Predicting Storm Surge

"One swell of a problem"

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Storm surge is defined to be the difference between the observed water lever and the predicted level of the astronomical tides and is a probable and dangerous consequence of high wind events. In low-lying coastal areas such as Lewes, this is especially significant due to the area's predisposition to flooding. Factors contributing to severity of the storm surge include storm track and intensity as well as the oceanographic and bathymetric conditions in the area. SLOSH, or Sea, Lake and Overland Surge from Hurricanes, has been used by FEMA, NWS and USACE since the 1970s. Storm surge level predictions made by SLOSH are accurate to within plus or minus twenty percent.

The purpose of this study is to research how storm surge predictions are made and what is needed to make them. Each member read scientific papers regarding storm surge models and also researched one particular area of interest. The different parts of the project were divided amongst group members: Dack researched storm track, Matt studied storm intensity, Brian investigated bathymetry, and Amy examined oceanographic conditions. This document presents the findings made by each group member regarding their area of study on this project.

Storm Track

Storm track was chosen as a variable of interest when predicting storm surge because ample evidence was identified flagging it as a necessary component to be studied if any worthwhile storm surge prediction was to be made. It was discovered that storm track is important to surge models because the height of a surge event will vary greatly based on distance from the storm and where the storm is located with regards to a location in interest. In our case the location of interest is Lewes, and it was hypothesized that its location inside the Delaware Bay could protect it from a direct surge impact.

Research was first conducted using textbooks, personal notes and from scientific papers recovered from online databases. From this research the following conclusions were made:

- Storm track is one of the more difficult elements of a storm to predict
- The two most prevalent sources of error are from *aleatory* (“random noise”) and *epistemic* (knowledge-based) sources
- Of the many methods used to predict storm track, the most accurate is by way of *ensemble* forecasting
- A storm or surge-causing event does not need to make direct landfall for its surge to be significant

Storm track is difficult to predict due mainly in part to the erratic shifts that a storm can undertake during its lifespan. A pressure system may influence the path of a storm or the storm may change heading if it encounters large-scale weather phenomenon, such as the Gulf Stream. There have been several papers published based on explaining how to minimize the error when predicting the track of a storm. Poroseva et al. (2007) put forth two new methods for quantifying uncertainty in storm track using customized mathematical techniques. They explain that aleatory influences are unavoidable when making predictions of this nature and cannot be avoided. On the other hand, epistemic error can be minimized by understanding as much as possible about the starting conditions of the storm, because track error can increase quickly if not enough is known about the storm conditions.

Ensemble forecasting involves using a combination of several model predictions into one averaged predicted storm track. Zhang and Krishnamurti proved that ensemble forecasting yields an improvement in the hurricane track forecasts. In the case studies they examined, track position errors were reduced greatly and the ensemble forecasts created were more accurate than the results from single models. As mentioned earlier, storms need not make direct landfall to create a devastating storm surge. Focusing on hurricanes, nor’easters and sub-tropical storms that impacted Delaware, our research shows that in several instances storms failed to make landfall or even pass over Delaware yet still created a large storm surge. Hurricanes Isabel (in 2003) and Esther (in 1967) and the Gale of 1878 were all at least ~75 miles from mainland Delaware but all created surges higher than 5 ft.

Bathymetry

Ocean bathymetry, while remaining relatively constant over time, remains difficult to evaluate in terms of storm surge due to the complex terrain of the sea floor and unpredictability of other factors, such as storm track and intensity. Dean and Dalrymple (1991) describe a series of equations applicable to the prediction of storm surge in two dimensions. This simplified scenario includes a linear coastline and a continental shelf of constant depth. In this model, storm surge operates partially as a function of wind shear stress, which in turn is the product of friction between the atmosphere and the ocean’s surface.

In most cases, we are interested in the shear stress vector component perpendicular to the coastline. To find this for a linear coastline is a matter of basic trigonometry, such as would be the case for the ocean-facing portion of Cape Henlopen. The Delaware Bay portion would be considerably more complex, and would face higher storm surge levels for a given shear stress due to channeling effects.

Surge height on shore is a result of many factors, but a few generalities can be drawn. In an oceanic scenario, storm surge comes in over a continental shelf. Storm surge height is directly correlated with surge run (the distance from the shelf break to shore) and inversely correlated with water depth over the continental shelf. In other words, a broad, shallow continental shelf will contribute to the largest surges. These relations are surmised in the following equation:

$$\frac{\partial \eta}{\partial x} = \frac{n \tau_{zx}(\eta)}{\rho g(h + \eta)}$$

Where:

N = surge height

x = horizontal position relative to shore (run)

pg = pressure due to gravity

h = water height (seafloor to mean sea level)

Perhaps counter-intuitively, given a fixed wind shear stress, surge height and wave height vary inversely according to bathymetry type. Areas with narrow, deep continental shelves may have relatively little storm surge but high wave height, whereas broad, shallow continental shelf areas are likely to experience high surge levels but waves comparatively smaller than those in other areas.

The shapes of coastlines and continental shelf breaks can dramatically influence storm surge levels during a storm. These structures can become extremely complex and difficult to understand, but a few basic characteristics of these structures and their effects are both important and easy to follow. A concave coastline will tend to deflect storm surge towards its center, whereas a convex coastline will disperse storm surge forces. Similar effects are observed to a lesser degree in the shapes of continental shelves. Another important feature of coastlines that often comes into play is channelization. In channelization of storm surge, storm surge will be funneled into a linear body of water such as a river, estuary mouth, or narrow bay. Due to the effect of channelization, local storm surge may be dramatically higher than that of surrounding areas.

Hurricane Opal, which made landfall in the panhandle of Florida in 1995, provides a clear illustration of how bathymetric conditions can dramatically increase storm surge. Opal was a weak category 3 hurricane when it made landfall near Pensacola, Florida. Despite being only marginally a major hurricane at landfall, and hitting the coast during low tide, Opal produced widespread storm surge in the area of approximately 15 feet, and storm surge data in certain areas were among the highest ever recorded in the United States, at up to 24 feet. Monetary damage from Hurricane Opal, which was primarily a result of storm surge, exceeded $3m. Factors contributing to these high storm surge levels included a broad, shallow continental shelf, a concave section of the shelf break that allowed for channelization, a smooth ramp from the sea floor to the continental shelf, a concave coastline, and numerous small bays and inlets that allowed for channelization.

Storm Intensity

In the context of hurricanes, the term “intensity” is used often to categorize storms according to a variety of parameters, such as the atmospheric pressure at the eye of the storms for the maximum wind speed. Intensity is defined as “the magnitude of a quantity (as force or energy) per unit (as area, charge, mass, or time)” (Merriam-Webster, 2008). In the case of hurricanes, the best way to describe the intensity is by analyzing the maximum sustained wind speed of the storm.

The force of wind blowing over a body of water for a period of time results in wind set-up, or the "piling up" of water along a landmass boundary (Figure 1). As the wind blows across the water, friction between the moving air and the surface of the water at the air-sea interfaces causes the wind to pull the water along.

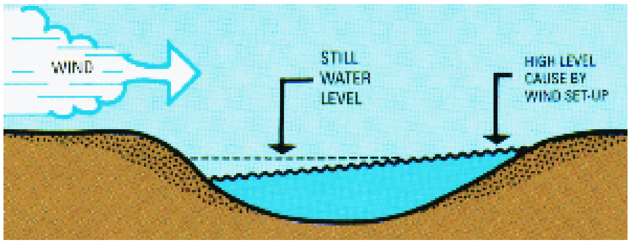


Figure 1. Wind set-up illustrated in a small lake. This same principle is applied to the ocean on a larger scale during hurricanes or other high-wind storm events. (http://www.epa.gov/glnpo/atlas/glat-ch2.html)

Recalling the input variables for the SLOSH model, note that wind speed is not one of the required input variables despite this discussion on wind speed, force, and set-up. SLOSH calculates a wind speed given the input variables (Jelesnianski, 1967), therefore observed wind speed is not entered into the model. Predicting storm surge is then the last step, with the predicted wind speed being used to create a prediction for storm surge. This is extremely advantageous because it does not depend on real-time or field-based observations of wind speeds in the middle of a storm in order to predict storm surge effects.

To predict wind speed, SLOSH assumes a geostrophic balance, or a balance between Coriolis and the pressure gradient:

[2] $$f\vec{V} = -\frac{1}{\rho}\vec{\nabla}p$$

where f is the Coriolis parameter, $\vec{V}$ is a velocity vector, ρ is the density of air, and $\vec{\nabla}p$ is the pressure field. With no net force acting on an air parcel (only Coriolis and pressure gradient forces are considered, and they are assumed to be in balance with each other), the flow is parallel to the isobars (lines of equal pressure) and at uniform speed (EuroMet

2008). The geostrophic wind, V_g, is then calculated from [2] and is used to formulate a storm surge forecast.

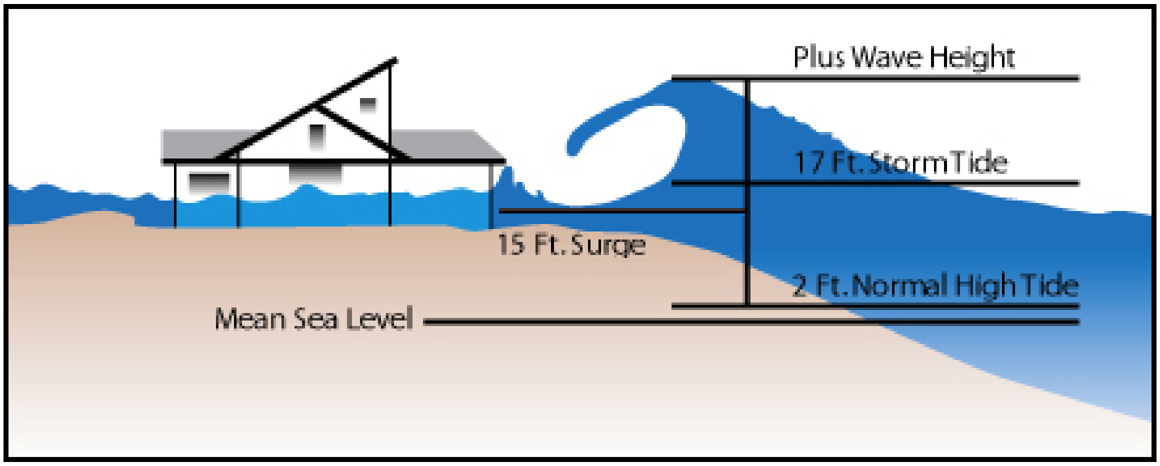
$$\vec{V}_g = -\vec{k} \times \frac{1}{\rho f} \vec{\nabla} p \qquad [3]$$

where $\vec{k}$ is the directional unit vector.

Oceanographic Conditions

The main categories of oceanographic conditions that have significant impacts on the storm surge height include pre-storm average water height, astronomical tides and pre-storm sea surface temperatures. As far as hurricane model input parameters are concerned, oceanographic conditions influencing storm strength and surge are well-resolved. For instance, water temperatures and storm strength are correlated in that wind speed increases approximately five percent for every degree that the ocean temperatures increase.

For hurricanes, sea surface temperatures at the eyewall are the most important to the dynamics of the hurricane, since changes there have the most direct influence on storm strength. The development of an existing storm is a combination of its initial intensity and the thermodynamics of the atmosphere and upper ocean through which it travels.



High and low tides do not increase or decrease storm surge, but tides and surge have an additive effect on the water level. Consequently, the most dangerous scenario occurs when the astronomical high tide coincides with the maximum storm surge. In order to be prepared for a worst case scenario, the SLOSH model computes a surge assuming maximum high tide. Therefore, when error is calculated for the surge model, deviations from the predicted maximum storm surge coinciding with tidal levels other than the astronomical high are not taken into account. This leads to lower error calculations than those reported to the public.

Conclusion

Damage resulting from storm surge is a threat that should not be underestimated. Historically, the United States government has adopted SLOSH as its “official” model of choice. With the development of new models in recent years, we believe the government should consider these new models as potential replacements or supplements to SLOSH. In Lewes, the threat of storm surge is prevalent. Although no hurricane has been recorder to have hit Lewes directly, it would be naïve to assume it will never happen. Twenty foot storm surges, like those predicted for Galveston, TX from hurricane Ike, are unlikely to occur in Lewes due to the local geography of Southern Delaware. However, Lewes’ low elevation makes it particularly susceptible to much smaller surges from distant tropical storms and nor’easters, so storm preparedness should always be emphasized in the community.

Having completed this project, we learned how readily available massive amounts of information are for broad topics such as storm surge. This required us to work together at sieving through information and selecting the most relevant and credible sources. We learned to utilize technological resources such as ITV and an evolving website to post our thoughts and findings. We worked well together as a group and completed tasks efficiently.

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