results were very good compared to what the ADCIRC model predicted.

The days before hurricane Gustav made landfall were very exciting times for the people in New Orleans. Just three years after Katrina, hurricane Gustav was threatening their city again. The city was evacuated because of the dangerous winds and the very high storm surges the storm could produce. The Prediction Model results showed that the surge levels close to the walls in the IHNC were very close to the height of the wall. CNN showed that the water was just below the top of this wall at the peak of the storm. The waves were just able to splash some water over this wall.

But for me, already back in Holland, this was also a very exciting time. I was able to see how the model I made was used in practice and that the results were reliable. I would like to thank everybody who made this possible!

Marcel van den Berg

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9 Appendices

9.1 Appendix 1: track and surge series for storms 11 and 18

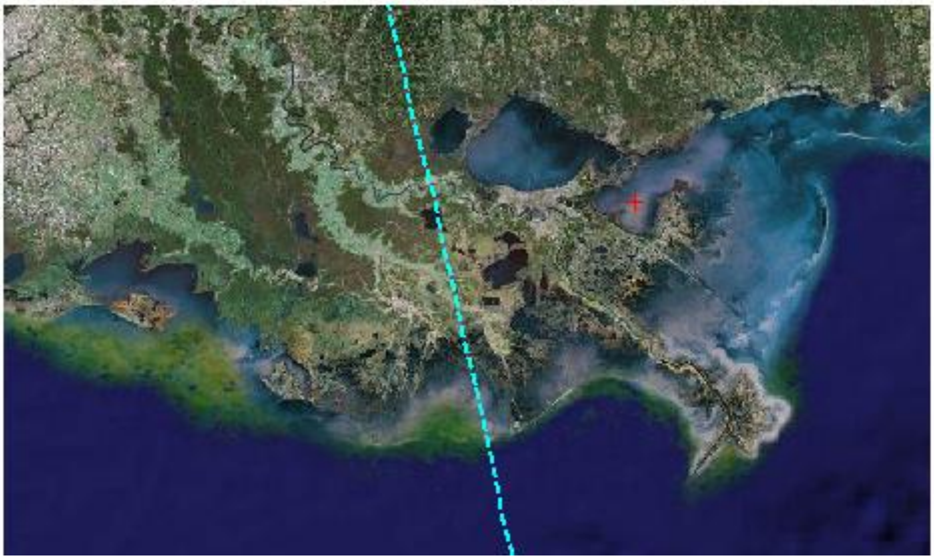

Figure 32: track of storm 18 and 11 (they have the same track), and location of surge point 316 of Q835 data set

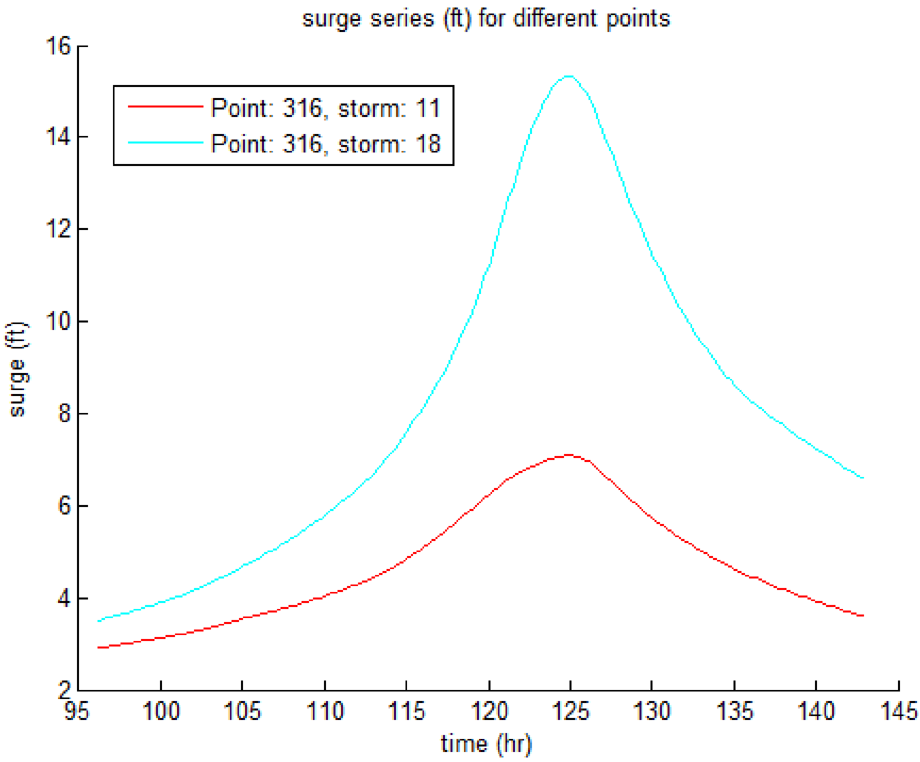

Figure 33: Surge series for point 316 of Q835 data set and storms 18 and 11

9.2 Appendix 2: Wind fields at landfall for storm 7,8 and 9

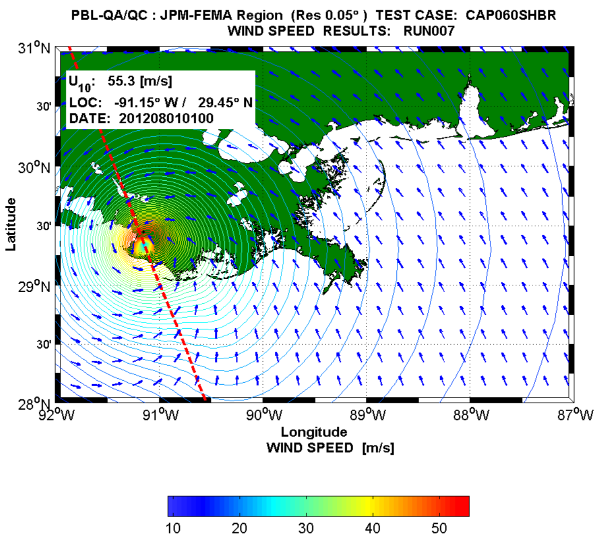

Figure 34: Wind speeds (U_{10}) at landfall for storm 7

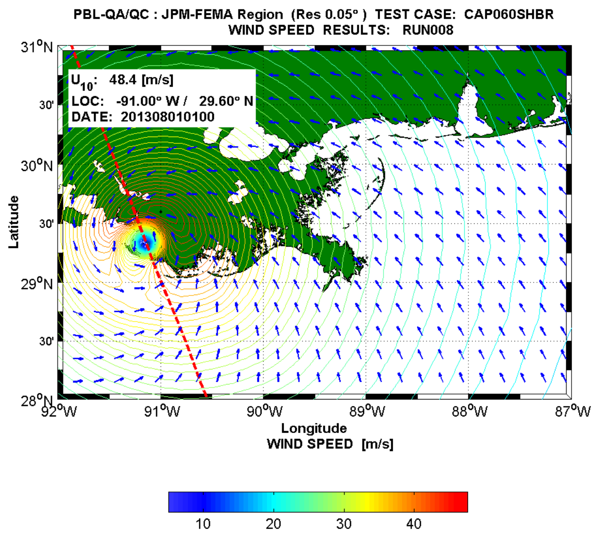

Figure 35: Wind speeds (U_{10}) at landfall for storm 8

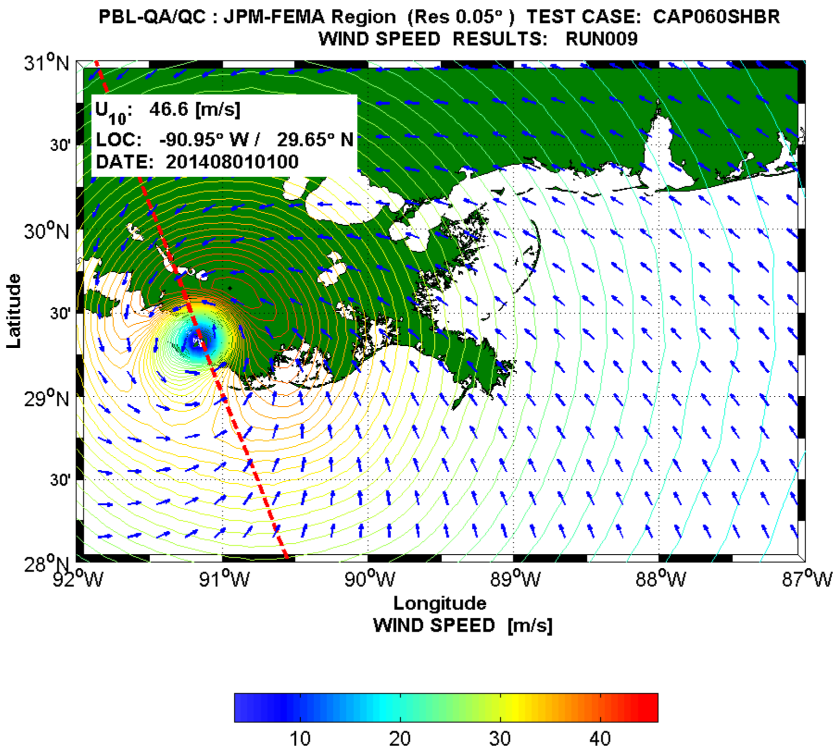

Figure 36: Wind speeds (U_{10}) at landfall for storm 9

9.3 Appendix 3: wind fields at moment of landfall for storms 49 and 162

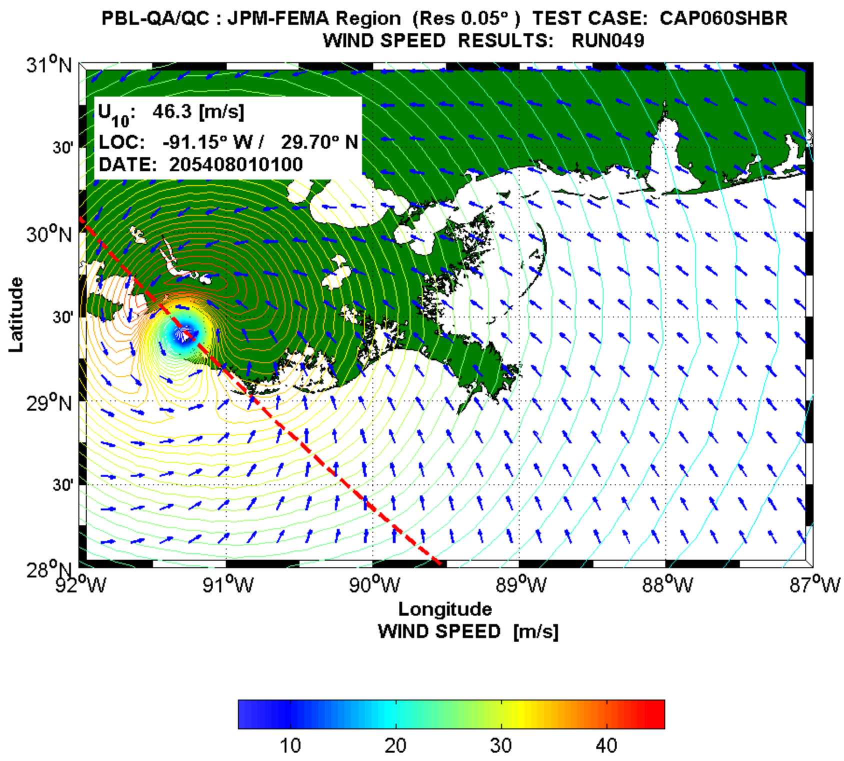

Figure 37: storm 49

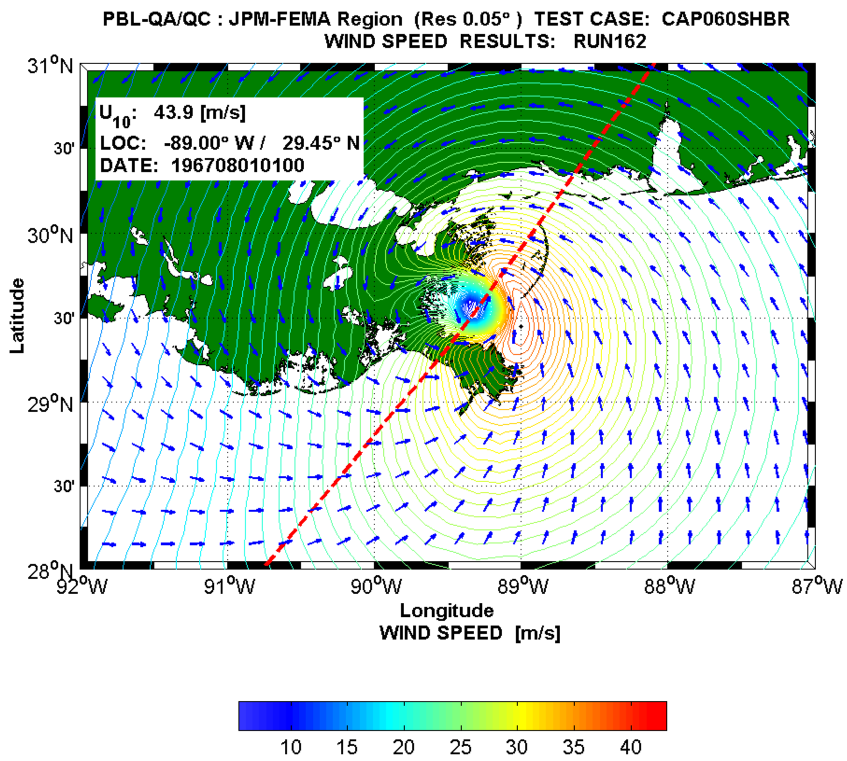

Figure 38: storm 162

9.4 Appendix 4: Improvement of surge predictions

The improvement for point 644 when using dominant wind speed, time-averaged dominant wind speed and by using a wind threshold is shown in the figure below.

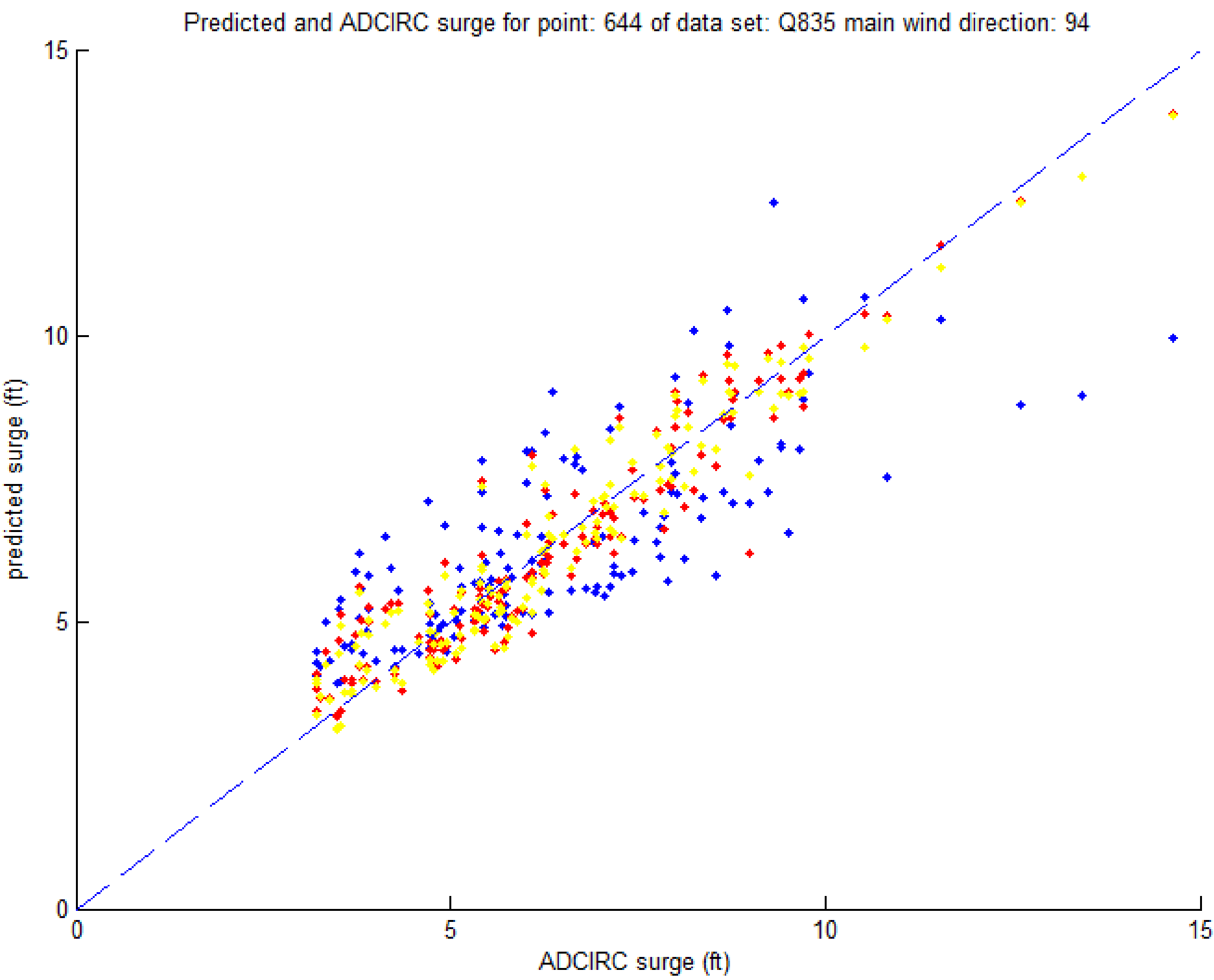

Figure 39: Predicted surge and ADCIRC surge for point 644 of the Q835 data set. The blue dots are the predictions for the 152 fictional storms when only the dominant wind speed with the direction of 94 degrees is taken as the predictor (R^2 =0,59). The red dots show the predictions using the dominant time-averaged wind speed (R^2=0,89). The yellow dots also take into account a wind limit of 24 m/s. This means that for the storms where the dominant time-averaged wind speed is lower than 24 m/s the maximum pressure is taken instead of the pressure at the moment of maximum dominant time-averaged wind speed. The R^2 then becomes 0,91. The best improvement, when taking into account this wind limit is seen for the red dot at an ADCIRC surge of 9 foot and a predicted surge of about 6 foot. The new predicted surge becomes 7,5 foot.

9.5 Appendix 5: steps taken in the prediction model surge calculations

For t = 1 to the number of track locations

compute pressure difference at location x,y and time step t => dp (x,y,t)

compute surface wind velocity at location x,y and time step t => $V_s(x,y,t)$

compute time-averaged dominant wind in direction β : $V_{d,int}(x,y,t,\beta)$

end

find maximum $V_{d,int}(x,y,t,\beta)$ => t of maximum $V_{d,int}(x,y,t,\beta)$ is t_{max}

if $V_{d,int}(x,y,t,\beta)$ < wind threshold

replace $dp(x,y,t_{max})$ with maximum of dp(x,y,t)

end

$\Delta h_{model}(x,y) = H_0 + A\, V_{d,int}(x,y,t_{max},\beta)\, V_{d,int}(x,y,t_{max},\beta) + B\, dp(x,y,t_{max})$

9.6 Appendix 6: Calibration of the coefficients and dominant wind direction

```
for every location(x,y)
    find maximum surge h_max
    for β = 1 to 360
        for s = 1 to 152  a loop for every storm
            interpolate storm track to improve precision
            for t = 1 to the number of track locations (track location over time)
                compute pressure difference at location x,y and time t : dp(x,y,t)
                compute surface wind velocity at location x,y and time t : V_s(x,y,t)
                compute dominant wind component in direction β : V_d(x,y,β,t)
            end
            find maximum V_d(x,y,β,t) => t of maximum V_d(x,y,t,β) is t_max for this storm
            find dp(x,y,t_max) for this storm
        end
        (result is V_d(x,y,β,t_max) and dp(x,y,t_max) for 152 storms)
        find best values for coefficients using multiple linear regression
         h_max,ADCIRC(x,y) = H_0 + A V_d(x,y,β,t_max) V_d(x,y,β,t_max) + B dp(x,y,t_max)
        (result is H_0, A, B for the current wind direction β)
        predict maximum surge in current wind direction for all storms
        h_max,model(x,y) = H_0 + A V_d(x,y,β,t_max) V_d(x,y,β,t_max) + B dp(x,y,t_max)
        find R^2 between h_max,ADCIRC(x,y) and h_max,model(x,y,t) for current wind direction β
    end
    find highest R^2 and store H_0, A, B, R^2, β_opt
    (result are the components of the prediction model for a single point for the maximum surge
    for an optimal component of the wind speed)
end
```

9.7 Appendix 7: Storm surge prediction based on standard storm parameters

Storm surge prediction with the parameters radius, central speed and pressure did not give very reliable results. Not just because only a few different values for the parameters are given; there are three minimum pressure values, the central speed also only has three different values and the radius of the maximum winds has about 10 different values. Because of this, three bands of surge predictions can be seen in figure 38 (one band at about 6 foot, one at about 8 foot and one at about 10 foot).The predictions are calculated with three coefficients before the parameters and starting surge level. The coefficient are estimated by using multiple linear regression for the following model: $H_{predicted}=H_0+A*pressure+B*radius+C*central\ speed$. Because of the unreliable results it is necessary to find other parameters that can predict the storm surge better.

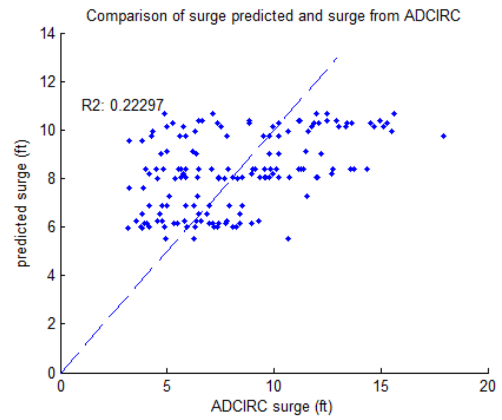

Figure 40: Surge prediction for point 144 of the Q835 data set, surge is predicted from the parameters pressure, radius and central speed. The predictions are the result of a multiple linear regression using the three parameters mentioned above.

Besides that the variability of the data about the pressure, radius and central speed available is relatively low, storm surge prediction with these parameters is difficult because of three different reasons:

(1) First of all there is no linear relation between the parameters and the storm surge. Using a multiple regression model will become very difficult for non linear relations. A way to solve this is to linearize the relations, but this is very hard for, for example, the relation between the distance from the storm track and the maximum surge is not easily linearized.
(2) The different parameters are correlated. The minimum pressure of an hurricane will result in a pressure profile. This pressure profile determines where the highest pressure differences will be present and thus will have some correlation with the radius of maximum winds. For the other parameters it can be imagined that correlations exist.
(3) Local geometry is very hard to implement in the predictions. Circumstances vary over the different points, the surge for two points at an almost equal distance from the same storm track, can be very different if these points are just west of the Mississippi levees or east from the Mississippi levees. These points experience the same pressure, and the central speed and radius of the hurricane will also be the same.

This is why other parameters have been used to predict the storm surge.