ROYAL HASKONING INC.

The future in seconds: *eSURF*

A model to estimate hurricane surge levels

Author:

ChuHui Lin

Supervisors:

Dr. Kathelijne Wijnberg (University of Twente)

Ir. T.M. Kluyver (Haskoning Inc.)

New Orleans, June 2009

Universiteit Twente
de ondernemende universiteit

ROYAL HASKONING

Preface

This report has been written as a bachelor research thesis. The topic of this report is the improvement of a model which estimates maximum surge levels. These surge levels display the effects of hurricane activities near the city of New Orleans and the larger Louisiana coast. This bachelor research thesis report was made within the framework of a Bachelor internship, which is respectively apart of the study Civil Engineering & Management at the Technical University of Twente.

In the past 3 months as an intern at Haskoning Inc. I have learned a great deal. It has provided me with a good sense of the role civil engineering can play in providing protection for cities below sea level. For me it has always been a dream to combine my academic interests with traveling around the globe. Haskoning has provided me with the possibility to live out this dream of working abroad, and at the same time provided me with a valuable insight in the ways in which consultancy companies operate in a foreign country with a different political environment. A further positive result of my internship regards the great improvement of my knowledge of Matlab, and consecutively the improvements I made with regards to reporting. Such competences are invaluable assets in the future. Asides from getting a better feeling for the ways in which water levels rise as a result of hurricane activities, and the hydraulic mechanisms that are the real cause of this increase, my internship has also led me to experience the huge economical and political differences between the Netherlands and the United States. Especially the stark contrast between the collective approaches on education and healthcare, which are typically Dutch, and the American approach with its emphasis on individualism, has been a huge eye-opener.

Because I am also very interested in macroeconomic, and the way in which a company will introduce a new product to the market, Haskoning has provided me with an additional challenge next to my main internship. This additional challenge will be a business plan on how to enter the market with a new product. This part of my internship took place in the Netherlands. It is a report on how to enter the market with the new model of eSURF. If you are interested in the business plan, be sure to read my report "*The future in seconds: eSURF, entering the market*"

I would like to take this occasion to thank ir. Maarten Kluyver and Dr. Kathelijne Wijnberg for their supervision. Maarten Kluyver for his support, comments and suggestions, Kathelijne Wijnberg for her excellent feedback and challenges she presented to me in order to constantly push me to improve myself. I would also like to thank Dr. ir. Mathijs van Ledden, ir. Ries Kusskens, ir. Ray Devlin and again Maarten Kluyver for giving me the opportunity to do my internship at Royal Haskoning Inc. in New Orleans. Also for the chance to take a look at how the U.S. Army Corps of Engineers do their work on the levee and floodwall systems in New Orleans. With this I also like to thank ir. Wiebe de Jong for showing me around at Royal Haskoning Nijmegen. I would also like to thank my newly made friends. Tom Smits, my eSURF buddy, Tjeerd Driessen for his help on improving my Matlab skills and Freek Kranen, for his constantly good mood and great contacts with the locals. At last I would like to thank my mother Siam H. Heng for letting me leave home for 3 months in order to pursue my dreams.

Summary

In this report a research will be done on the improvement of the beta version of eSURF. This model named eSURF is a surge level prediction model. These surge levels are caused by hurricanes nearing the coast of New Orleans. The model was made by Van den Berg (2008) and is called the beta version of eSURF. The beta version needs to be improved because this model lacks the capability to also provide a good estimation for surge levels points far from the hurricanes track. This shortcoming was noticeable during hurricane Ike in the fall of 2008. This hurricane made landfall at the coast of Texas, but due to its enormous wind field still caused a surge on the east coast of New Orleans 210 miles away from the hurricanes track. This research aims at adding a relationship to eSURF that accounts for surge levels caused by the hurricanes span of wind field.

The relationship is found in the kinetic energy a moving object has. This energy could then be put into relationship with the extra surge levels that a hurricane provides for points far away from a hurricanes track. The real challenge is putting the kinetic energy of a hurricane in relationship with the distance, because this energy will only provide an extra surge level for points that are at a distance from a hurricane. But at the same time it needs to be left out for points that are near the hurricanes track. The solution lies in the usage of a logarithm with distance as its function. To look at the improvement and to see if eSURF does provide reliable surge level prediction, a validation has been made on 5 historical storms. The validation is based on the observed maximum surge levels and the surge levels predicted by the beta version and eSURF with the kinetic energy.

The validation showed that eSURF is an improvement on the beta version and still gets a better fit to the one on one line in the regression model, meaning a better representation of the reality. This is especially the case with hurricane Ike, which, after all, motivated this research. The validation also shows that improvement is needed on the distribution of the kinetic energy over the distance between a hurricane and the chosen surge point. In this rapport a logarithm is used with distance as its function. This logarithm function has been chosen because a low kinetic energy is contributing to points nearby the hurricane and a larger part of the kinetic energy is contributing to points further away from the hurricane. The problem lies with the continuity of the logarithm, and the distribution of the kinetic energy value over the distance. The recommendation is to do further research on this distribution factor of integrated kinetic energy.

The conclusion of this research is that eSURF is ready to assist as a good reliable source for a first estimation of the surge level around the coast of Louisiana and especially for the city New Orleans. Although the model is improved with Integrated Kinetic Energy, it did not need to pay for it in time to execute the tool. The tool is still as fast as the beta version and thanks to the new parameter more accurate when it comes to predicting the relentless reality.

Table of Content

1. Introduction

1.1 Background

New Orleans city is a place near the Gulf of Mexico to the south of Louisiana, USA see figure 1. The city is situated between three bodies of water. To the North of New Orleans city Lake Pontchartrain, to the eastside Lake Borgne and to the south the Gulf of Mexico, see figure 4. Due to the economical growth in this city people began to live in areas that are beneath the sea level, and levees and floodwalls where built to protect these people from floods. Due to climate change, sea level rise and the downward movement of the soil because of the drainage system in the city, New Orleans became an even deeper polder surrounded by a lot of water. People that live in the city are used to the fact that during hurricane season parts of their homes will flood because of heavy rainfall. However in 2005 hurricane Katrina came and struck New Orleans more severe than just a few feet of water caused by rain. Due to the funnel shape on the eastside of New Orleans, seawater was pushed into the Gulf Intracoastal Waterway (GIWW) all the way into the Inner-Harbor Navigation Canal (IHNC). This tremendous force was too much for many floodwalls. They eventually gave way to the high surge levels, they broke, gave way or failed. Because New Orleans is mainly situated under sea level, this failure of the levee system brought about a mass flood of the city. After Katrina more attention is being paid to hurricane protection, because the city of New Orleans doesn't want to see such a flood ever happen again.

Figure 1 - Overview of study area New Orleans

To protect the city not only stronger and higher floodwalls and levees are needed, but also a better awareness of the sea level rise during hurricane activities. This information needs to be as accurate as possible, and needs to be available fast in order quickly to set up a reliable evacuation plan.

The city depends on the U.S. Army Corps of Engineers (USACE) to provide the evacuation system. This organization is now using a very detailed computer model, called ADCIRC, to help them determine the surge levels caused by a hurricane or tropical storm that is expected around New Orleans. A major disadvantage of this program is the computation time that is needed to provide surge level estimation. An estimation of the surge levers can take up to 6 hours to calculate. The surge level calculations are based on a forecasted hurricane track. But in the 6 hours that ADCIRC needs to calculate the surge estimation, the hurricane could easily change its direction from the forecasted track in such a way that the predicted surge levels will generally be outdated by the time the ADCIRC calculations are finished.

To aid the USACE with this time problem, a tool has been developed to calculate the surge levels around New Orleans in just a few seconds. This tool is called eSURF, which stands for experimental surge forecast. This program is based on a huge data set of 152 simulated hurricanes and their predicted surge levels by ADCIRC. eSURF uses a relationship between the maximum surge levels and different characteristics of a new hurricane. With this relationship a surge level prediction can be made for a forecasted hurricane track and its characteristics at different chosen points in and around the New Orleans area and the larger Louisiana coast.

1.2 Problem description

The existing beta version of eSURF, provided by Van den Berg (2008), is using two characteristics of a hurricane. These characteristics are pressure and wind speed. But what this model does not take into account is the magnitude of a hurricanes wind field. Hurricane IKE (2008) exhibited larger surge levels than calculated with eSURF beta. To improve the model a new characteristic is needed in order to also take the spatial extent of a hurricane into account.

The new characteristic comes from the work of D. Powell and A. Reinhold (2007), in which they refer to Integrated Kinetic Energy (IKE). This Integrated Kinetic Energy is a new way to scale potential storm damage. The idea is based on the kinetic energy a forward going mass has. This idea was picked up during hurricane Ike. This hurricane had an average wind speed and was ranked 2 on the Saffir-Simpson Scale. But Ike had such a huge wind field that it caused a high surge level (e.g. at the gate of B.Bienvenue-MRGO, 210 miles away from the hurricanes center. This surge level was around 8.16 feet.)

1.3 Objective

The objective is to improve the existing beta eSURF prediction model by introducing Integrated Kinetic Energy (IKE) as a “new” characteristic of the storm, and thereby accounting for the higher surge levels at points further away from a hurricanes track. Besides improving the beta eSURF model, the model also needs to be validated with historical storms. Hurricanes are highly dynamic, therefore next to the validation a sensitivity test needs to be preformed to see how the model will react with slight changes in input parameters.

1.4 Research question

The overall problem sketched in section 1.1 can be broken down into several smaller research questions.

The research questions are:

- How can we include *Integrated Kinetic Energy (IKE)* in the eSURF model?
- Does including the new parameter *Integrated Kinetic Energy (IKE)* into eSURF improve the prediction of maximum storm surge levels?

1.5 Research approach

At first a literature study will be made to understand how hurricanes develop, how they build up their strength and also which physical parameters cause water levels to rise. This also defines the study area of our research. Next to this another literature study will be done on the different ADCIRC input data and how eSURF will be using these data. At last the magnitude of hurricanes will be explained as an introduction to the upcoming explanation of the Integrated Kinetic Energy theory.

After the literature studies, Integrated Kinetic Energy will be introduced to the model by adding this as an extra parameter. The first validation approach is to check if the R^2 has a better fit with the maximum surge levels with the ADCIRC point-set data. This validation will be a comparison to the R^2 of the beta version of eSURF. The second validation is between the model eSURF and 5 historical hurricanes and their measured water elevation data, this again in comparison with the beta version.

1.6 Outline report

The outline of this report is based on the research approach. In chapter 2 an explanation will be given on where hurricanes start to increase and get there destructive form. Besides this, the different physical parameters that cause water levels to rise as a result of hurricanes are explained. With this the study area will be outlined, and it will be clear how hurricanes are scaled nowadays. The chapter concludes with an explanation of the ways in which ADCRIC can be used as input data for eSURF.

In chapter 3 the beta model will be explained along with the use of the parameters in that model. After this *Integrated Kinetic Energy (IKE)* will be introduced and it will be explained how this extra parameter is fitted and implemented in the 'new' eSURF model.

The validation of the newly made model will be shown in chapter 4. In this chapter the improvements of the new model will be validated against historical storms. A comparison will be made between the beta and the release version of eSURF.

The last chapter consists of a conclusion and recommendations for further improvement.

2. New Orleans Hurricane Season

The hurricane season is between June and November and usually peaks in the months August and September. During these months heavy rainfall can be expected, and the surge levels produced by hurricanes against levees and floodwalls can cause the city to flood from time to time. But where do these hurricanes come from and what are the causes that create surge levels?

2.1. Hurricanes and their origin

Hurricanes originate in tropical warm waters, commonly with a temperature of around 26 ^{o}C, where the Coriolis Effect is strong. Moving objects, such as air or water particles, are affected by the earth's rotation. These particles will be deflected to the right for the northern hemisphere, and to the left for the southern hemisphere. This was described by a French Mathematician Gaspard Gustave de Coriolis in 1835. He defined an equation for the Coriolis force as followed:

$$\text{Coriolis force per unit mass} = 2\Omega \cdot \mathrm{V} \cdot \sin(\theta) \qquad (1)$$

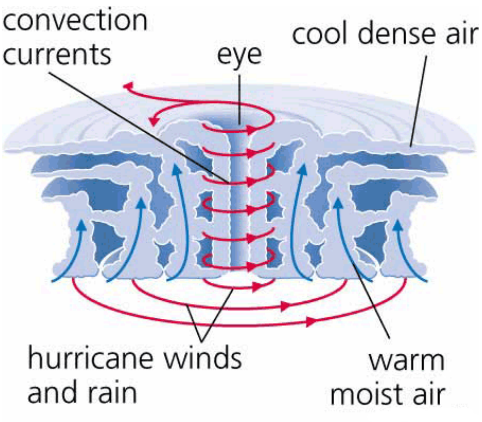


Figure 2 - Anatomy of a hurricane

Where Ω stands for the angular velocity of the earth, this is $\frac{2 \cdot \pi}{24\ hours}$, V is the velocity of the moving object relative to the earth's rotation and θ is the latitude in [^{0}].

If the θ is 0 it means that the object is moving on our earth's equator, which causes the Coriolis force to be null. A Hurricane that reaches the Gulf of Mexico could be formed near the west coast of Africa, north of the equator, and due to the coriolis effect it will always be rotating counter clockwise. *(Persson, 1998)*

Because of the warm seawater clouds begin to form due to evaporation. A mass of clouds can start to build up because the wind level near the equator is low. The moist air rises and will eventually cool down and condensate. This condensation will release latent heat, which is heat that can be released or absorbed when a substance changes it state. So by condensation it will automatically heat up its surrounding, thus creating a lower pressure which leads to more air being sucked inwards and pushed upwards to the cloud mass. Because of this continuous cycle, the cloud becomes bigger and wider, it will show the first signs of a tropical storm.

If the progress of building up cloud mass stays stable and wind speeds of 74 mph are reached, a hurricane of category 1 will be the result. A hurricane can be up to a 1000 km in diameter and have an 'eye' of around 20-60 km in diameter.

The wind speed is the effect of the large pressure difference in the hurricane and the rotating effect caused by the Coriolis Effect. Due to a low pressure area, air of the high pressure surrounding is drawn to the low pressure. Combining this with the rotating effect a hurricane can begin to build up its destructive rotating force. This rotation is counterclockwise and it is creating wind speeds in the horizontal direction.

Hurricanes that start in front of the west coast of Africa can travel westwards across the Caribbean and then to the north across the southern coast of the US *(NB. that this is not always the case)*. A hurricane can travel at speeds from 15 to 60 mph. Some will follow a straight line, others will loop or wobble. However, a hurricane can only survive over sea, once they hit landmasses they will quickly dissipate. They dissipate over land because they need warm water to sustain themselves. What a hurricane needs is moist air to keep the flow of latent heat constant; by hitting land this intake of moist air will be stopped. Once this warm water source is taken away the hurricane will slowly dissipate. Another reason why hurricanes dissipate overland is the friction caused by land, the hurricane cannot keep its stable shape and therefore dissolves. *(NOAA, FEMA, University Corporation for Atmospheric Research, 1999)*

2.2. Factors influencing maximum water levels

Different factors cause water levels to rise near the coastline. Some of them occur by nature, some are caused when a hurricane is entering the Gulf of Mexico. In this paragraph these factors will be defined, starting with the least important and ending with the most important factor.

1. High and low Tide

The most frequent water level changes are due to astronomical tide level change. These astronomical forces will force the water level to climb up or drop, which is commonly called high or low tide. Storm surge will most likely do more damage during high tides than during low tides.

2. Bathymetry

There is a factor that is not caused by an external force. This is the local bathymetry of the coast, because water height can be influenced by the local bathymetry. It is logical that a higher surge level will occur in shallow water depth. Also a feeble slope of the bathymetry towards the coast could cause a huge effect on the surge level that occurs by wind driven sea water.

3. *Pressure difference in a hurricane*

The cause of rising water is related to atmospheric pressure in a hurricane. Just above the surface of the sea, in the 'eye' of the hurricane, there is a low pressure. This pressure difference with the surrounding will cause a slight increase of the water level underneath the hurricane; it is also called a pressure surge.

4. Wave-driven water level set-up

Waves are also causing a higher water level at the shoreline. The waves are generated by the power of the wind. When waves move into shallow water they will break. As they break, the wave height decreases, causing a cross-share gradient in the radiation stress. This gradient causes an increase of the water level near the shoreline, which is also referred to as wave set-up. Another phenomenon is wave running up a gently sloping shore, it tends to elevate above the mean water line. This may exceed twice the wave height before breaking.

5. Wind induced surge

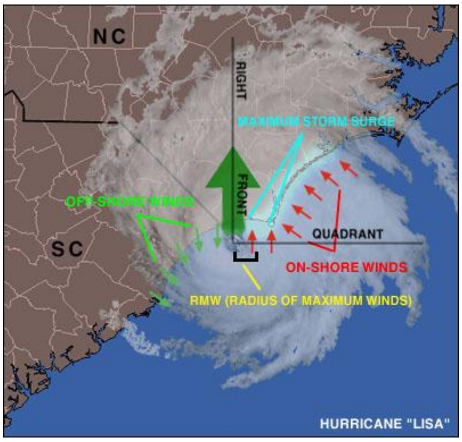


Figure 3 - Hurricane Quadrant section

Strong surface winds causes water currents at an angle to the wind direction, this effect of the waters behavior is known as the Ekman Spiral. The spiral effect is a consequence of the Coriolis Effect, which has been explained earlier. In water with sufficient depth this can result in a net water transport perpendicular to the wind direction. But in the presence of a coastline this may result in a set-up or a set-down of the water level. This depends on the direction of the wind relative to the shoreline. As the hurricane gets into shallow water, the full Ekman spiral can no longer develop and on shore wind stress will also cause on shore water transport, hence cause water levels set-up near the shoreline. Offshore blowing winds will similarly cause a set-down of the water level near the shoreline. Hurricanes in the northern hemisphere are turning counterclockwise, causing a set-up on the first quadrant (this is the right front quadrant of a hurricane). A set down of the water level near the shoreline will be on the second quadrant, which is the left front quadrant. *(NOAA, FEMA, University Corporation for Atmospheric Research, 1999)*

2.3. The study area

New Orleans is a city that is surrounded by a lot of sea, lake and river water. It is located near the Gulf of Mexico, with the Mississippi river parting the city. This city has an average yearly rainfall of 1570 mm. Due to the location of New Orleans, hurricanes will most likely make landfall in or near the coast of Louisiana. To protect the city against floods the city uses a system of levees and floodwalls. This system is called the Greater New Orleans Hurricane and Storm Damage Risk Reduction System (HSDRRS). The study area can be seen in figure 4.

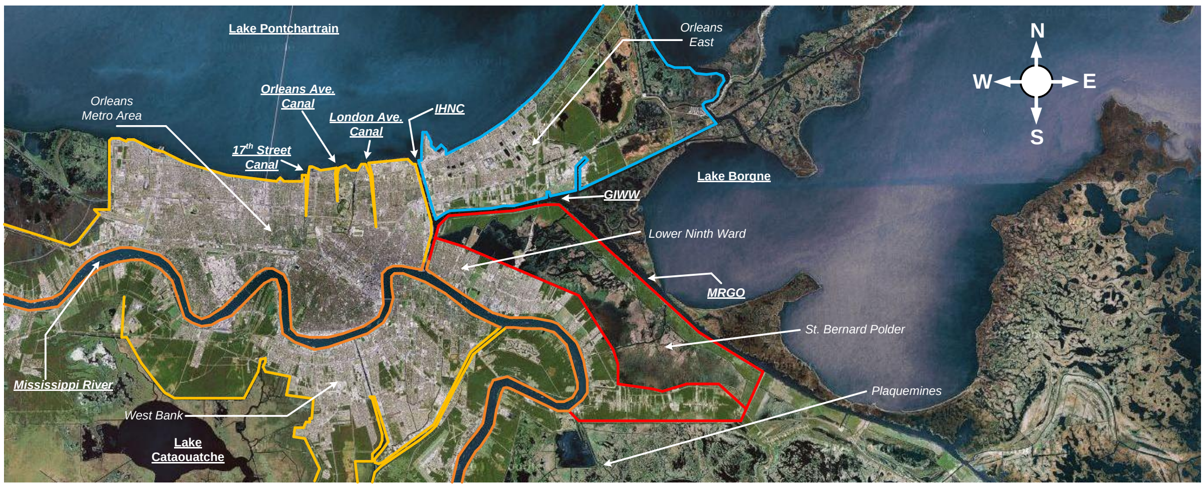


Figure 4 - Hurricane Protection System New Orleans

As can be seen in figure 4, New Orleans is surrounded by water. To the north lies Lake Pontchartrain, to the east Lake Borgne and to the south Lake Cataouatche. The Mississippi divides the city in an east and west bank. During hurricanes wetlands will be inundated because they are mostly outside the levee/floodwall systems. One of the most struck wetland is to the south of the city and is called the Plaquemines area.

Hurricanes will most likely travel from the southeast to the northwest, over the Gulf of Mexico. If the path of the hurricane is making landfall on the west side of New Orleans, in combination with the counterclockwise rotation of hurricanes in the northern hemisphere, sea water will be pushed against the east side of New Orleans into the funnel shape. Due to The Mississippi levee systems water will also rise against the east side of this levee system. During hurricane Katrina (2005) this also happened. The result was that the water was pushed against the levee system up north to Lake Borgne. Due to the funnel shape water was pushed into the GIWW and IHNC. But water of Lake Pontchartrain was also pushed to the north side of the city into the three canals because those canals weren´t closed. Large places where flooded because of failure of the system. This failure occurred due to the huge amount of water against the floodwalls. At first there was some overtopping, but because they used I walls instead of T walls. The overtopping created erosion behind these I walls. The system became weaker and eventually gave way to the tremendous water force. One of the major floods was in the lower parts of the city; this is New Orleans East, the north part of the Metro Area and Lower Ninth Ward, see figure 4.

eSURF covers an even larger area because eSURF is using ADCIRC points to calibrate. These points cover the larger Louisiana coast, see figure 5. *NB.: that not all the points are shown in this image.*

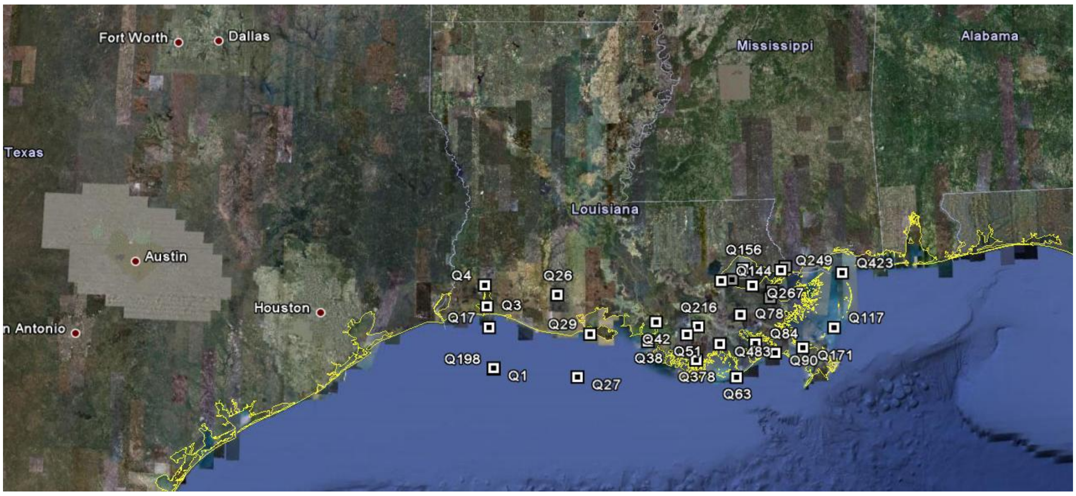


Figure 5 - Points set along the coast of Louisiana

2.4. Saffir-Simpson Scale

In the 1960s Herbert Saffir came up with a way to scale hurricanes based on wind speed and pressure for potential damage, and in the 1970s Robert Homer Simpson expended it with the surge and flood damage. As of that moment the Saffir-Simpson Hurricane/Intensity Scale was used as a hurricane scaling model.

The Saffir-Simpson scale can be divided in to 5 categories and two additional classifications. A hurricane will be measured and then scaled to one of the categories. The categories are as followed:

Category	Wind Speed (mph)	Pressure (mBar)	Surge Level (ft)	Damage Level
Tropical Depression	<38	N.A.	N.A.	*None to Minimal*
Tropical Storm	39-73	>990	0-3	*Minimal*
1	74-95	980-989	4-5	*Minimal*
2	96-110	965-979	6-8	*Moderate*
3	111-130	945-964	9-12	*Extensive*
4	131-155	920-944	13-18	*Extreme*
5	≥156	<920	≥19	*Catastrophic*

Table 1 - Saffir-Simpson Hurricane Scale

Using this system every hurricane can be scaled to a category, thereby giving people an indication of how high the damage of a hurricane will be. *(The Saffir-Simpson Hurricane Scale, 1972)*

Unfortunately this scale is very outdated, especially in terms of surge. As a result the scale is often incorrect when it comes to real life surge levels. The reason for this misjudgment is the hurricanes spatial variability throughout the whole of the hurricane. This is why it is impossible to give an indication of the surge levels of the whole of a hurricane, especially since the scale only takes into account wind speed and minimum pressure.

This misjudgment of hurricane storm surge levels also occurs when the dimension of a hurricane is larger than normal. This means that the scale does not take into account the physical size of a storm, because lower wind speeds can still cause serious surge levels if they keep on pushing long enough. A good example is hurricane Ike. The hurricane was scaled as a category 2 on landfall. On the scale it means a moderate damage level with surge heights of around 6 to 8 ft. It came on land near the coast of Texas and caused a surge level of 12 ft. at Bolivar Peninsula. Because the size of the hurricane was so huge, a water level at the eastside of New Orleans at the B.Bienvenue-MRGO could be measured of 8.16 ft. So it did more damage than the category in which it was scaled, and the indication of did not take into account the fallout for a place 210 miles away from landfall.

To deal with this underestimation by the Saffir-Simpson scale, a new prediction scale is being considered. This new scale is based on the kinetic energy a forward going mass has. The Integrated Kinetic Energy will be explained more thoroughly in chapter 3.2.

2.5. ADCIRC

The model ADCIRC (ADvanced three-dimensional CIRCulation model) is a computer program for solving time dependent, free surface circulation and transport problems in two and three dimensions. The program can also be used to calculate surface elevation of a body of water, taking into account tides, storms, river discharges and more.

ADCIRC uses a high detailed triangle grid (node) of the whole of the southeast of America. It covers the Gulf of Mexico and the Caribbean Sea. The boundary of the grid is set in the Atlantic Ocean. The nodes in these grids on the open sea are larger but when they are closer to the coastal areas they become smaller and more packed. 90% of the nodes are very close and packed, these nodes are less than 100 ft. apart from each other. Because this grid is so detailed the predictions that ADCIRC can produce are highly accurate.

To calculate water level elevation ADCIRC is using a lot of input data to try and represent, as good as possible, the reality. ADCIRC uses all of the levees, lakes, canals and other structures that are important to storm surge set-up in their model. It is also looking at the natural levees or structures that have a certain height such as railroads that are heightened. What ADCIRC also takes into account are the wetlands and rivers that could affect storm surges, besides this the bathymetry in the gridded domain is also used in the model. (FEMA. 2008)

In this research the local bathymetry, all levees, lakes, canals and other structures that are important to storm surge set-up will not be directly taken into account, but will be taken into account indirectly. This is because these factors are included in 152 ADCIRC, which means they are automatically included in the model of eSURF.

2.5.1. Hypothetical storms

As mentioned before ADCIRC is a very detailed model to predict surge levels. The data that will be used for eSURF is also based on data provided or computed by ADCIRC.

To acquire the needed maximum surge levels for eSURF, 152 hypothetical storms were calculated with the ADCIRC model. This has been done to cover the Louisiana area, mainly New Orleans. What these hypothetical storms also cover is a wide range of differed sizes of storms and their different parameters. The hypothetical storms consist of 5 parameters like storm number, track number, the minimum pressure, the radius of maximum wind, central speed and the Holland-B parameter. The storms are listed in a file from 1 to 152 and associated with a storm track list. This track list defines every location on the storm's path by a number of latitude and longitude coordinates. So for every track the parameters of a chosen storm can vary very quickly over the path. This has been done to represent how hurricanes realistically behave over time.

2.5.2. Maximum surge level data

The 152 storms that go into the ADCIRC model provide 152 calculations, and thus also provide the 152 maximum surge dates that are needed for eSURF. The surge data are given on various locations around New Orleans. These points are divided into 3 sets, the so called D1479, Q835 and L274 set (See figure 5). The D-set is a set that consists of 1479 points; points that are all near the levees of Lake Pontchartrain, Lake Borgne and the Mississippi River. The second set is the Q835. This set is a quality control set and is based on 835 points. These points are all located around New Orleans, on the west coast of Louisiana and near the coast of the Mississippi state. The last set is the L274, this set consists of 274 points and is a LACPR (Louisiana Coastal Protection en Restoration) set. These points are all located around the larger New Orleans area and the southwest of the wetlands.

For every set the surge level is calculated by ADCRIC by using the data obtained from the 152 storms and all their time steps. For points that do not have a surge level, or that are on dry land, the points get the value -999ft. In the end every point has a maximum surge level, and 3 charts based on the data of the 152 storms. These 3 charts will then be used as input data for the model eSURF.

3. Storm surge prediction model eSURF

The model eSURF forecasts the maximum storm surge levels a hurricane can produce. In this chapter the set-up of this model will be explained and discussed.

3.1. The way eSURF works

The program eSURF uses a model to estimate surge levels. eSURF stands for Experimental SURge Forecast. The idea behind this program is to create a model that can quickly provide maximum surge level estimates, all based on a hurricane forecast provided by the National Hurricane Centre (NHC). They forecast the storm track, the cone of probability and the various parameters of a hurricane. These parameters are pressure, radius of maximum winds, central speed and the Holland-B parameter.

But to execute this program fast and swiftly, a huge amount of data needs to be prepared. eSURF basically is, a very clever and fast search tool. The end user will only use the fast and clever part called eSURF. The calculation behind eSURF is called the setup phase. To explain how this works a flow chart, figure 6, has been added.

First of all an assumption is made that supposes that the surge level has a linear relationship to the different parameters of a hurricane. In this chart the improvement with Integrated Kinetic Energy is not taken into account, this will be explained later in chapter 3.2.

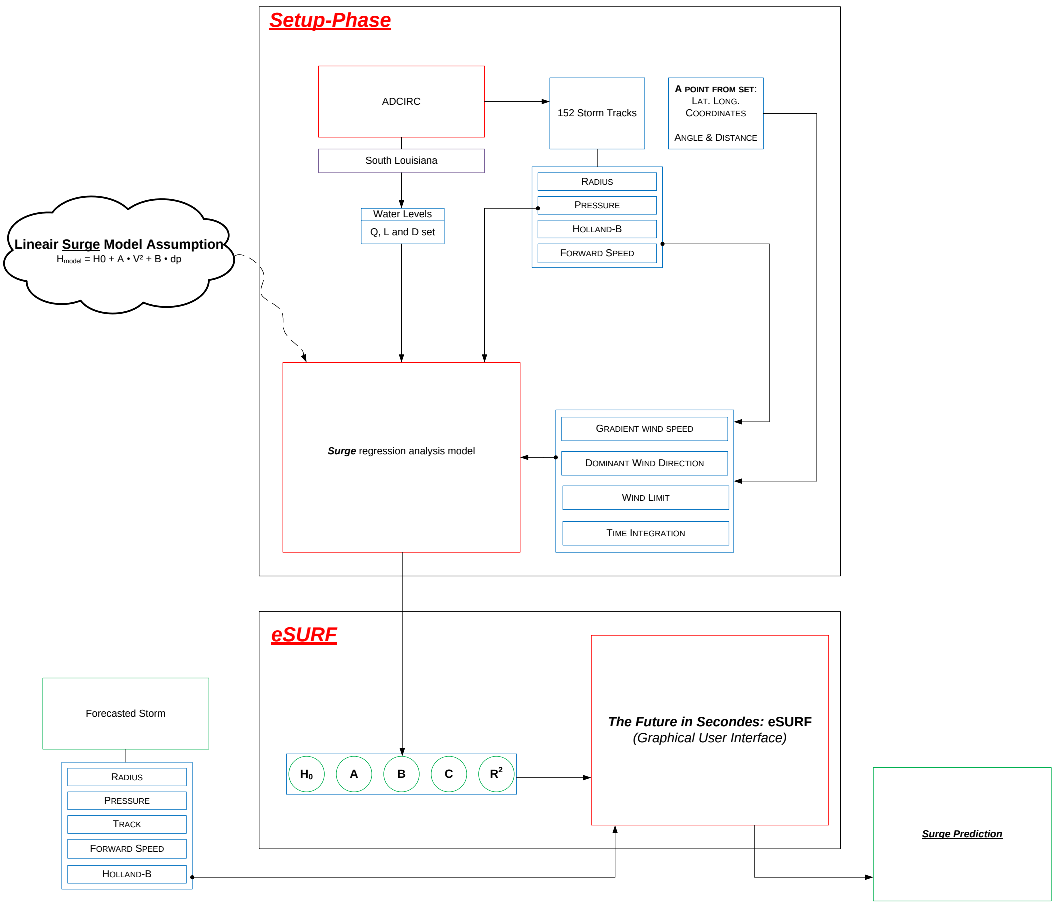


Figure 6 - Flow chart of the beta version

As stated above, the model comes down to 2 steps. The first step (the setup-phase) is to prepare the input data for eSURF. This input data is based on the 152 ADCIRC storms and their calculated maximum surge levels. It also uses a combination of the 4 different parameters; pressure, radius of maximum winds, central speed and the Holland-B parameter. At last it also takes into account the distance between the hurricane to every point of the 3 data sets Q, D and L, and the angle a hurricane makes in relation to these points that are used.

This relationship is formulated as a linear assumption. The equation can be described as follow:

$$H_{max\ surge\ level} = H_0 + A \cdot V^2 + B \cdot dp \qquad (2)$$

The setup phase ultimately comes down to filling in the blanks; the best fitting water zero level (H_0) and the coefficients A and B. This in relationship to the maximum surge levels and the different parameters (V^2 and dp). What the setup phase does is using a multiple-linear-regression to find the best correlation (R^2) for every point from the 3 data sets Q, D and L. To do this a iteration is used to look for the best correlation fit (R^2) between the maximum surge level and the different parameters V^2 and dp. The model does this by altering the H_0, A and B coefficients for every wind angle and distance from the center of the hurricane to each point during the entire track, because the wind direction on each individual point and the distance between the center of a hurricane to each individual point influence how high the surge level will be. By using the multiple-linear-regression calculation, the maximum surge level from the 152 ADCIRC storms will be compared to the calculated storm surge level. Every time the best combination of H_0 and the coefficients A and B will be stored away, this is determined by looking for the best R^2 value. Eventually there will be a list for every point with the best H_0, A and B coefficients for every one of the 152 storms, and this is called the prepared data. This is what the setup phase is looking for and is calculating. This step is a time consuming step, since it may take up to 15 hours in total to calculate this for every point of the 3 data sets.

The second step is eSURF, which is also the only step for the end user. Here eSURF is using the pre-collected data from the setup-phase to forecast a new surge level for every point from the 3 data sets Q, D and L, based on the user inputted hurricane track and parameters of the hurricane. The equation is the same as that of step 1 but this time H_{model} is being calculated rather than used.

$$H_{model} = H_0 + A \cdot V^2 + B \cdot dp \qquad (3)$$

As said H_{model} is actually the wanted parameter, it's a calculated surge level for the chosen point. And because it was fitted with the best possible H_0, A and B coefficients based on the 152 ADCIRC data, the surge level output H_{model} should come close to actual measured data. *NB.: That in both equations the symbols marked in red are the ones that needs to be calculated and needs to be found. The once that are marked in blue are the known values that are used as input.*

This is how eSURF works in its basic form. Both equations use the V^2 and dp parameters, which are actually made up of different equations using the four characteristics of a hurricane. These four parameters are pressure, radius of maximum winds, central speed and the Holland-B parameter. In the upcoming paragraphs these four parameters will be explained also the dominant winds speed; V^2 will be explained.

3.1.1. Central speed

The central speed of a hurricane is the speed with which the hurricane is moving forward. This parameter is not physically altering the surge levels for every point. What it does is altering the gradient wind field of a hurricane. If there is no forward moving motion from the hurricane itself, the hurricane will spin around its own axis, thereby creating perfect circles. By putting forward motion into a hurricane the shape will change as shown in figure 7.

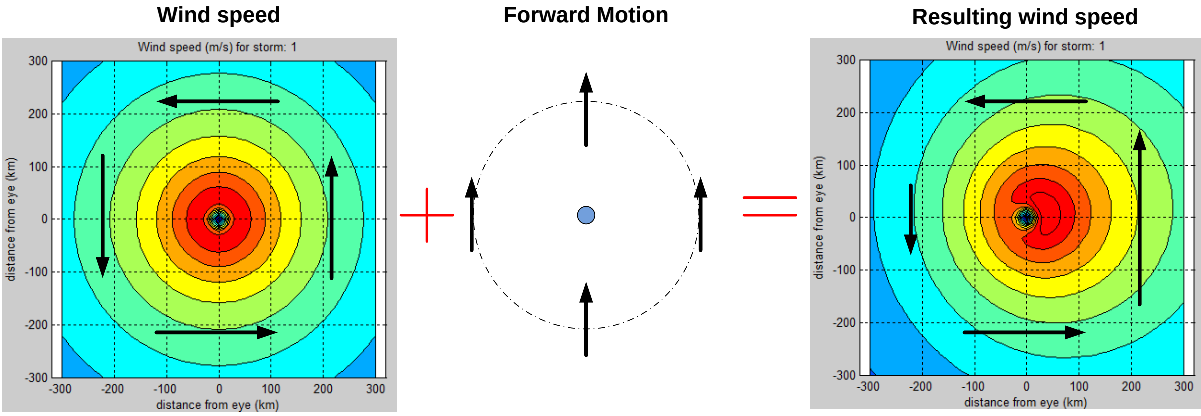


Figure 7 - Gradient wind field with forward motion. Red is where the highest wind speeds occurs in a hurricane.

How much the central speed will contribute or take off of a surge level at a point, depends on where the hurricane is passing the point. Because a hurricane in the northern hemisphere is rotating counterclockwise, the points that are on the right hand side of the hurricane have a greater gradient wind speed due to the extra speed from the forward motion. Points that are located at the left side of the passing hurricane will experience a slight decrease in the gradient wind speed.

3.1.2. Radius of maximum winds

The radius of maximum winds is the distance between the low pressure point in the hurricane and the highest maximum wind speeds that occur in a hurricane. Figure 8 shows that the radius of maximum winds is around 40 km, which is 22 nautical miles.

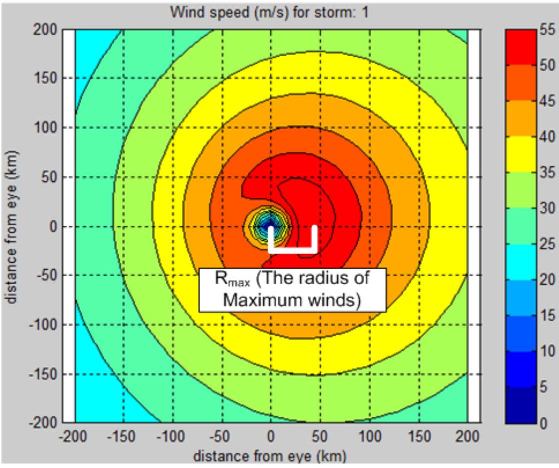


Figure 8 - Radius of Maximum winds

The R_{max} specifies the location of maximum wind speeds in the hurricane. A larger R_{max} does not necessarily mean a higher wind speed. What it does mean, though, is that the max wind speed is further away from the center of the hurricane, giving smaller differences in pressure and producing a higher storm surge further away on the right hand side of the hurricane.

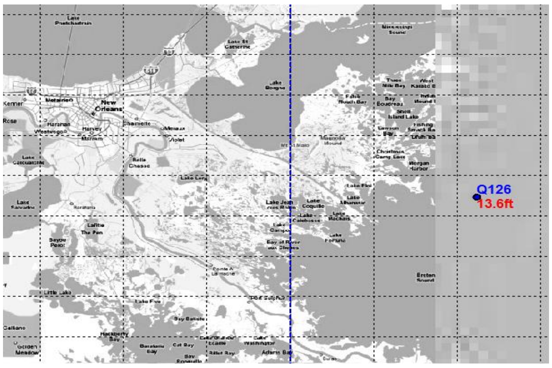


Figure 9 - Storm track with point of interest

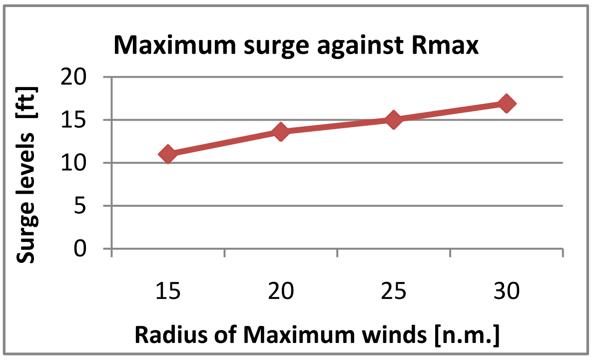


Figure 10 - Surge level against Rmax for point 126

This effect can be seen in figure 9 an figure 10. The chosen point is 126 of the Q-set, this is an offshore point on open waters and it is to the east of New Orleans. This point is chosen because it is on open waters, so the location local effects will not interfere with the surge levels. The storm track (the blue line in figure 9) is hurricane Katrina. Every other factor has been kept the same. In figure 10 it can be seen that the surge level is rising with every increase of the radius of maximum winds. The max wind speed has been the same throughout the calculation, it has remained 53.3 m/s.

The explanation of this increase in surge level is that a larger body of water is put into motion because the wind speeds are affecting a larger area, and thus results in a higher surge level. *NB.: Points on the left hand side of the hurricane will experience a set-down in surge height because of the offshore blowing winds.*

3.1.3. Pressure

The pressure distribution equation is based on the work of Schloemer (1954). He took the spatial distribution of the atmospheric pressure and formed the following equation:

$$p(r) = p_0 + \Delta p \cdot e^{\left[-\left(\frac{r_m}{r}\right)^B\right]} \qquad (4)$$

In this equation $p(r)$ is the atmospheric pressure at a distance r from the center of the hurricane. p_0 is the pressure at the center of the hurricane. Δp stands for the pressure difference between the normal pressure at sea level(1013 mBar) and the pressure at the center of the hurricane. r_m expresses the radius of maximum winds, where r is the distance of the point of interest to the center of the hurricane. The B is the Holland-B parameter, of which a detailed description will be given in paragraph 3.1.4.

In theory there is a linear relation between the surge level and the pressure differences between the center and the surroundings of the hurricane. A drop in pressure of 100mbar will result in a water rise of 1m. The pressure is lowest in the center of the hurricane, and peaks in the area dubbed the radius of maximum winds. Beyond this point the pressure differences will become smaller, and so the surge levels will be at their highest point in the center of a hurricane. (Vickery & Skerlj, 2006).

3.1.4. Holland-B

The pressure profile of a hurricane is expressed by the Holland-B parameter. The pressure profile is most influential around the hurricanes eye wall. A high Holland-B parameter results in a narrow pressure profile, and consequently in a higher pressure difference between the lowest pressure point and the highest pressure point. A low Holland-B parameter sorts the opposite effect. This parameter can vary between 0.7 and 1.5. The most commonly used Holland-B parameter is 1.27, which is the value that is also used to avoid over- or underestimation of the pressure profile in case there is no available data on the Holland-B parameter.

In figure 11 the pressure profile is displayed. The green line has a Holland-B value of 1.8, the red one has been set on 1.27 and the blue one is set on 1.0. The figure clearly shows that a higher Holland-B value depicts a hurricane with a narrow eye.

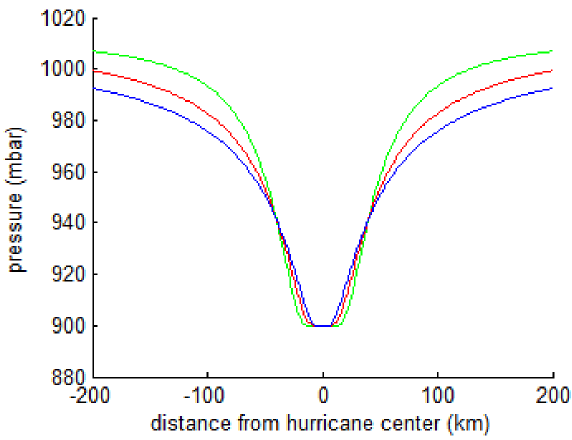


Figure 11 – Pressure profile of a hurricane where only the Holland-B parameter is changed (picture source: Van den Berg 2008)

3.1.5. Dominant wind speed

In the equation the V^2 variable stands for the dominant wind speeds on a point. To calculate this a relation between the gradient wind field and a specific point can be conducted. The upper layer of the hurricane is called the gradient wind field, an area that is characterize by friction free wind speeds. The equation to calculate the gradient wind field can be derived from a combination of the gradient balance equation and the pressure distribution of a specific hurricane. After this we will use Blaton's adjusted radius of curvature to describe the asymmetry in the wind field. To get to the whole gradient wind field equation, we'll first have a look at the gradient balance equation.

$$\frac{1}{\rho}\frac{\partial p(r)}{\partial r} = \frac{V_{gr}^2}{r} + fV_{gr} \qquad (5)$$

With ρ as the air density [kg/m^3], $\frac{\partial p(r)}{\partial r}$ as the slope of the pressure profile, p as the atmospheric pressure, [hPa], V_{gr} as the gradient wind speed in [m/s], r as the distance to the center of the hurricane in [m] and f as the coriolis parameter [1/s] *(Klaver, 2006) & (Vickery, 2000).*

Blaton is using an adjusted radius of curvature to account for the asymmetry in the wind speeds. This asymmetry is the result of the storm's movement in a forward direction with a constant speed. The adjusted radius of curvature is described by Blaton with the following equation.

$$\frac{1}{r_t} = \frac{1}{r}\left(1 + \frac{C_{fm}}{V_{gr}} sin(\emptyset)\right) \qquad (6)$$

Where r_t expresses the distance to the center of the hurricane in [m], r stands for the radius of an isobar[m], C_{fm} expresses the forward movement of the hurricane [m/s], V_{gr} as the gradient wind speed in [m/s] and $\emptyset$ as the angle of the radius vector and the direction of hurricanes movement [^{0}] *(Klaver, 2006) & (Vickery, 2000).*

By combining the gradient wind field equation (5) with the pressure distribution equation (4), and substituting r in equation (5) with r_t from the equation of Blaton (6), the following relation can be expressed:

$$V_{gr}(r) = \frac{1}{2}\cdot\left(C_{fm}\cdot sin(\emptyset) - f\cdot r\right) + \sqrt{\frac{1}{4}\left(C_{fm}\cdot sin(\emptyset) - f\cdot r\right)^2 + \frac{B\cdot\Delta p}{\rho}\cdot\left(\frac{r_m}{r}\right)^B\cdot e^{\left[-\left(\frac{r_m}{r}\right)\right]^B}} \qquad (7)$$

Again V_{gr} stands for the gradient wind speed in [m/s], C_{fm} for the forward movement of the hurricane [m/s], $\emptyset$ for the angle of the radius vector and the direction of hurricanes movement [^{0}], f for the coriolis parameter [1/s], r for the radius to the center of the hurricane (not the Blaton adjusted radius)[m], B for the Holland-B parameter [-], Δp for the pressure difference between the normal and the minimum pressure [Pa], ρ for the air density [kg/m^3] and r_m for the radius of the maximum winds [m].

To find the wind speed for a specific point we first need to calculate the distance. The specific points and the storm track are both given in latitude and longitude coordinates. To calculate the distance between two points the following equation can be used:

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

This equation consist of $\emptyset_s, \lambda_s; \emptyset_f, \lambda_f$ are the latitude and longitude coordinates of the different stand and forepoints. In the equation only $\Delta\lambda$ is used, which is the difference between the stand and forepoints longitude. $\hat{\sigma}$ stands for the angular distance. If this angular is multiplied by the radius of the earth, the distance between two points can be found. The radius of the earth is 6372,795km

Because now the gradient wind field is known and the distance between two points, this way the dominant wind speed can be calculated. The dominant wind speed is introduced because surge levels will be higher if the wind is blowing perpendicular to an object like the shore or a levee. For offshore points the northern blowing wind will most likely be the dominant one.

3.2. Integrated Kinetic Energy

IKE is an indicator of the potential destructive power of a hurricane. It is based on the kinetic energy of a forward going mass, and is then applied on hurricanes because they also have a forward going mass. This application was first done by D. Powell and A. Reinhold (2007), who were seeking to improve the assessment of the potential damage a hurricane may cause. Ironically the hurricane that really illustrated the importance of their addition was named hurricane Ike (2008). On the Saffir-Simpson scale this hurricane was classified as a category 3 hurricane at landfall, primarily based on the winds speeds around the "eye". But due to the sheer size of the wind field, wind forces were only gradually decreasing away from the hurricanes "eye". Because of this the wind could still produce enough energy to affect a large body of water. Hurricane Ike caused a surge level of 8.16 ft. in New Orleans, which lies at a distance of 210 miles from the hurricanes eye.

Our improvement of the beta version consists in taking the kinetic energy of a hurricane into account, a factor that was left out in the beta version of eSURF. The kinetic energy is important because a hurricane with a tremendous wind field can still generate a high surge level far away from the hurricane track. Hurricane Ike illustrates this point. It was classified as a category 2 hurricane, but the kinetic energy of hurricane Ike was even greater than that of Katrina. To capture this aspect of hurricanes with eSURF, a better understanding is needed of how the kinetic energy of a hurricane is built up.

3.2.1. Gradient wind field

The first step in calculating the IKE consists of determining what the wind field of a hurricane looks like. This can be done by calculating the gradient wind field. In paragraph 3.1.5 this has already been explained.

3.2.2. Theory of IKE

When the gradient wind field is determined the IKE can be calculated. This calculation is based on the *translational kinetic energy* equation. This translational kinetic energy is one of the 3 kinds of kinetic energy that stems from the theory of Gottfried Leibniz and Johann Bernoulli. This translational kinetic energy consists of the energy of a moving mass. It is, in other words, the movement of mass from one point to another. By multiplying the mass of the object by $\frac{1}{2}$ and the square of the objects speed, we can calculate the translational kinetic energy.

$$E = \frac{1}{2} \cdot m \cdot V^2 \qquad (8)$$

With m as the mass the moving object has [kg], and V as the speed of the mass of the object in [m/s], we obtain E as the translational kinetic energy of an object measured in [J] or [(kg m/s^2) (m)]. *(Translational kinetic energy 2009)*

This can also be applied on the mass of moving water or air, where the motion is caused by a hurricane. The integrated kinetic energy (IKE) equation is as follows:

$$IKE = \int \frac{1}{2} \cdot \rho \cdot U^2 \, dV \qquad (9)$$

In this equation IKE is measured in [TJ], ρ is the density of the air in [kg/m^3] and U is the wind speed in [m/s]. The equation shows that the IKE is expressed in terra joule, not in Joule, because the gradient wind field is expressed in cubic kilometers [km^3]. *Powell, M.D. and Reinhold, T.A. (2007)*

By using the gradient field equation (7) the hurricanes wind speed can be calculated for the whole of the hurricane, and can be used in the IKE calculation. But IKE is not calculated on basis of the entire upper layer, since it is too big to base the IKE calculation on. The reason for this is that a hurricane usually has a trapezium shape. Basing the IKE calculation on the gradient wind field will eventually lead to an overestimation. This overestimation can, however, be sorted out by use of the surface wind field, which is a trimmed down version of the calculation of the gradient wind field. It is based on the theory of Brunt, D. (1939), who showed that the surface wind speed can be calculated by using the following equation:

$$V_s = V_{gr} (cos\ \alpha - sin\ \alpha) \qquad (10)$$

V_s stands for the surface wind speed, V_{gr} for the gradient wind field and α for the angle of deflection of the surface wind direction from the isobar.

The ratio, as given by Klaver (2006), between the parameter V_s/V_{gr} is 0.5 for a hurricane over land and 0.7 for a hurricane over water. This means that there is more friction over land than over water. In the literature a ratio of 2/3 is often used, but for the eSURF model a calibrated parameter of 0.83 is used because a standard ratio of 0.7 lead to an underestimation of the IKE. The calibration was based on the best fit with known IKE values from historical storms.

After the surface wind field is calculated it is possible to integrate the wind field. The IKE integration is used to calculate the kinetic energy of the whole hurricane. We first integrate the surface wind field, and then integrate the whole volume of the hurricane. Because eSURF is calculating a hurricanes surface wind field over cubicles of 1 km^3, the integration can be managed by adding the whole surface wind field.

The IKE calculation of *Powell, M.D. and Reinhold, T.A. (2007)* is based on three rings of the wind field. The first one is IKE-TS, which stands for 'tropical storm', and is the outside ring of a hurricane with the lowest wind speeds. It is the circle between 34 and 50 knots, which is between 17.5 and 25.7 [m/s]. The middle ring is called IKE-TS-50 and is based on the section between 50 and 64 knots, which means wind speeds of around 25.8 to 32.9 [m/s]. The last ring is where the highest wind speeds of the hurricane are located. It is called IKE-H, and is next to the 'eye' wall. Wind speeds here are higher than 60 knots, which is 33 [m/s].

A ring structure is used because a hurricane is not circular at all times. The IKE depends on where the highest wind speeds are at every isobar. But because the IKE in eSURF uses one by one square kilometer grids for surface wind speed, which are then integrated over a pack of 1 km, the use of the different isobars is unnecessary. This is yet another advantage of eSURF. In figure 12 the surface wind field for hurricane Ike has been modeled.

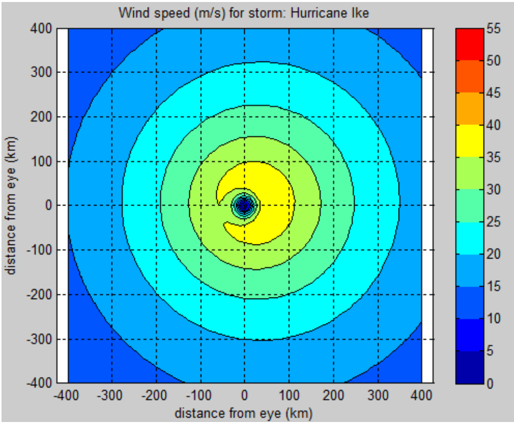


Figure 12 - The Surface wind field of Hurricane Ike

3.2.3. IKE implementation

In equation (3) the surge level that is calculated consists of the water zero level $H_{0,}$ the coefficients A, multiplied by the V^2, and B, multiplied by dp. In the new equation the surge level will also have a linear relation to the IKE. This is done because the beta version underestimated hurricanes further away from the point, hurricanes that can produce a significant surge because of the span of their wind field. To also take the IKE into account, the regression model has been enhanced leading to the following alteration of equation, which includes the coefficient C and the IKE parameter (3):

$$H_{model} = H_0 + A \cdot V^2 + B \cdot dp + C * (IKE * \log(r)) \qquad (11)$$

The altered equation uses the extra coefficient C, an additional IKE parameter and the minimum distance between the 'eye' of the hurricane and the point of interest (r). log(r) is used because the IKE only influences points that are at some distance from the hurricanes track. Points nearby the hurricanes track are only affected by the local effects of the hurricane, but points that are outside the scope of the local effects take into account an extra surge effect generated by the IKE. In order to achieve this effect, the distance needs to be a part of the equation. Figure 13 shows the scope of the wind field of hurricane Ike, and displays a schema which shows the distance between the hurricane and one specific point.

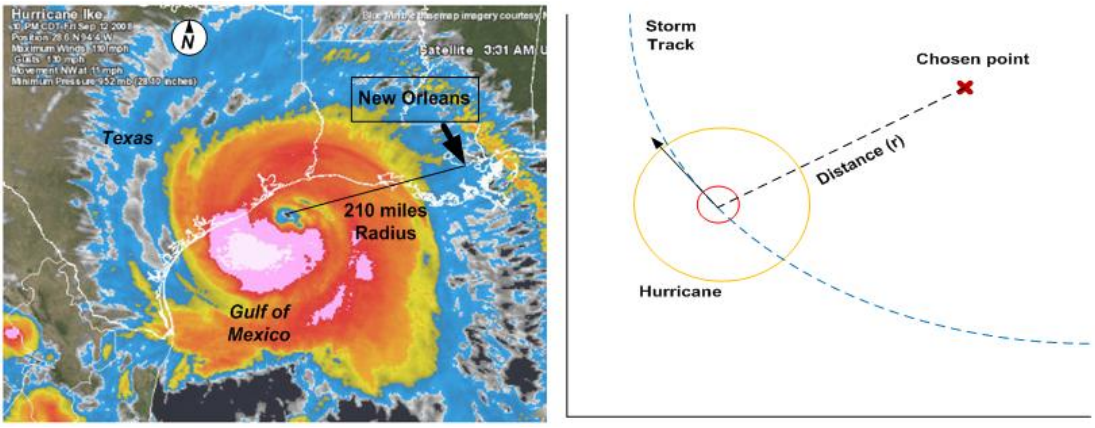


Figure 13 - Hurricane Ike on the left side and a schema of hurricane Ike on the right

The new multiple-linear-regression now takes into account 4 coefficients; H_0, A, B and the new coefficient C. The basic steps explained in chapter 3.1 are still the same, but are now done with four coefficients. This is how IKE is implemented in eSURF. The new flowchart is as follows:

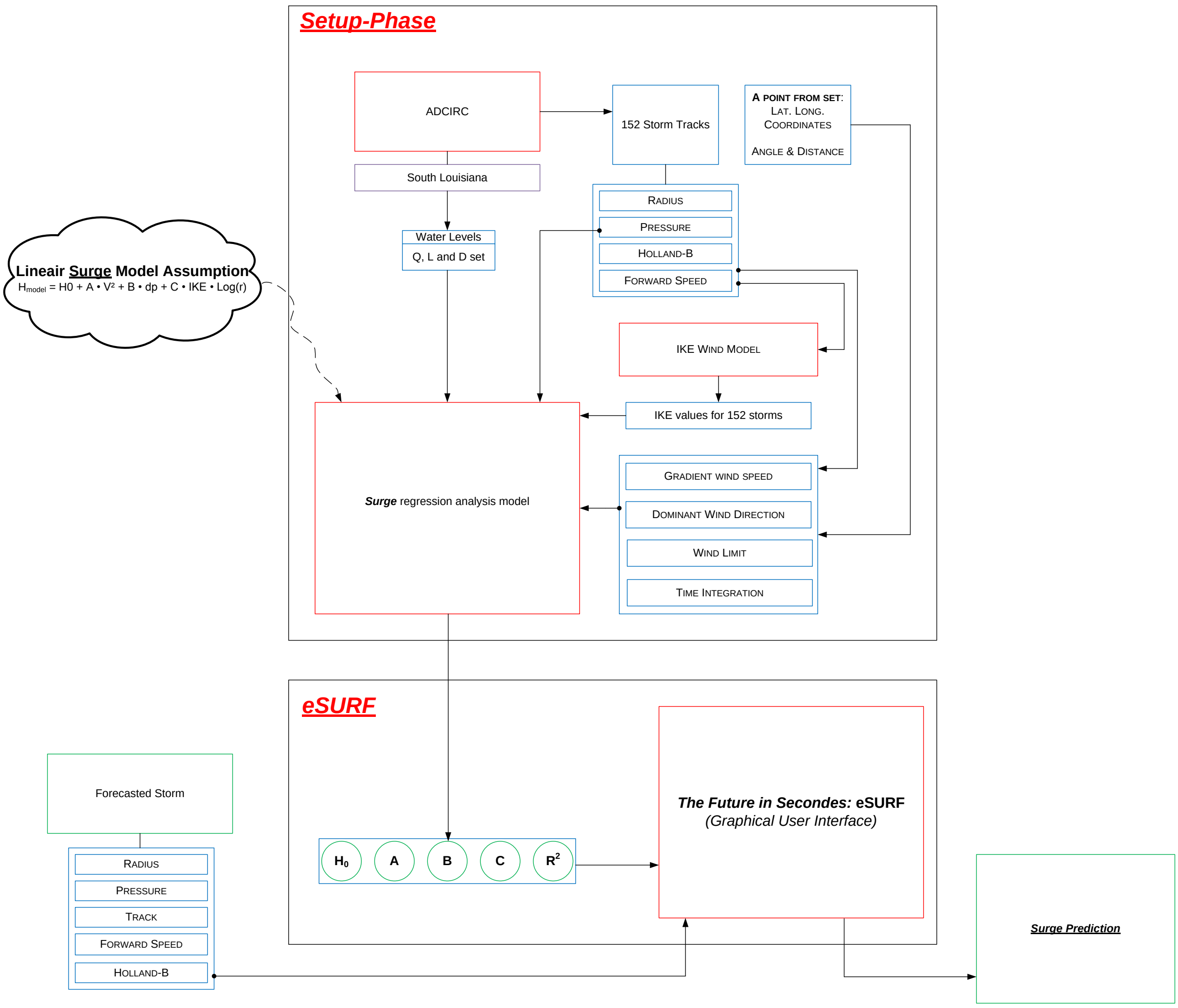


Figure 14 - Flow chart of the improved eSURF with IKE

3.2.4. The changes in R^2

The introduction of a new coefficient to the equation will improve the regression coefficient R^2. A selection of the total of 8 points is shown here in table 2. *NB.: that this has been validated for 54 points, all showing the same result.*

Stations	Points Qset	eSURF Bèta R2	eSURF IKE R2	∆ R2
Algiers Lock - GIWW (76240)	765	0,5503	0,6159	0,0656
Lake Pontchartrain at Lakefront Airport (85670)	550	0,5814	0,6104	0,0291
Bayou Bienvenue Floodgate East - MRGO (76025)	305	0,8534	0,8586	0,0052
	654	0,5747	0,6041	0,0294
Chef Menteur Pass nr Lake Borgne (85750)	648	0,7508	0,7662	0,0154
Rigolets near Lake Pontchartrain (85700)	574	0,7769	0,7909	0,0140
Bayou Trepagnier Control Structure -North (85663)	165	0,8512	0,8515	0,0002
Caillou Lake (Sister Lake) SW of Dulac, LA (USGS)	49	0,9384	0,9388	0,0003

Table 2 - R^2 change between the beta and the release version of eSURF

By introducing the new parameter IKE to the equation, the R^2 of every point is improved. Table 2 shows that some points have show more improvement than others. The points that show the most dramatic improvement are those that already had a low R^2 in the beta version. Points that had a high R^2 value in the beta version show only a slight improvement when the IKE is integrated in eSURF. The rate of improvement varies between 0.002 and 0.06.

Based on table 2 we can conclude that the integration of the IKE into eSURF has a positive effect, in comparison to the beta version of eSURF, on the regression R^2. This is, however, to be expected, since the regression can look for a best fit between the maximum surge level and not only V^2 and dp, but also the new coefficient IKE. This leads to a better regression fit, since the fit is closer to the value 1.0 which stands for a perfect model fit, and consequently to a better fit for every point. Please note that this is not evidence that eSURF is improved by adding IKE to the equation. The fit of R^2 can still improve, even if an extra parameter was included that is not related to IKE, because the adding of an additional fitting parameter shall always leads to a better fit of R^2.

4. Prediction Model Validation

The model eSURF has been improved with the addition of the IKE. Now a validation is needed to test the prediction capabilities of eSURF. This test consists in comparing the outcome of the model with the data of historical storms. The validation thus requires 5 historical storms. These are hurricanes Ike *(2008)*, Betsy *(1965)*, Andrew *(1992),* Katrina *(2005)* and Gustav *(2008).* Besides this, eSURF will also be compared to the beta-version to get a clear picture of its improvements.

4.1. Selection of points near gages

The validation process requires a selection of surge level points from the huge amount of available data, which is why we will only look at the points of the Q-set because its points are spread evenly over the city of New Orleans and the larger Louisiana coast. Of this set 712 points have actual ADCIRC maximum surge level data, and so 712 points can be used. As a further criterion of selection only points with a correlation (R^2) of at least 0.6 will be used. This leaves us with 577 useable points. But this is still too much to make a manageable validation.

1	17th Street Canal 1 - ICS Lake-side
2	Algiers Lock - GIWW
3	Bayou Bienvenue Floodgate East - MRGO
4	Bayou Boeuf Lock - West
5	Bayou Dupre Floodgate - MRGO side
6	Bayou Trepagnier Control Structure -North
7	Caillou Lake (Sister Lake) SW of Dulac, LA
8	Catfish Point Control Structure - South
9	Chef Menteur Pass nr Lake Borgne
10	Cross Bayou Canal at Hwy 61 - South of Control Str
11	Golden Meadow Floodgate (South)
12	Harvey Canal at Boomtown Casino
13	Harvey Lock at GIWW
14	Lake Pontchartrain at Lakefront Airport
15	Lake Pontchartrain at Mandeville
16	Lake Pontchartrain at West End
17	Orleans Ave Canal 1 - ICS Lake-side
18	Rigolets near Lake Pontchartrain

Figure 15 - Chosen validation Gages

In order to find a suitable amount of data points for our validation, all the gages around New Orleans are checked for actual measured data of hurricane IKE and Gustav. The gages with actual measured data, in combination with the points that have a R^2 of 0.6 at least and are near these gages, will be used for the validation. The gages that are in the Mississippi river are not taken into account, because water measures in the river often vary and do not represent the actual surge levels produced by hurricanes. Eventually there are 18 gages and 54 Q-points that are close-by that can be used for the validation. The following gages, see figure 15, are used for the validation. In appendix 8.2 a map can be found of all the chosen gages and the points.

As a last step in making the 54 points and the 18 gages operational, a mean has been taken for every gage with its nearby points. Eventually the validation of the hurricanes will be executed with the mean of every gage, which means a total of 18 gages, and the mean of their 54 points, per storm. This is a manageable way to perform the eSURF validation.

4.2. The 5 Historical storms

For the validation on surge levels, 5 historical storms will be used. For the completeness the beta version is also included to assess the prediction improvement achieved by including IKE. Two historical hurricanes have actual measured data, these are the historical storms Ike and Gustav. For hurricane Andrew and Betsy only there is only data from a few gages, because not all gages were operational during these storms. For hurricane Katrina little measured data was found, therefore the validation is only based on the data provided by ADCIRC. In figure 16 a selection of points and gages can be seen in the funnel. The yellow thumbtacks are gages, and the white square blocks are the chosen points around these gages.

Figure 16 - Funnel with gages and chosen points

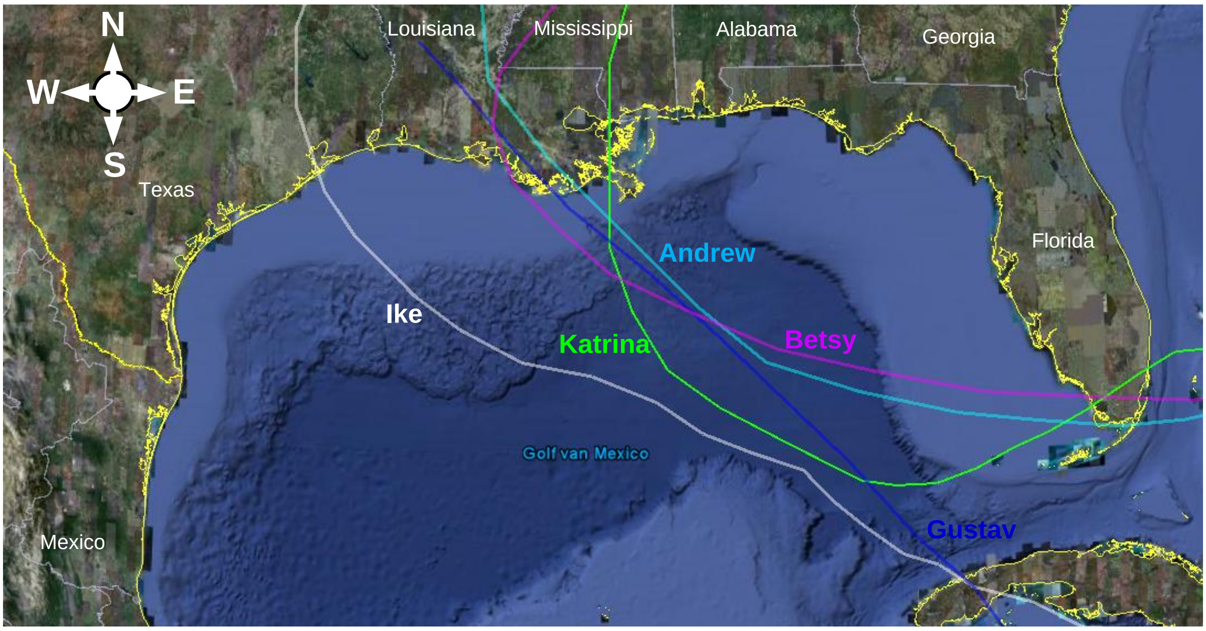


Figure 17 - 5 historical storm tracks

In figure 17 the 5 historical storm tracks are shown. The white track is hurricane Ike, the purple track is hurricane Andrew, dark blue is hurricane Gustav, light blue is hurricane Betsy and green is hurricane Katrina.

Every hurricane is schematized by 4 parameters; pressure, radius of maximum winds, central speed and the Holland-B parameter. To find the best suiting combination for every hurricane, different information sources have been used. These are the hurricane reports from the National Hurricane Center, storm tracks information from the website Sura Scoop, the Whitepaper from D.T. Resio (2007), Validation Runs from the Bricka and information on hurricanes from Wikipedia.

To start the validation of eSURF the right parameters need to be chosen. The best way to do this is to validate the parameters at landfall because this represents the actual influence that a hurricane has had at a chosen points the best. The following parameters are chosen for the validation:

Hurricane	Ike	Betsy	Andrew	Katrina	Gustav
Pressure [mbar]	952	948	955	934	954
Radius of Max Winds [n.m.]	34	40	16	23	21
Central Speed [mph]	9	20	9	8	10
Holland-B [-]	1.06	1.27	1.27	1.10	1.2

Table 3 - The used parameters for our historical hurricanes

The chosen parameters are based on the best sources in articles there were to be found. But there are some parameters that could not be found (indicated in red in table 3). These parameters were then chosen based on satellite images and the known IKE-values. The Holland-B parameter is based on articles as well, but for hurricane Betsy and Andrew no information was found. These two are set on 1.27 because for unknown Holland-B parameter the best choice is 1.27 as explained in 3.1.4.

The central speeds of the historical storms were also unknown, which is indicated in blue in table 3. These were chosen based on information on the the hurricanes produced. Luckily the equation isn't all that sensitive to the maximum wind speeds parameter, and so no significant errors will occur as a result of this.

4.3. eSURF beta and release version validation on historical hurricanes

4.3.1. Validation Hurricane Ike 2008

The first validation concerns hurricane Ike. This hurricane made landfall on 13 September 2008 at Houston, Texas. The thing that made this hurricane stand out was the enormous span of its wind field. This wind field was around 420 miles in diameter (780km). Because of this huge span, surge levels were also observed in New Orleans. The beta version of eSURF has therefore been improved with Integrated Kinetic Energy to cope with this underestimation. Hurricane Ike had an IKE value of 151TJ.

For an overview of the forecasted surge levels, figures have been made of the validation between eSURF and the measured data. We have also made a comparison between the beta version and eSURF to see what the improvements are.

In figure18 the surge levels for hurricane Ike are shown. In this figure, the blue columns are the observed surge levels, the red columns are the surge levels predicted by the beta version and the green columns are the surge levels predicted by eSURF.

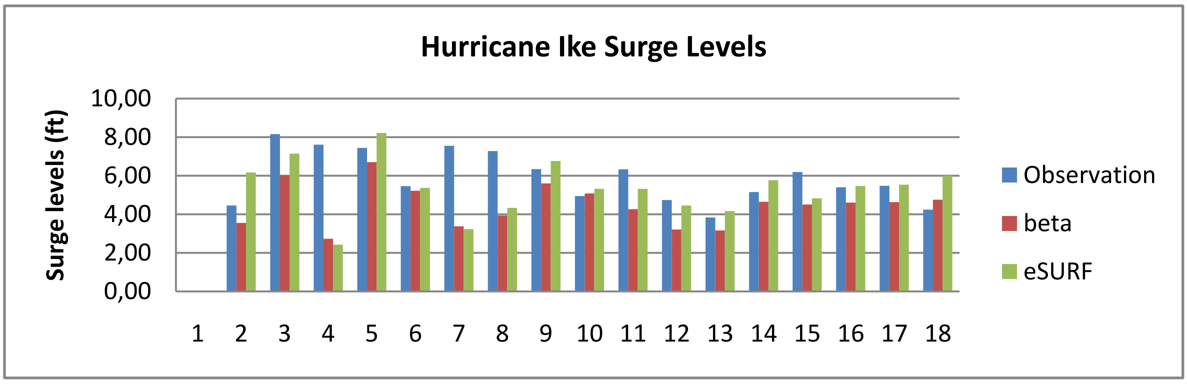


Figure 18 - Different surge levels for hurricane Ike around the 18 gages

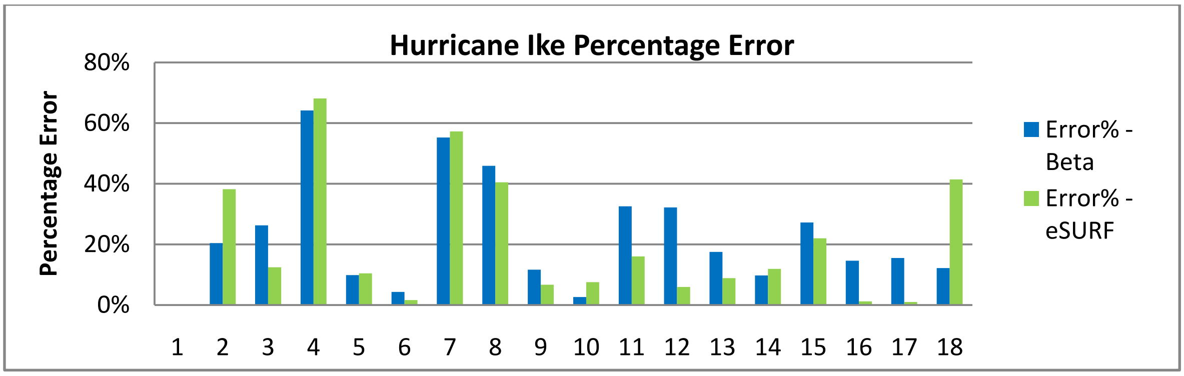


Figure 19 - The error percentage which shows how good the predictions are in comparison to the observed data

In figure 19 the error margin of the predicted data has been calculated. This margin of course checks against the observed data, and was calculated with the following equation: (ABS((predicted-observed)/observed)*100%)). To eliminate all the negative values, only the absolute value has been calculated. This has been done to gain a better comparison between the error margins of the beta version and eSURF.

In both figures, 18 and 19, the x-axis displays the 18 gages which were used for the validation. The y-axis displays the surge levels or the error margin. The figures show a total of 11 improvements and 6 deteriorations. This means that overall the model with Integrated Kinetic Energy is an improvement of the beta version. By using the following calculation the average improvements and deteriorations can be calculated. The equation is as follows: (ABS((predicted_beta-obs)/obs)-(predicted_eSURF-obs)/obs)*100%))/(#improvements or deteriorations). Improvements are where eSURF scores better than the beta version. For hurricane Ike this is 7%. The same equation can then be used to calculate the deteriorations of eSURF compared to the beta version. This is 4 %, meaning that eSURF is on average better than the beta version.

The improvements of eSURF can also be seen in a regression graphic, see figure 20. In these two graphics there are two lines, a dotted line and a blue line. The dotted line is the one on one line, the blue one is the regression line. Figure 20 consists of two figures. On the left side the regression graphic is shown for the beta version, on the right side is the regression graphic is shown for eSURF. They both depict a regression between the maximum observed surge levels on the x-axis and the predicted surge levels on the y-axis. The first thing that can be noticed is that the regression line of eSURF is closer to the dotted one on one line, which means an improvement for most points.

What can also be noticed are the differences in the R^2 values. The beta version has an R^2 value of 0.25, eSURF has an R^2 value of -0.00459. This is strange because this means that all the points together are uncorrelated. The problem lies in the values of two gages and their chosen points. These are the gages that are located to the south west of Louisiana. In the figures they are highlighted with a red circle. It becomes clear that these two gages don't shift up in the calculated eSURF surge levels, some of their points even dropped a bit. This means that the regression that is calculated for eSURF is out of perspective. Additionally it needs to be said that a good correlation does not mean that the used model is good, for example when every point in the cloud of points is in a tight straight pack but all 10% lower or higher than the one on one line. The correlation can still be as high as 0.98, but the comparison between the measured data and the calculated data (the one on one line) can still be off by as much as 10%. This could explain the problem at hand.

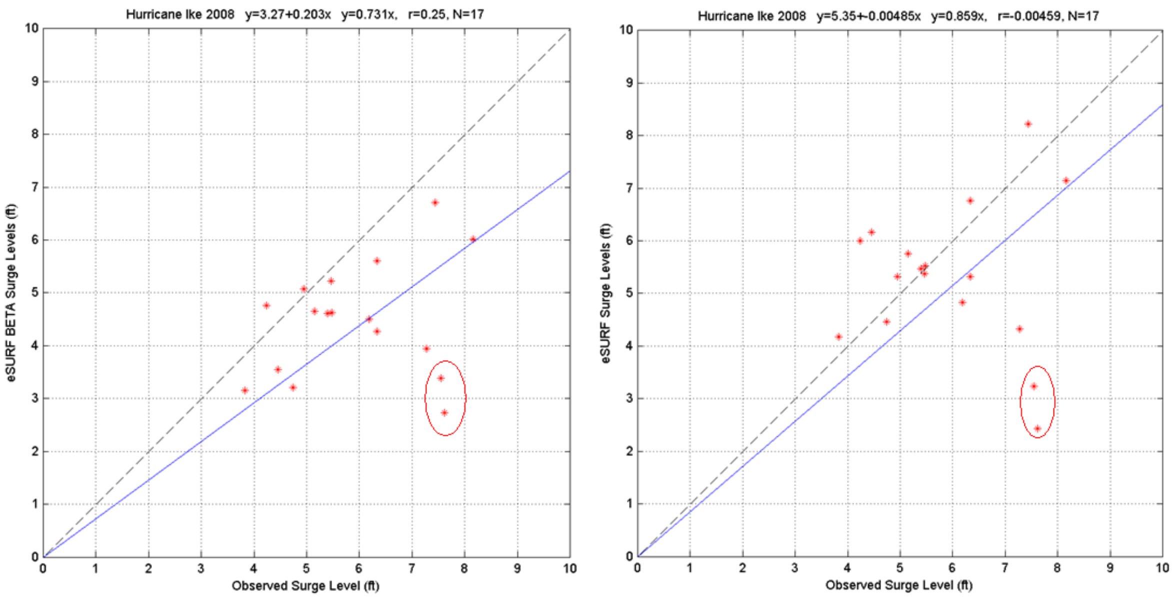


Figure 20 - On the left is the regression graph for the beta version, on the right the regression graph for eSURF

The good thing is that most of the points get a shift upwards, meaning that the IKE-value in part does what it is supposed to do in the new equation. It's weird though that there are still points that shifted down wards. The cause of this lies in the distribution factor of the IKE. The distribution factor introduced in paragraph 3.2.3 was Log(r). If you plot this in a graphic it would look like the graphic to the left in figure 21.

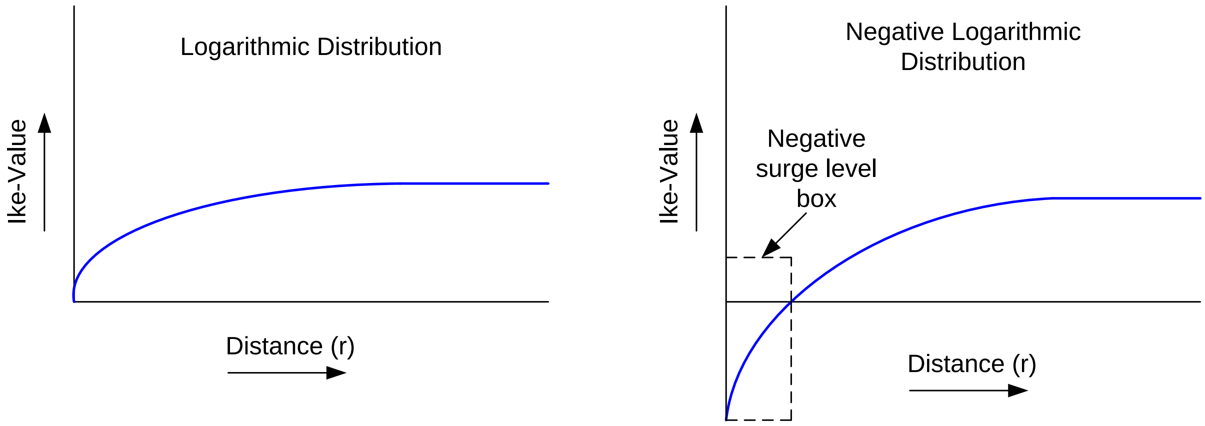


Figure 21 - The distribution plots by the logarithmic factor, on the left the normal logarithmic and on the right the possible negativity of the logarithmic.

On the right side of figure 21 the negative part of the logarithm can be seen. This means that the distribution could be negative if the C coefficient were to be negative, which influences the surge level of points near the hurricane. This is what is happening here in these regression figures. Only points near the southwest of Louisiana were negative affected by this logarithm, which caused them to shift downwards.

4.3.2. Validation Hurricane Betsy 1965

This hurricane devastated the city of New Orleans almost half a century ago. Hurricane Betsy made landfall on the 10th of September 1965, near Grand Isle, Louisiana. Unfortunately not a lot of information on this hurricane is still available. A lot of the parameters used to validate this hurricane are based on estimations. Betsy was typified by an extremely large 'eye' of 40 miles (64km). Because of this the radius of maximum winds is scaled at 40 nautical miles. For the validation Betsy is based on measured data for gages Mandeville (15) and West End (16). The other gages are based on ADCIRC data.

The information and predictions on hurricane Betsy are presented in the same way as was done for hurricane Ike. In figure 22 the surge levels for hurricane Betsy are shown. In this figure, the blue columns are also the observed surge levels, the red columns are the surge levels predicted by the beta version and the green columns are the surge levels predicted by eSURF.

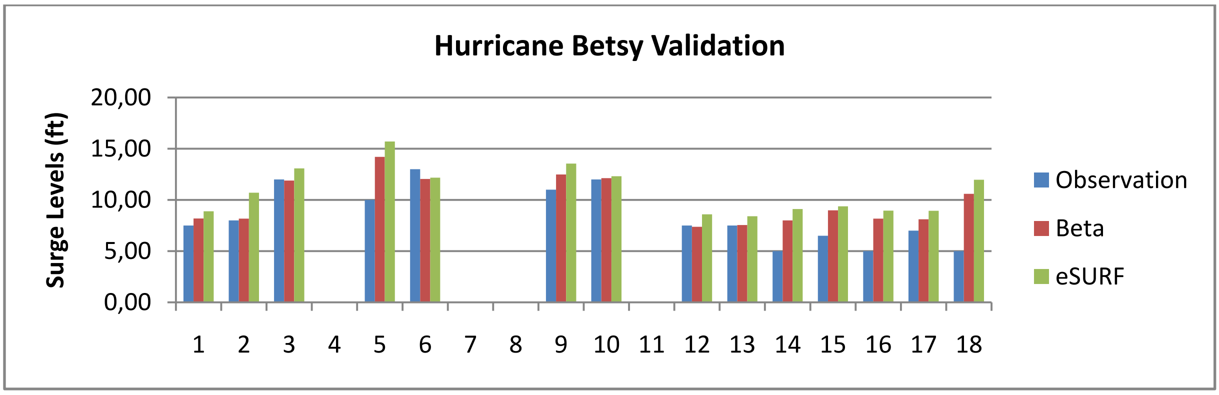


Figure 22 - Different surge levels for hurricane Betsy around the 18 gages

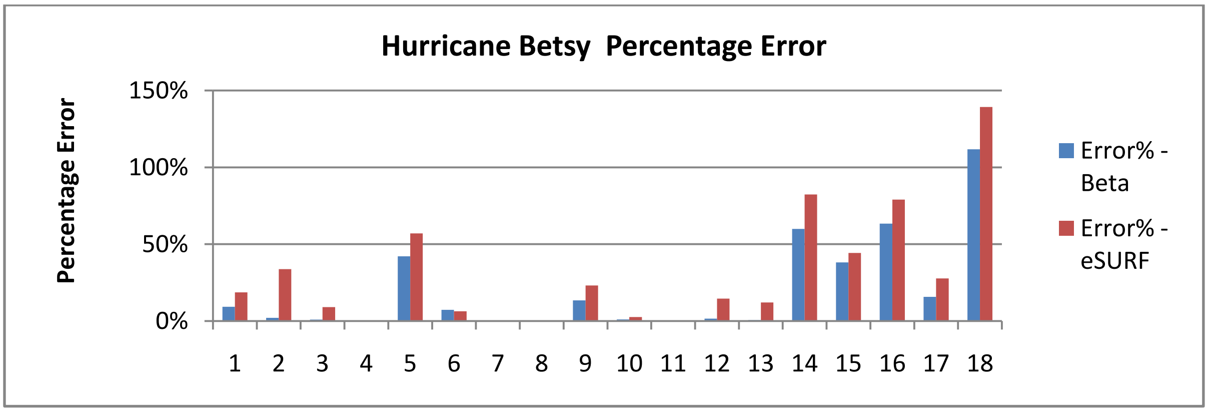


Figure 23 - The error percentage on how good the prediction is in comparison to the observed data

In figure 23 the error margin of the predicted data has again been calculated. Again the margin checks against the observed data. The equation used is: ((predicted-observed)/observed)*100%).

Figure 22 and 23 show that eSURF performs worse than the beta version. Every surge level predicted by eSURF is higher than the beta version, and hence higher than the observed data. This also shows clearly in figure 23, which depicts the error margins. In figure 24 the regression graphs are shown. Here we can see that the beta version already overestimates in comparison to the one on one line on the one on one line. Adding the IKE value, as in eSURF, will only result in an even higher surge level.

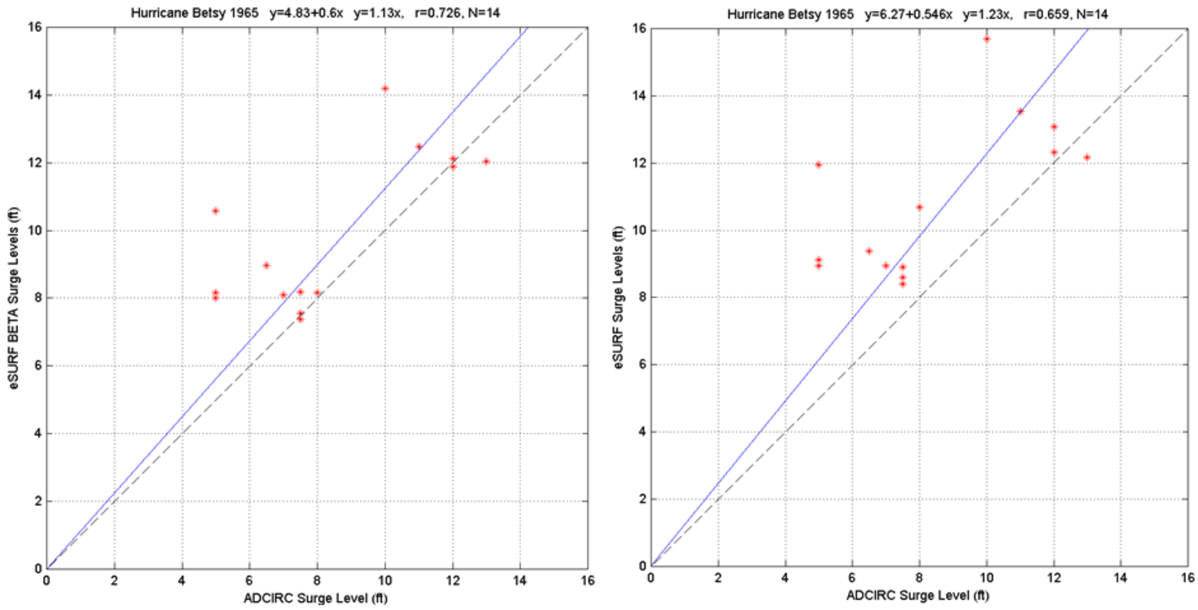


Figure 24 - On the left is the regression graph for the beta version on the right the regression graph for eSURF

For this hurricane the surge calculation is way off because the estimated IKE value for hurricane Betsy is overestimated. This estimation for hurricane Betsy is 209TJ, which is 58 TJ higher than that of hurricane Ike. This means that the radius of maximum winds is further away from the center, which is a represented by the Holland-B parameter (A higher Holland-B parameter gives a larger hurricane 'eye'). Unfortunately no data has been found on the different parameters, the only data that is still available concerns the pressure at landfall and the 40n.m. of the radius of maximum winds, which is based on the whitepaper of D.T. Resio (2007).

But how come that eSURF overestimated the surge levels so drastically? Why was eSURF so far off in the case of Betsy, especially in comparison to the beta version? The answer lies with the input data that eSURF is using. As previously explained, eSURF makes use of a database that consists of the data of 152 ADCIRC storms. This database contains all the relevant parameters, such as the pressure, the radius of maximum winds, the forward speed and the Holland-B parameter. In addition to this, eSURF is also using the distance between the storm track and a chosen point, the angle and the track itself. However, these last few parameters are fixed and cannot be the cause of the overestimation of hurricane Betsy. So the problem must lie with the 152 storms that were used by ADCIRC.

A first reason for an under- or overestimation of a hurricane could have to do with the hurricane tracks of the 152 storms that make up the data for the database that eSURF is using. If a hurricanes track is not in the same range as, or close to, the hurricane tracks of the 152 storms that eSURF uses, problems could arise. Hurricane Betsy was well in between these 152 tracks. Hurricane Ike, on the other hand, was nowhere near these 152 tracks and still did well in the validation. It seems that this cannot be the cause of this problem.

So the problem must lie with the data that is used to calibrate the parameters that aren't fixed. These are the central speed, which will be calibrated to a value between 6 and 18 mph, the pressure, which will be calibrated between 900mbar and 960 mbar, the radius of maximum winds, which will be calibrated between the 6 and 35 n.m. and the Holland-B parameters, which will be around 1.27. Hurricane Betsy was outside the range of the database with respect to the parameters central speed and radius of maximum winds. This is the reason that hurricane Betsy is so overestimated by eSURF. eSURF requires the parameters of the storms that are used to be within the bounds of the database it is using.

4.3.3. Validation Hurricane Andrew 1992

The 3rd hurricane that will be used in this validation is hurricane Andrew. This hurricane made landfall on the 26th of August 1992, to the west of New Orleans. The IKE value was rather small, on August 24, two days before landfall, the IKE value was around 16TJ. The estimation of the IKE value at landfall is 37TJ. The data used in this validation is based on the measured data of gages Chef Menteur Pass (9) and Rigolets near Lake Pontchartrain (18). The other gages are based on ADCIRC data.

Again the data is presented in the same format as with hurricanes Ike and Betsy. The forecasted surge levels are again presented in figures for an easy overview. In figure 25 blue shows the observed surge levels, red the beta surge levels and green the surge levels predicted by eSURF.

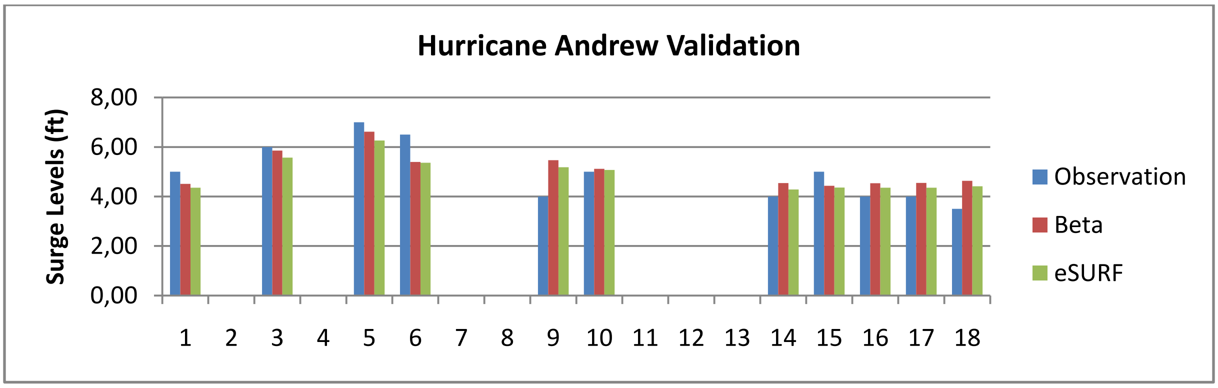


Figure 25 - Different surge levels for hurricane Andrew around the 18 gages

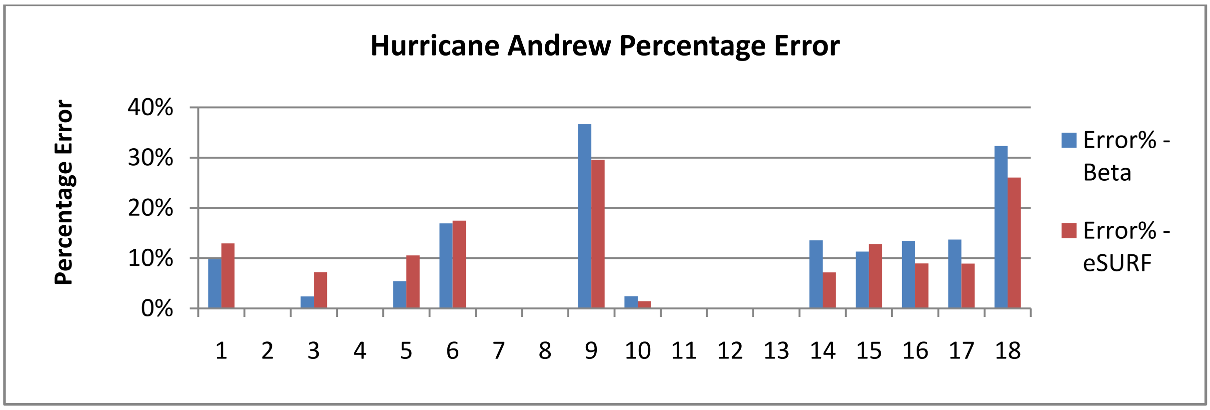
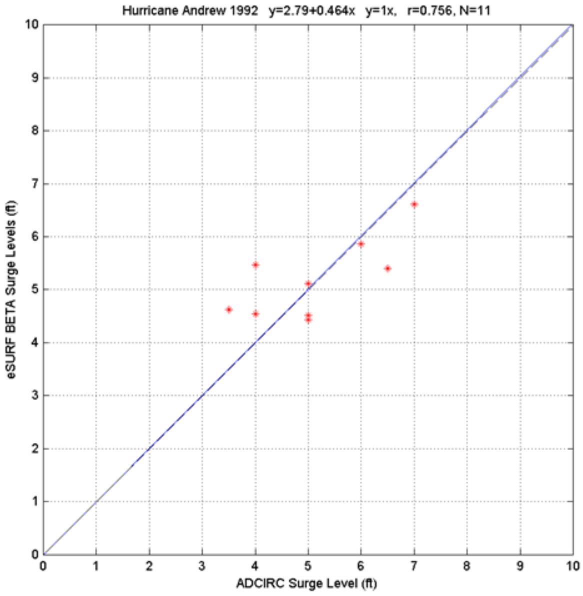


Figure 26 - The error percentage on how good the prediction is in comparison to the observed data

In figure 26 the error margin of the predicted data has again been calculated. Again the margin checks against the observed data. For Andrew only 11 gages could be used because there was no data found for the other gages. Figure 26 clearly shows that 6 gages show improvement, and 5 show deteriorations. It follows that the addition of the IKE does not really overall improve or worsen the beta version. The same results can be seen by calculating the average improvement; eSURF improved the model with an average of 3% against 1% deterioration.

This can be explained by the fact that the IKE value of hurricane Andrew was not really high, and the distances between the hurricanes track and the points were not very large. This can also be seen in the regression figure 27.



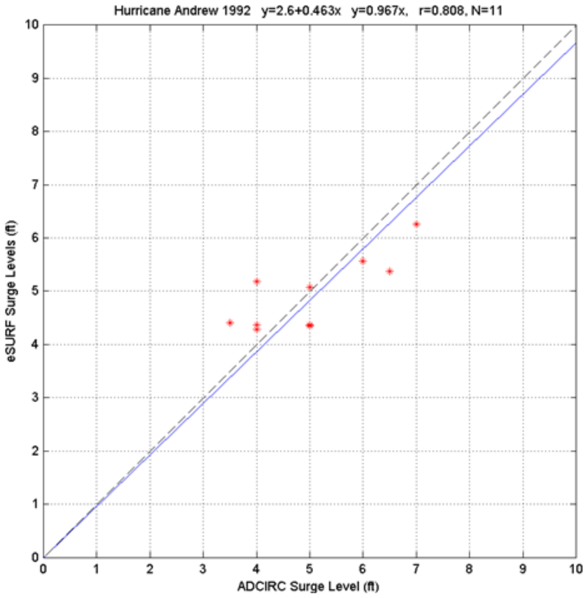


Figure 27 - On the left is the regression graph for the beta version on the right the regression graph for eSURF

This figure again shows that not much has changed; the points are still all around the one on one line. The regression line is lower in the eSURF figure, but it is still very close to the one on one line. Again this can be explained by the distribution of the IKE value, the distance between the hurricanes track and a certain point has not been taken into account. As a result the IKE value is still shifting all the points downwards. Because the hurricane was so close to the points the negative logarithms influences the surge levels on the different points. Despite the better regression coefficient of eSURF, on the right of figure 27, the differences remain small and rather unimportant. As said before, a better regression coefficient does not automatically mean a better representation of reality.

4.3.4. Validation Hurricane Katrina 2005

The 4th validation concerns hurricane Katrina. This hurricane made landfall on the 29th of August 2005, near the eastside of New Orleans. It was a relatively large hurricane with a radius of maximum winds of around 23 n.m. and a wind field that was almost 120 miles in diameters (190km). The validation of this hurricane is based on ADCIRC hurricane data, because little measured data was to be found for hurricane Katrina.

Again the data is presented in the same format as with hurricanes Ike, Betsy and Andrew. The forecasted surge levels are again presented in figures for an easy overview. In figure 28 blue shows the observed surge levels, red the beta surge levels and green the surge levels predicted by eSURF. Figure 29 shows the error margin of the predicted data, which has again been calculated and checked against the observed data.

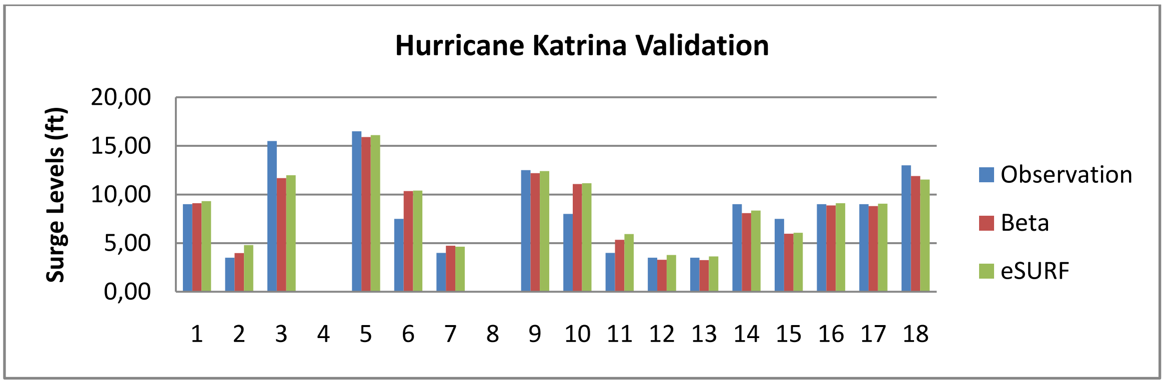


Figure 28 - Different surge levels for hurricane Katrina around the 18 gages

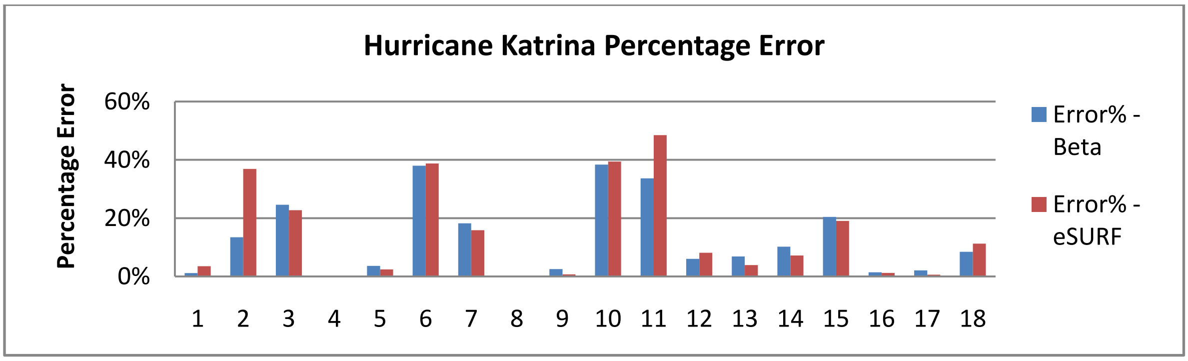
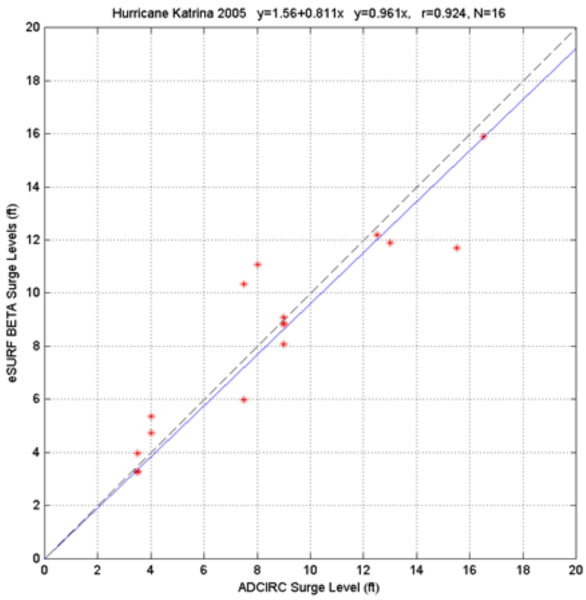


Figure 29 - The error percentage on how good the prediction is in comparison to the observed data

Figure 28 and 29 clearly show that eSURF scores a little better on some points, and a little worse on others with this hurricane. Out of a total of 16 points, because gage 4 and 8 had no value, 9 were more accurate than the beta version. What also stands out is that gages 2 and 11 have a much higher error margin. This is also reflected when we calculate the overall improvement of eSURF, the overall improvement of eSURF is 1% and the overall deterioration is 3%. These margins are largely due to the high error percentages of gages 2 and 11.

Figure 28 shows that the differences in surge level between beta and release version are not that big. This is a good sign because Katrina had an IKE value of 130TJ at landfall, but because of the way the IKE modeled in eSURF the parameter will only really matter if the points are far away from the storm track. Hurricane Katrina was rather close to most of the points, so the difference between the beta version and eSURF should not be too much. This conclusion also follows from the regression model, see figure 30.



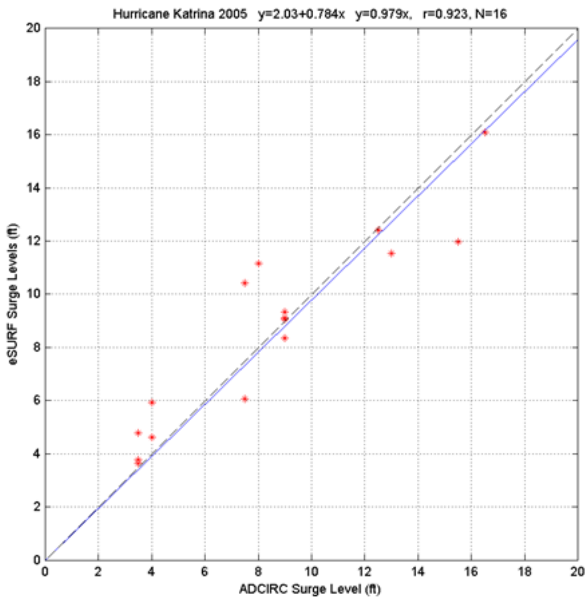


Figure 30 - On the left is the regression graph for the beta version on the right the regression graph for eSURF

Figure 30 shows that the regression line of eSURF better fits the one on one line. This means that overall, the release version of eSURF is an improvement of the beta version.

But there is still something going wrong at gages 2 and 11, what is causing the huge overestimation of these two surge levels? Yet again the cause lies with the distribution of the IKE-value. Gages 2 and 11 lie far away from the hurricanes track, on the left side and thus the offshore winds. This causes the surge levels there to lower. However, due to the misdistribution of the IKE value the logarithm increased the surge levels of these far away points rather than diminishing them. The same can be seen by look at gage 18. Because it was too close to the hurricanes track, it got a negative IKE surge level despite its being to the right of the hurricane.

4.3.5. Validation Hurricane Gustav 2008

The last hurricane that will be used as a validation storm is Gustav. This hurricane made landfall on the first of September 2008, to the west of New Orleans. In comparison to Katrina it was quite a small hurricane.

Again the data is presented in the same format as with hurricanes Ike, Betsy, Andrew and Katrina. The forecasted surge levels are again presented in figures for an easy overview. In figure 31 blue shows the observed surge levels, red the beta surge levels and green the surge levels predicted by eSURF. Figure 32 shows the error margin of the predicted data, which has again been calculated and checked against the observed data.

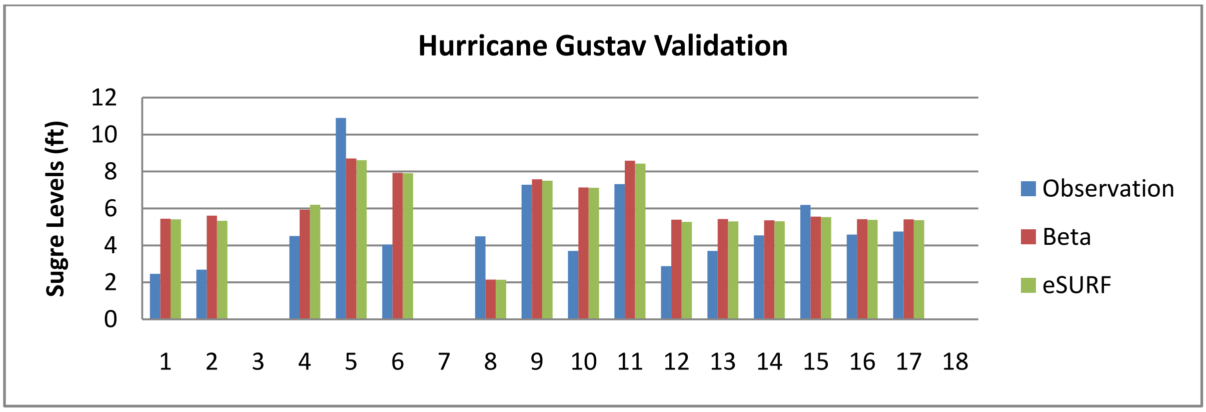


Figure 31 - Different surge levels for hurricane Gustav around the 18 gages

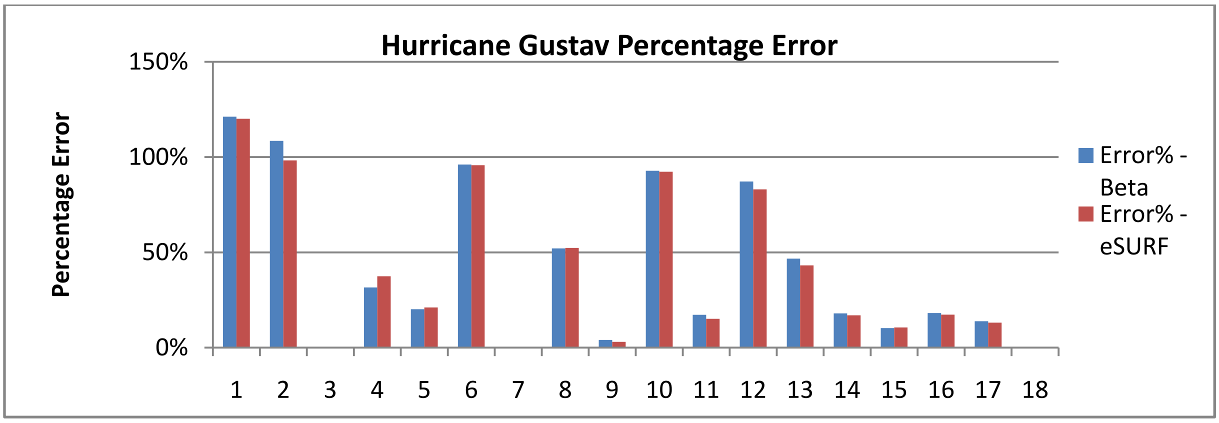


Figure 32 - The error percentage on how good the prediction is in comparison to the observed data

Figure 32 shows that for gages 1, 2, 6, 10 and 12 the error percentage are very high with both eSURF the beta version. This is caused by the location of these gages, directly to the east of the hurricanes track. As a result of this location, they get the maximum wind speeds and pressure. This problem may be caused by the initial parameters that were chosen. Hurricane Gustav was already overestimated by the beta version to begin with.

It can further be seen that eSURF tries to reduce this error by taking the IKE into account. Out of a total of 15 gages, 9 show improvements and 6 show deteriorations. The overall improvement is 2%, and the overall deterioration is 0%. This means that there is some improvement and no deterioration. What also follows from figure 31 is that the correspondence between the beta version and eSURF, both have almost the same surge levels for most of the gages. This can also be seen in the regression plots, see figure 33.

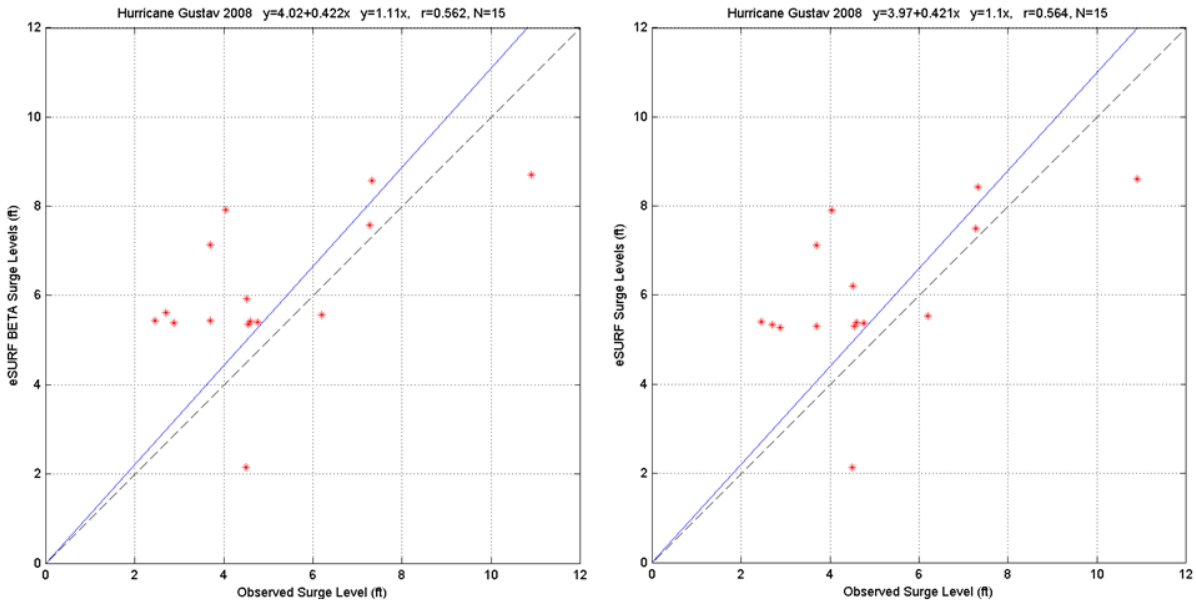


Figure 33 - On the left is the regression graph for the beta version on the right the regression graph for eSURF

The two regression plots are very similar to each other. Both have a correlation of 0.56 and are close to the one on one line. With Gustav the release version did not really improve the estimation, but eSURF also did not make a worse estimation than the beta version. This is probably because the IKE value of Gustav is very small compared to that of Katrina, because the pressure of Gustav at landfall was rather high. No additional information on the IKE value of Gustav was found, but eSURF calculated Gustav to have had an IKE value of 64 TJ.

4.3.6. Discussion and comparison of eSURF against the beta version

Overall, the validation with the new release version of eSURF does show some progress with respect to hurricanes that are at some distance from the surge points. Although for hurricane Betsy the release version of eSURF was completely off, eSURF still does show some improvement on the other validated hurricanes.

In table 4 the different outcomes of the validation of the 5 historical hurricanes are shown. The first column of importance shows the quantity of improved gages with the observed data. In the columns after that the average improvement and deteriorations are shown. The table shows compares the outcomes of eSURF with those of the beta version. The last 2 columns the linear fit to the one on one line. This one on one line is the line that represents the perfect fit of the observed data and the data calculated. The closer this value is to 1, the better the regression line fits to the one on one line.

Hurricane	Quantity of used gages	Quantity of improvement of eSURF against beta	Quantity of deterioration of eSURF against beta	Average improvement of eSURF against beta	Average deterioration of eSURF against beta	Linear fit of eSURF	Linear fit of Beta
Ike (2008)	17	11	6	7%	4%	0,859	0,730
Betsy (1965)	14	1	13	0%	13%	1,230	1,130
Andrew (1992)	11	6	5	3%	1%	0,967	1,000
Katrina (2005)	16	9	7	1%	3%	0,979	0,961
Gustav (2008)	15	9	6	2%	0%	1,100	1,110

Table 4 - Resume of the 5 historical hurricanes validation

Hurricane	Improvement in quantity	Average percentage improvement	Improvement in linear fit	Results
Ike (2008)	+	+	+	++
Betsy (1965)	-	-	-	--
Andrew (1992)	+	+	-	+
Katrina (2005)	+	-	+	+
Gustav (2008)	+	+	+	++

Table 5 - The improvement of eSURF against the beta version

Table 5 gives and overall impression of the improvements and deteriorations that eSURF produced in respect to the 5 historical storms. Hurricane Ike and Gustav show improvement in the respects average percentage improvement and improvement in the linear fit. Hurricane Andrew and Katrina also show improvement of eSURF in some respects, improvement in quantity, though for Andrew there is also deterioration in the respect linear fit and for Katrina there is deterioration in the respect average percentage improvement. The big mishit for eSURF is Betsy, which shows deterioration in all respects. This problem has already been discussed section 4.3.2.

The logarithmic distribution factor needs more attention, for it is causing a lot of gages to be under- or over estimated. The logarithmic distribution does not fully represent the effect the IKE would have in reality, because logarithm not only causes points far away to increase their surge levels, but points nearby could as well. Another problem lies with points that are too far away, as they may receive too much of an increase in surge levels. The ideal distribution factor is illustrated on the right in figure 34.

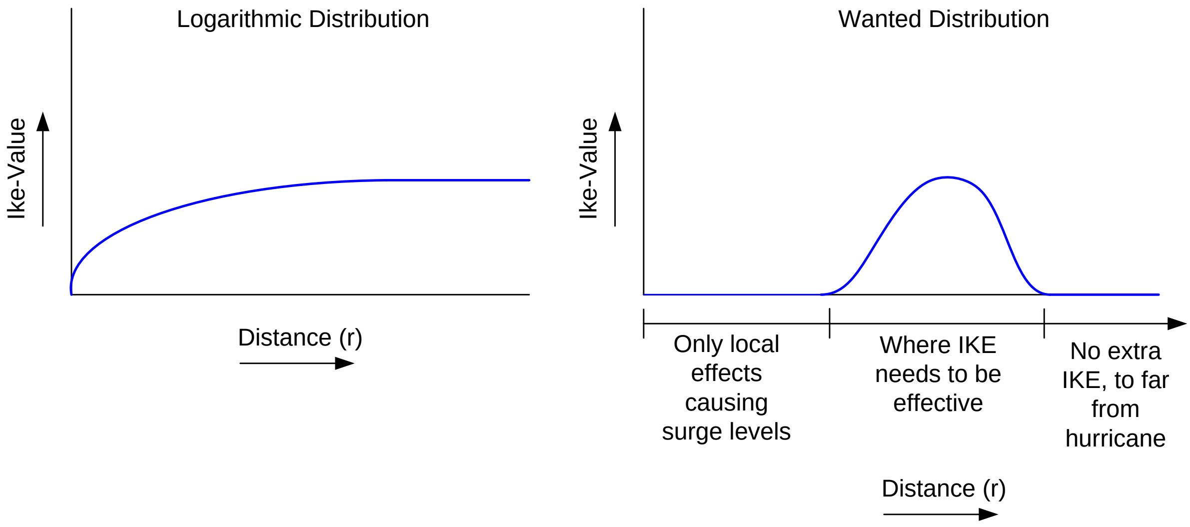


Figure 34 - On the right side the now in used distribution factor, on the left side the wanted distribution factor

This figure shows the disparity between the distribution of the IKE-value that is now being used and the ideal distribution curve. It is recommended that more research is done on this point.

4.3.7. Conclusion

The validation proves that implementing the IKE in eSURF does lead to some improvements, but also to a lot of deterioration. Leaving hurricane Betsy aside, because this hurricane could not be fully represented by eSURF, the four other hurricanes did show some overall improvements.

Overall eSURF is now better enabled to calculate the surge levels of hurricanes far outside the 152 ADCIRC storms tracks, but that still have parameters within the bounds of the database. The input in eSURF has to correspond with the data in the database in order for eSURF to produce good surge level predictions. In the case of hurricane Betsy too much information was absent, and especially the Holland-B parameter and the right radius of maximum winds caused problems here.

The most important problem with eSURF, has to do with the distribution factor. The logarithm that was used caused a lot of problems with the validation. The first problem has to do with points that are too close to the hurricanes storm track, the logarithm caused these points to end up with a negative surge level, and thus a lowering of the surge levels. A second problem has to do with points that are too far away. Rather than lowering the surge levels, the logarithm never seizes to add up leading to increases that are far too large for points that are too far away to realistically be influenced by the hurricane. The last problem is that the logarithm does not take the location of a specific point in perspective to the hurricane into account. This is what happened with the validation of Katrina, where the two gages on the left showed an increase in surge levels instead of a decrease. Although these problems did not do the validation any good, it is still a step in the right direction to take into account non-local effects on points that are far from the hurricane.

5. Conclusion and Recommendation

5.1. Conclusion

The inclusion of Integrated Kinetic Energy is meant as an improvement of the beta version of eSURF. The surge level estimation model is already using four parameters; pressure, radius of maximum winds, central speed and the Holland-B. These four parameters are used to calculate the maximum surge level with the following equation: $H_{model} = H_0 + A \cdot V^2 + B \cdot dp$

The IKE is added to this equation because the beta model of eSURF leaves out an important additional parameter, namely the span of the hurricanes wind field. This parameter needs to be included in order to take into account the non-local effects a hurricane can have on points that are further away from the hurricanes track. This is necessary in order to calculate the increase of the surge levels of these points. The scope of the beta model only includes the radius of maximum wind speeds and the outcome of the dominant wind speed, and thus leaves out the fact that wind speeds lower than the dominant wind speed can still lead to an increase of surge levels on points that are further away. The only thing that Is need to achieve this result, is for these lower wind speeds to sort their effect on a body of water for an extended period of time. Hurricane Ike illustrates this point perfectly, for the sheer size of Ike's wind field lead to an increase of surge levels of points over 400 km away. Ike came on land in Texas, but still managed to lead to an increase of 8.16 ft near New Orleans, as can be observed at the funnel gage B.Bienvenue-MRGO.

The outcome of this research is that the predictive power of eSURF can be improved by taking the IKE into account. This leads to better predictions of the increase of surge levels of points outside the 152 ADCIRC storm track boundaries. eSURF thus uses the next new equation in order to accommodate the IKE: $H_{model} = H_0 + A \cdot V^2 + B \cdot dp + C * (IKE * \log(r))$. In this equation IKE is used together with a new coefficient C, which is added to improve the value of R^2. From the new equation it also follows that IKE only provides an increase in surge level for points that are further away from the hurricanes track. This has been done by introducing a logarithm with a function on the distance r. This r variable is the minimum distance between the hurricanes track and the point of interest. The logarithm is meant to secure an extra increase in surge level for points further away from the storms track, while leaving points nearby as unaffected as possible.

The new equation does a better job at approaching the harsh reality at the points that are outside the scope of the 152 ADCIRC storm tracks, as is clear with hurricane Ike. However, the addition of the IKE also leads to unwanted results with the other four hurricanes, especially Betty. The validation clearly shows that eSURF performs better than the beta version on some gages, but worse on others. Out of a total of 18 gages, most predictions improved with eSURF. The average improvement was also often better, though not as high as expected. The validation leads to the conclusion that a lot of work still needs to be done, especially with regards to the distribution factor of the IKE. As explained in 4.3.6 the logarithm used in the new equation needs a better distribution factor. Again Ike serves as an example. Figure 34 depicts an ideal logarithm, one that takes into account all the problems discussed in chapter 4.3.6. Unfortunately we did not manage to improve the distribution factor in our short research period.

5.2. Recommendation

As already mentioned in the conclusion, the largest problem with the new eSURF is the distribution factor of IKE. Figure 34 clearly shows that the ideal distribution curve only increases the surge levels of points further away from the storms track. The current distribution curve, however, continues to increase surge levels even further away, leading to absurd results for points that would normally be left unaffected by the hurricane. This problem needs to be solved by coming up with a equation that only increases the surge levels of points that are at the right distance from the hurricanes track. The distribution factor should have a certain area in which it builds up and consequently builds down it's effects, as can be seen by looking at the ideal curve of figure 34.

The second recommendation is to think of a way to determine whether the IKE should lead to an increase or a decrease of the surge levels. The validation of hurricane Katrina shows that the current implementation of the IKE can lead to negative surge levels. This is due to the fact that eSURF did not take into account that those points were affected by off-shore blowing winds, which lead to a decrease in surge levels. On these points eSURF can still be improved, and a lot of research can still be done.

6. Afterword

There are still a lot of things to can be improved for IKE to be really successful. On the other hand what can be said is that the validation really helped in getting this inaccuracy on the table, because when one is only looking at the charts of eSURF (Appendix 8.3) against the ADCIRC runs, it look like a really good estimation. This validation also helps in getting a better feeling for what eSURF is capable off.

At the moment that I'm finishing typing my report, eSURF is fully in use for a test hurricane called Mike by the USACE. They also said that they are going to use our made model for the upcoming hurricane season. The beta model once made by Van den Berg (2008) has been evolved to a real valuable addition in predicting surge levels in and around New Orleans.

It has been a really great experience for me to be in a special culture like New Orleans. I really felt sorry for people that got flooded by the hurricane or worse lose a close by friend. Therefore working on this project and being a part of this new way of prediction, really was a wonderful experience. I would like to thank everybody that has made this possible for me and am wishing the next group of students all the luck and fun in improving the best ever model, eSURF.

- The Future in Seconds: eSURF -

Made by: Marcel van den Berg (2008), Tom Smits & Chuhui Lin (2009) and now it´s your turn…

7. References

Articles and Book references

Bricka Validation Runs (*Date unknown*) Graphics are driven from the PBL and TROP files. Retrieved from supervisor T.M. Kluyver (Msc), New Orleans Haskoning Inc. (2009, May)

Federal Emergency Management Agency (FEMA, 2008), Flood Insurance Study: Southeastern Parishes, Louisiana, Offshore Water Levels and Waves, Intermediate Submission 2, U.S. Army Corps of Engineers.

Klaver, E.N. (2005) *Probabilistic analysis of typhoon induced hydraulic boundary conditions for Suo-nada Bay* [Electronic version] Msc. Thesis, Delft University of Technology, Delft, The Netherlands. Faculty of Civil Engineering & Geosciences. *(160 pages)*

NOAA, FEMA, University Corporation for Atmospheric Research (1999) *Hurricane Basics* [Electronic version] Retrieved March 25, 2009 from http://hurricanes.noaa.gov/pdf/hurricanebook.pdf (*19 pages)*

Persson, A. (1998) *How Do We Understand the Coriolis Force?* [Electronic Article in Bulletin of the American Meteorological Society] Retrieved February 18, 2009 from http://www.aos.princeton.edu/WWWPUBLIC/gkv/history/Persson98.pdf *(page 1373 to 1385)*

Powell, M.D. and Reinhold, T.A. (2007) *Tropical Cyclone Destructive Potential by Integrated Kinetic Energy* [Electronic version] Retrieved March 18, 2009 from http://www.aoml.noaa.gov/hrd/Powell/BAMS_IKE_Paper_final.pdf *(page 513 to 526)*

Resio D.T. (2007) *White Paper on Estimating Hurricane Inundation Probabilities*. U.S. Army Corps of Engineers. *(126 pages)*

Van den Berg, M. (2008) *A Predictive Model for Hurricane Surge Levels in New Orleans*, BSc. Thesis, Twente University of Technology, Enschede, The Netherlands, Faculty of Civil Engineering & Management. *(46 pages)*

Vickery, P. J., Skerlj, P. F., Twisdale L. A., (2000) Simulation of Hurricane Risk in the U.S. Using Empirical Track Model [Electronic Journal of Structural Engineering] Retrieved April 13, 2009 from http://wiki.basemgt.com/servlet/JiveServlet/previewBody/1039-102-1-1072/Vickery-etal-2000b.pdf;jsessionid=5BB967AAB2307230F8CE5F16E3164776 *(page 1222 to 1237)*

Internet references

Sura Scoop, Historical Hurricanes pressure and track information (2009, May) Retrieved May 11, 2009 from http://www.scoop.sura.org/Storms

Wikipedia Hurricanes information for Historical Storms (2009, May) Retrieved May 11, 2009 from http://en.wikipedia.org/wiki/hurricane_ike

The Saffir-Simpson Hurricane Scale (1972, November) Retrieved April 14, 2009 from http://www.nhc.noaa.gov/aboutsshs.shtml

Translational kinetic energy (2009, April) Retrieved April 21, 2009 from http://en.wikipedia.org/wiki/Kinetic_energy

8. Appendices

8.1. List of used symbols

Pressure equation:

p_0 the pressure at the center of a hurricane [mbar]
Δp the pressure difference between pressure sea level and pressure at hurricane center [mbar]
r_m the radius of maximum winds [n.m.]
r the distance between a chosen point from the sets to the center of the hurricane [n.m.]
B the Holland-B parameter [-]

Gradient balance equation:

ρ the air density [kg/m^3]
p atmospheric pressure [hPa]
V_{gr} the gradient wind speed [m/s]
r the distance to the center of the hurricane [m]
f the coriolis parameter [1/s]

Blaton, adjusted radius of curvature equation:

r_t the distance to the center of the hurricane [m]
r the radius of an isobar [m]
C_{fm} the forward movement of the hurricane [m/s]
V_{gr} the gradient wind speed in [m/s]
Ø the angle of the radius vector and the direction of hurricanes movement [^{0}]

Kinetic energy equation:

E the translational kinetic energy of object measured in [J] or [(kg m/s^2) (m)]
m the mass the moving object has [kg]
V the speed of the central mass of the object [m/s]

The integrated kinetic energy (IKE) equation:

IKE is measured in [TJ]
ρ the density of the air in [kg/m^3]
U the wind speed in [m/s]
NB.: IKE is in Terra Joule and not in Joule this is because the gradient wind field is based on a cubic kilometer [km^3]

Gradient wind field equation:

V_{gr} the gradient wind speed	[m/s]
C_{fm} the forward movement of the hurricane	[m/s]
$\emptyset$ the angle of the radius vector and the direction of hurricanes movement	[^{0}]
f the coriolis parameter	[1/s]
r the radius of an isobar	[m]
B the Holland-B parameter	[-]
Δp the pressure difference between the normal pressure and the minimum pressure	[Pa]
ρ the air density	[kg/m^3]
r_m the radius of the maximum winds	[m]

8.2. Overview of the validation gages an chosen points

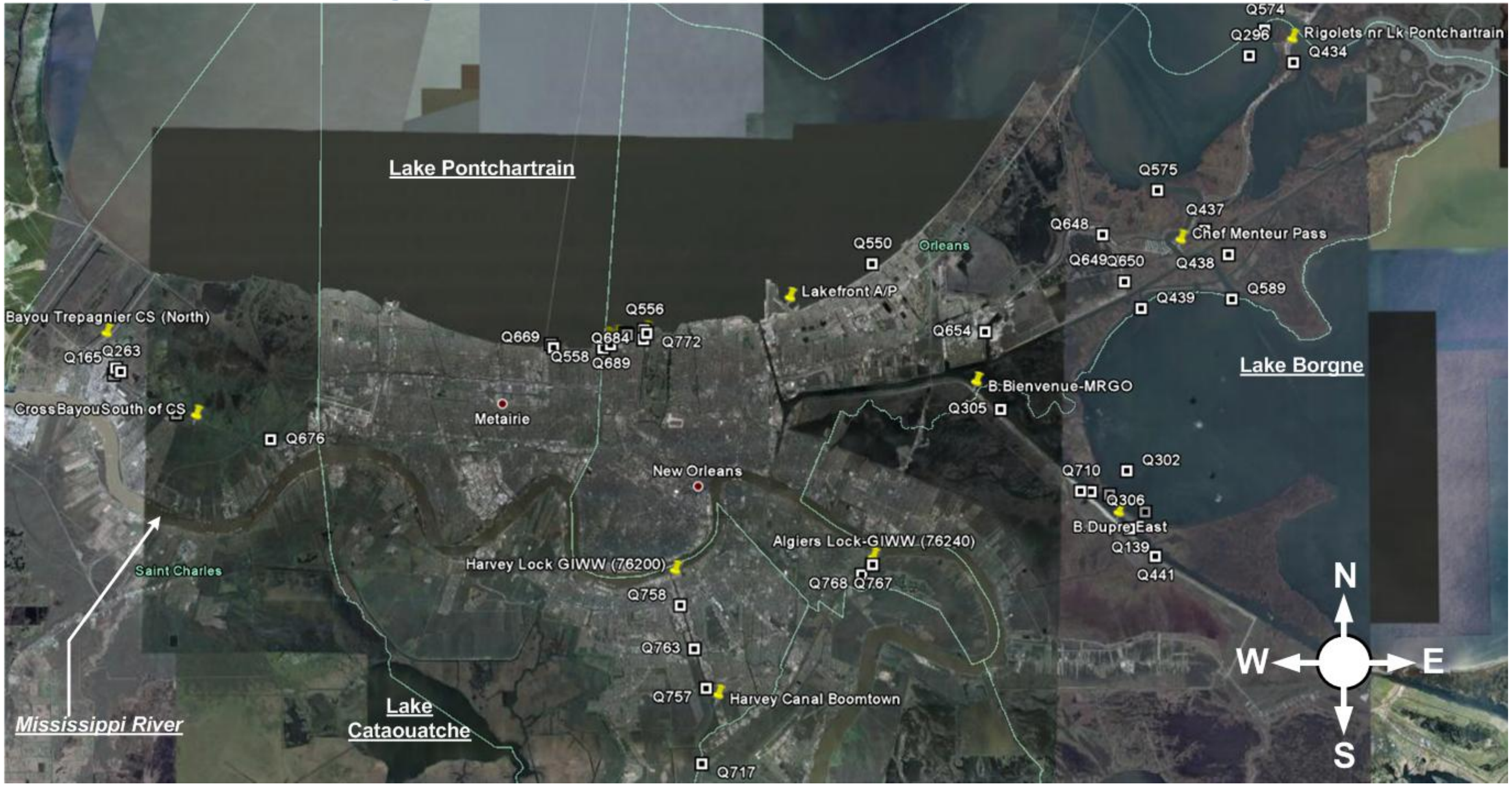


Figure A 1 - Overview of the chosen validation gages and corresponding surge points

The yellow thumbnails are the chosen gages for the validation around New Orleans city, the points are chosen to represent the surge height at these gages.

8.3. Validation charts eSURF against ADCRIC charts

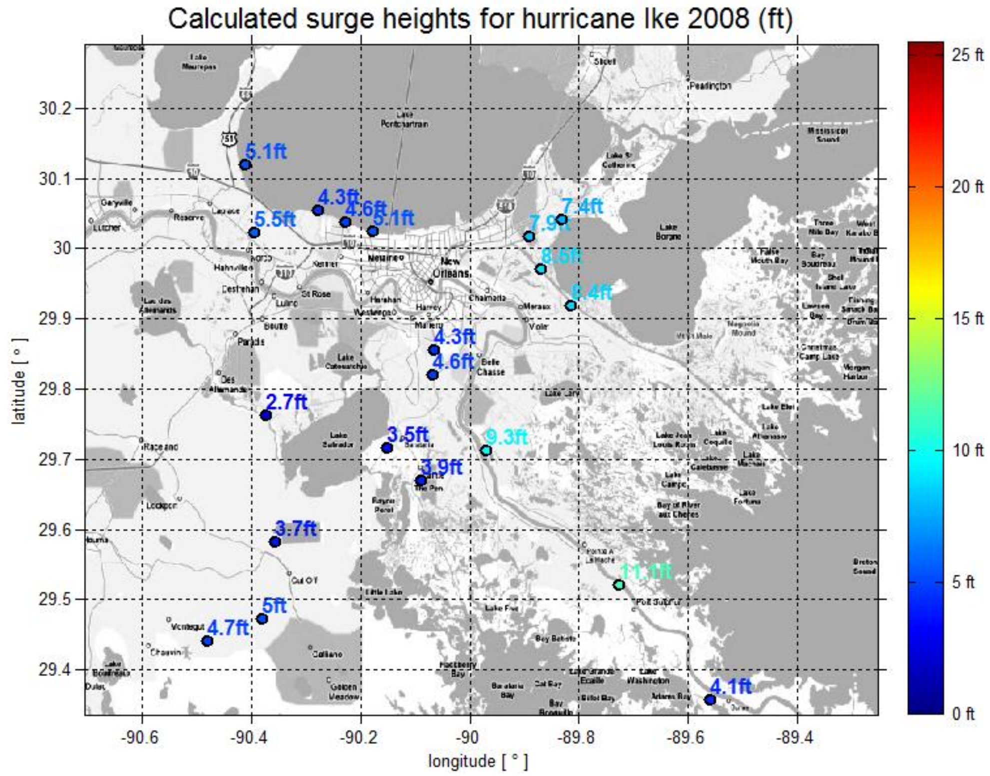


Figure A 2 - eSURF predicted surge levels for hurricane Ike

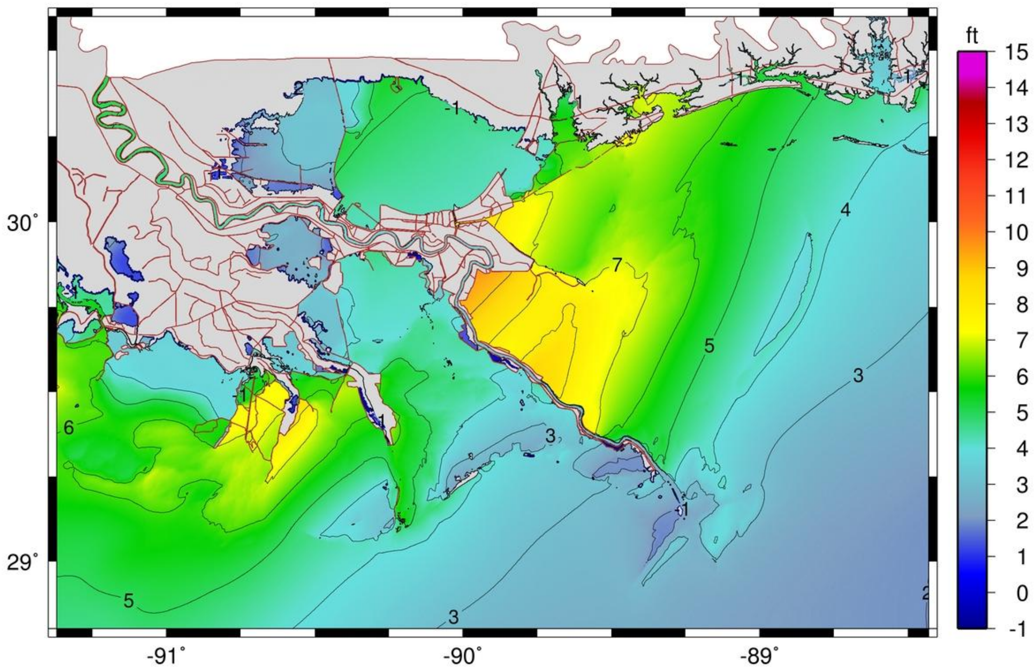


Figure A 3 - ADCIRC predicted surge levels for hurricane Ike

In figure A 2 and A 3 can be seen that the comparison between the predicted eSURF is pretty close to what ADCIRC has calculated.

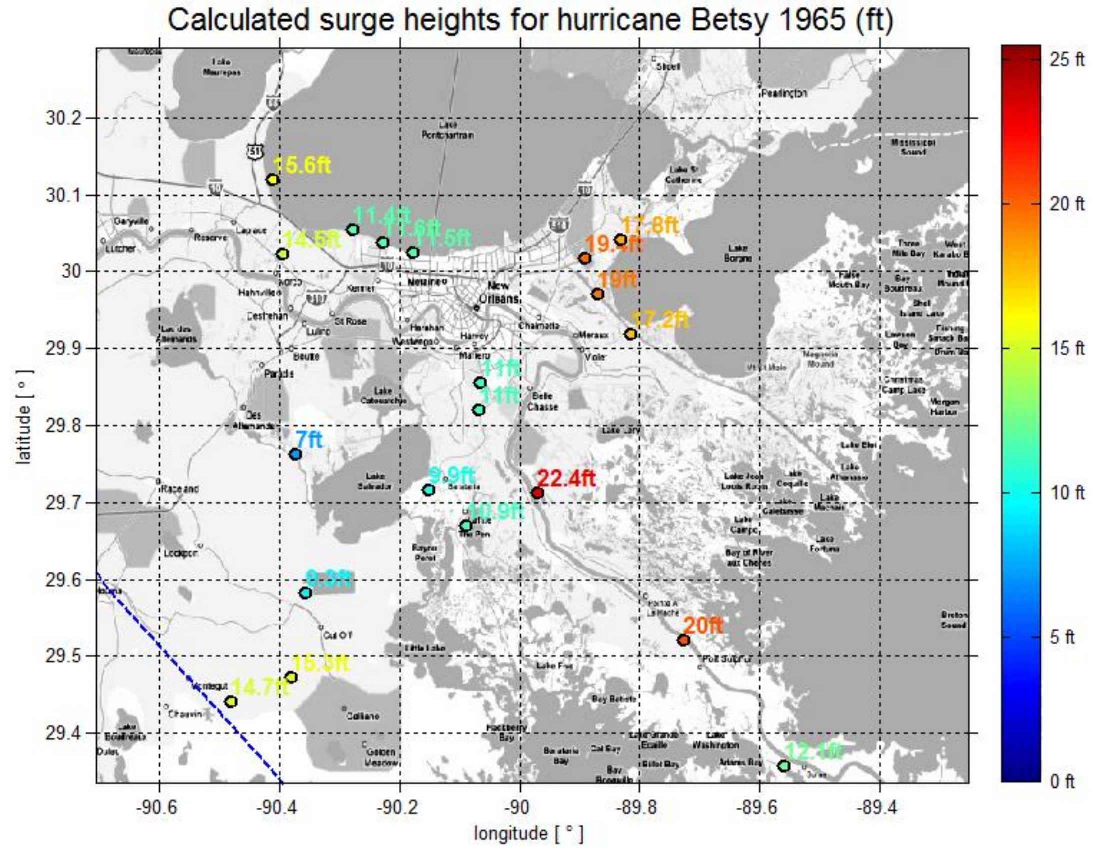


Figure A 4 - eSURF predicted surge levels for hurricane Betsy

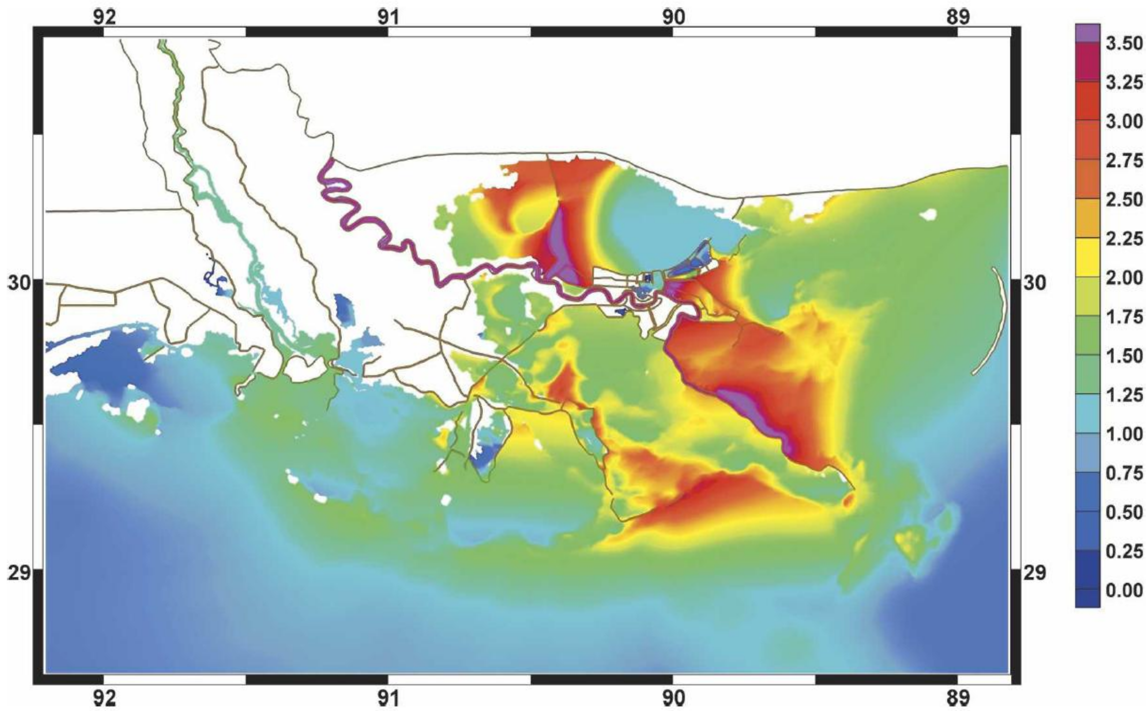


Figure A 5 - ADCIRC predicted surge levels for hurricane Betsy

In figure A 4 and A 5 can be seen that the comparison between the predicted eSURF and that of ADCIRC are not so good, especially at the north side of New Orleans in Lake Pontchartrain.

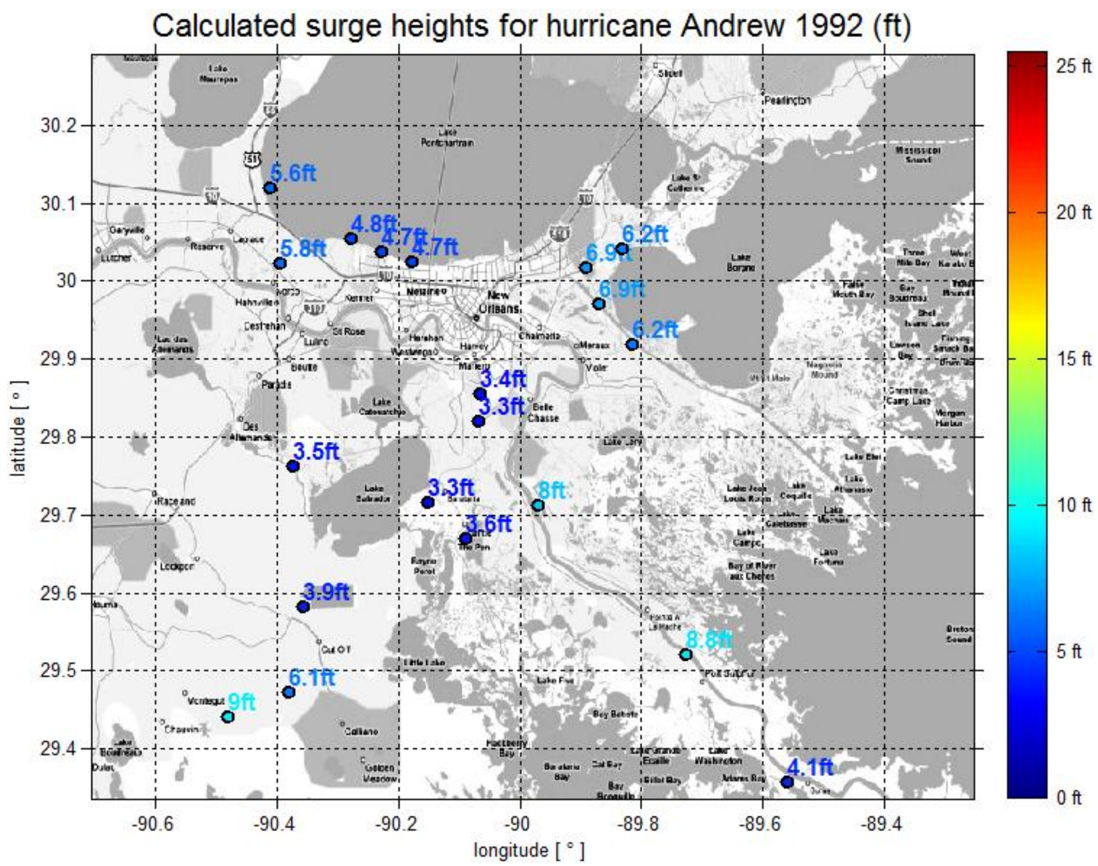


Figure A 6 - eSURF predicted surge levels for hurricane Andrew

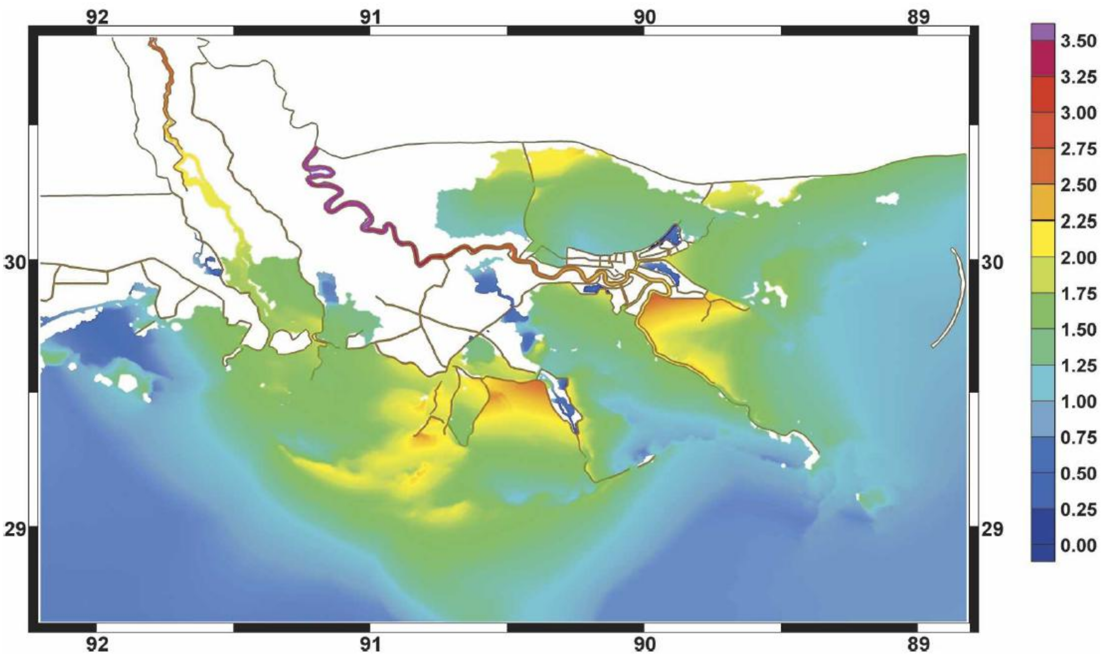


Figure A 7 - ADCIRC predicted surge levels for hurricane Andrew

In figure A 6 and A 7 can be seen that the comparisons between the predicted eSURF are close to what ADCIRC has calculated.

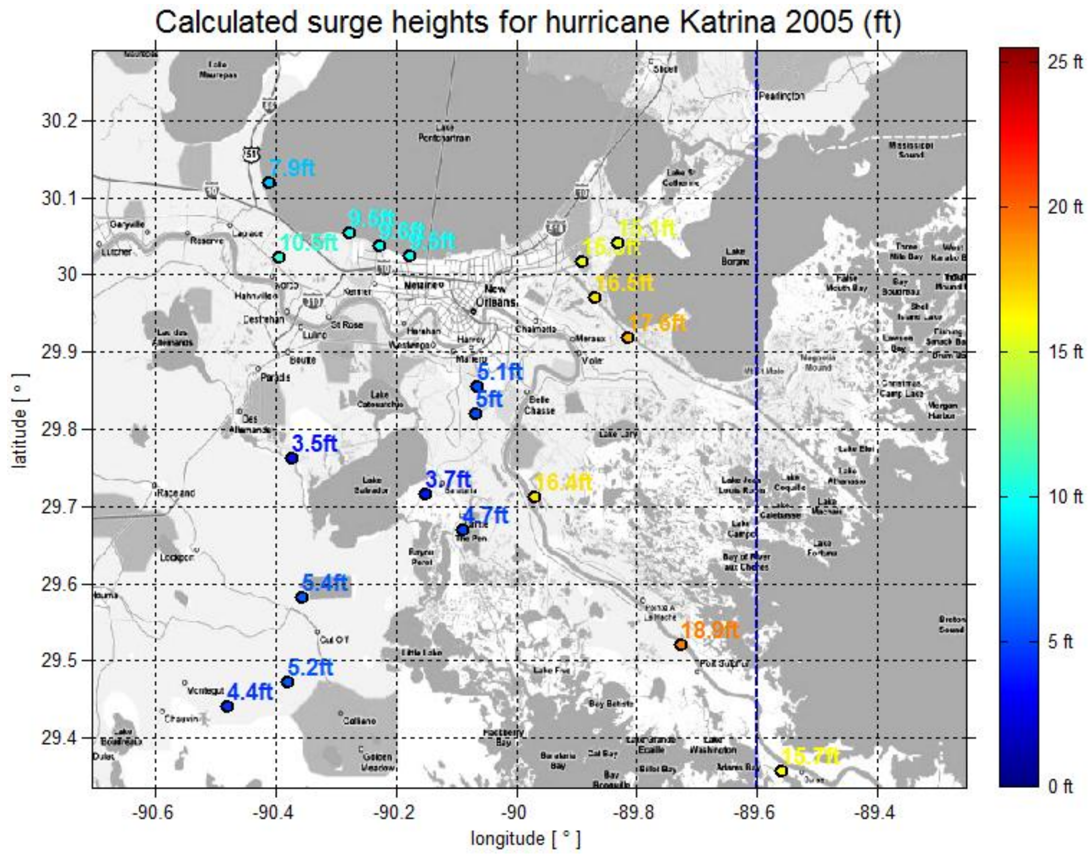


Figure A 8 - eSURF predicted surge levels for hurricane Katrina

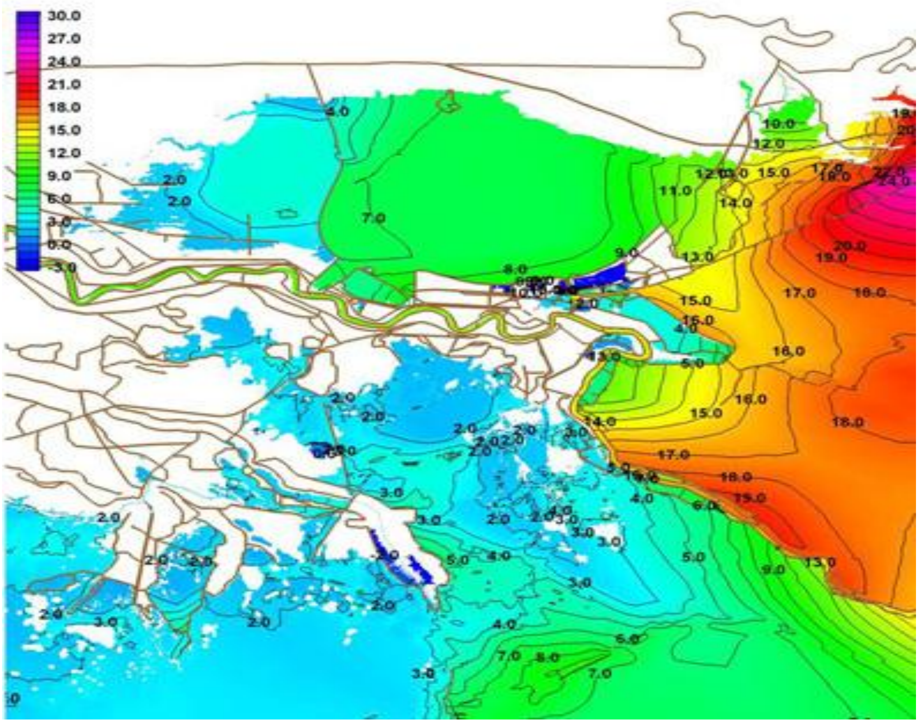


Figure A 9 - ADCIRC predicted surge levels for hurricane Katrina

In figure A 8 and A 9 can be seen that the comparisons between the predicted eSURF are close to what ADCIRC has calculated. *Please note that figure A 8 is in meters.*

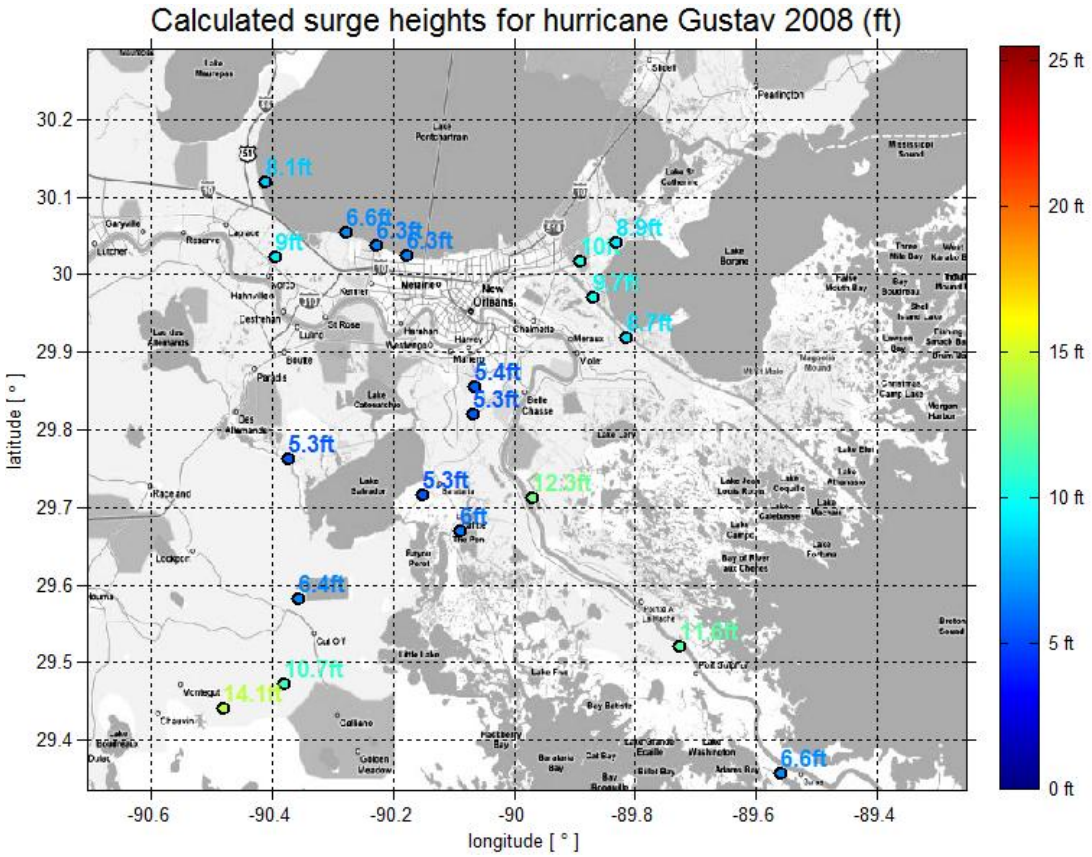


Figure A 10 - eSURF predicted surge levels for hurricane Gustav

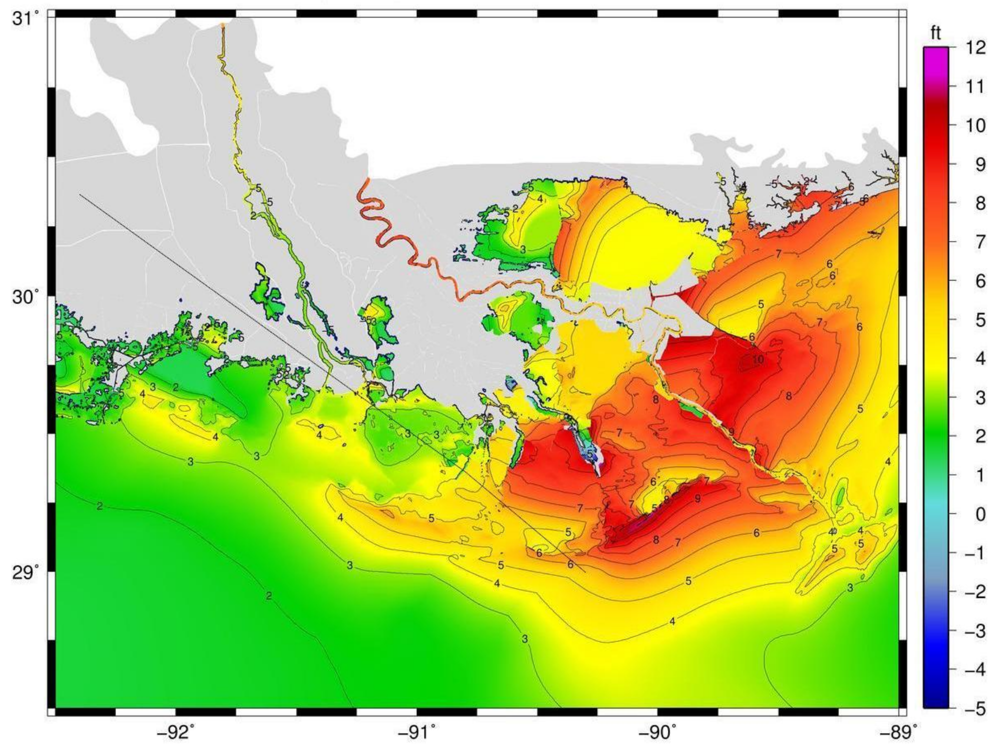


Figure A 11 - ADCIRC predicted surge levels for hurricane Gustav

In figure A 10 and A 11 can be seen that the comparisons between the predicted eSURF for the funnel and Lake Pontchartrain close to what ADCIRC has calculated.