

Conveying Coastal Inundation Potential Associated with Extratropical Cyclones

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Terms in *italics* are defined in Appendix A

Abstract

Storm surge is a dangerous and potentially life-threatening result of tropical and *extratropical cyclones*. The potential impacts of storm surge/*storm tide* can be very difficult to communicate before the storm arrives, thus a visual depiction of areas that could be inundated from storm tide would be very useful to the Emergency Management community. The National Hurricane Center has made strides in producing such a visualization for *tropical cyclones*, however it does not currently exist for extratropical cyclones. Using geospatial software, a recreation of *coastal inundation* potential from the storm tide associated with *Hurricane/Post-tropical Storm Sandy* in the New York City Tri-State area was developed by subtracting Sandy's storm tide from a digital elevation model. The resulting dataset compared to actual impacts correlated well, thus expectations are high that applying the same methodology to extratropical cyclones would also yield adequate results. The ability for the National Weather Service to provide a visualization of potential coastal inundation for extratropical cyclones to their customers and partners would be another step forward in meeting their mission of saving lives, property and enhancing the national economy (National Weather Service 2017b).

Introduction

Tropical and extratropical cyclones are two of many potential high impact events that emergency management (EM) officials in coastal communities have to contend with. The impacts from storm surge associated with these types of weather systems can prove to be extremely challenging for meteorologists to convey for several reasons. The evolution of geographic information systems (GIS) is making it easier to provide decision makers with the information to move people out of harm's way.

The National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) has developed several tools to aide an EM's evacuation decision making process when moderate to major coastal flooding from storm surge threatens their jurisdiction. Recently, there has been confusion amongst government officials, the media, and even meteorologists on what storm surge is and the extent to which it will affect a community since it can be measured from many different *vertical datums*. With the exception of *mean sea level* (MSL), these vertical datums are not widely known by many people outside of the scientific community. Referencing storm surge data to these datums does not convey the critical nature of the potential hazard so they can prepare accordingly. Additionally, probabilistic storm surge maps are only produced by the National Hurricane Center (NHC) when the U.S. coast is threatened by a tropical cyclone. There have been many extratropical cyclones that produce moderate to major coastal inundation, but the NWS does not have any visualization tools to display potentially impacted areas associated with these types of storm systems in a way that people can understand. This project will address the confusing manner in which extratropical storm surge data are currently conveyed from the NWS NY, NY office and focus on a process to create inundation maps based on storm surge forecasts from extratropical storms issued by NWS NY, NY in feet above ground level

(AGL). The paper concludes with results validated by comparing a portion of the output inundation raster to impact statements received from the EM community after Hurricane Sandy.

Background

Coastal inundation is primarily caused by severe weather events along the coasts, estuaries, and adjoining rivers. These storms, which include hurricanes and *nor'easters*, bring strong winds and heavy rains. The winds drive large waves and storm surge on shore, and heavy rains temporarily raise water levels. Storm surge is one of the main causes of coastal inundation and is extremely dangerous because it is capable of flooding large coastal areas, causing severe devastation (National Oceanic and Atmospheric Administration 2017c).

Although storm surge is often a threat to life and property in coastal communities during tropical and strong extratropical cyclones, it is also the least understood by government officials, the media, and even meteorologists. Due to the complexity of this hazard and the realization that it has not been conveyed properly by experts in recent years, an alternative way to communicate this critical piece of information is imperative.

Storm Surge vs. Storm Tide

The first issue that must be addressed is the fundamental difference between storm surge and storm tide (Figure 1). Emphasis should be placed on the latter since it is the total water level, surge and tide combined.

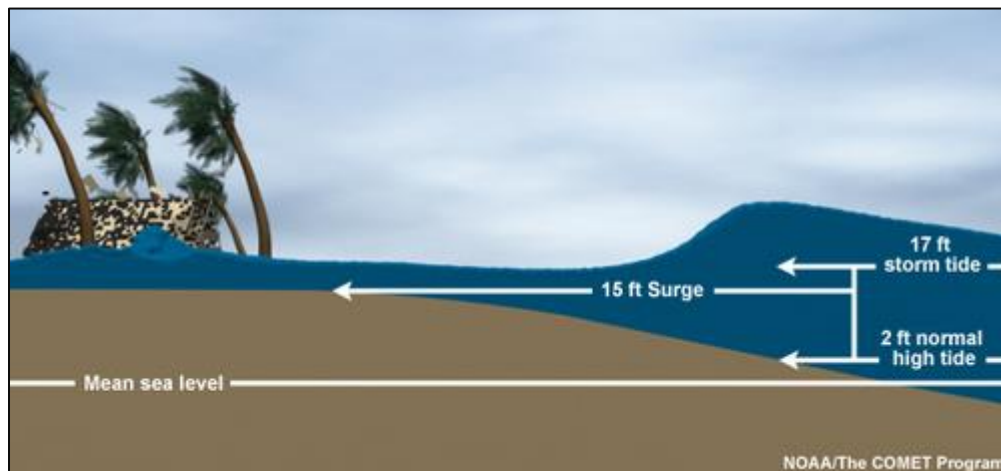


Figure 1 – Example of storm surge vs. storm tide referenced to *Mean Sea Level* (National Hurricane Center 2017c).

Population Density

There is a growing concern regarding the population density along the U.S. Coast, which is projected to continue to increase through 2020, and protecting this increasing population from coastal hazards. According to the 2013 National Coastal Population Report, which analyzed data from the 2010 census, 123.3 million, or 39 percent of the U.S. population is concentrated in counties directly on the shoreline. If current population trends continue, it is projected that an additional 10 million will settle along the U.S. coast by 2020, putting more of the population at increased risk from extreme coastal storms. (National Oceanic and Atmospheric Administration 2013).

Sea Level Rise

Sea level rise is also causing trepidation as it will exacerbate the severity of flooding along the coast in the future. Since the early 1990's, the Intergovernmental Panel on Climate Change (IPCC) has performed extensive research on climate change and has concluded that global mean sea level rise has been occurring since the end of the Industrial Revolution. Modelled projections indicate that it will continue to occur over the next few hundred millennia. According to the Fifth Assessment Report of the IPCC (2013), the primary contributions to changes in water volume in the ocean are thermal expansion, i.e. the expansion of the ocean water as it warms, and the transfer of water currently stored on land, mainly glaciers and ice sheets, to the ocean (Stocker et al. 2013). Additionally, the IPCC is certain that the global mean surface temperature has increased since the late 19th century and that each of the past three decades has been successively warmer at the Earth's surface than any of the previous decades, with the decade of the 2000's being the warmest. This has resulted in a transition to higher mean rates of sea level rise during the late 19th to early 20th century from relatively low mean rates of rise over the previous two millennia (Stocker et al. 2013). Figure 2 shows past *proxy data* in purple, tide gauge data in blue, red and green, and altimeter data in light blue. Future sea level rise projections, derived from various global climate models, are indicated in red for very high greenhouse gas emissions, and blue for very low emissions (Church et al. 2013). Despite the level of greenhouse gas emissions, projections from these global climate models indicate that sea level rise will continue through the end of the 21st century and likely beyond (Stocker et al. 2013).

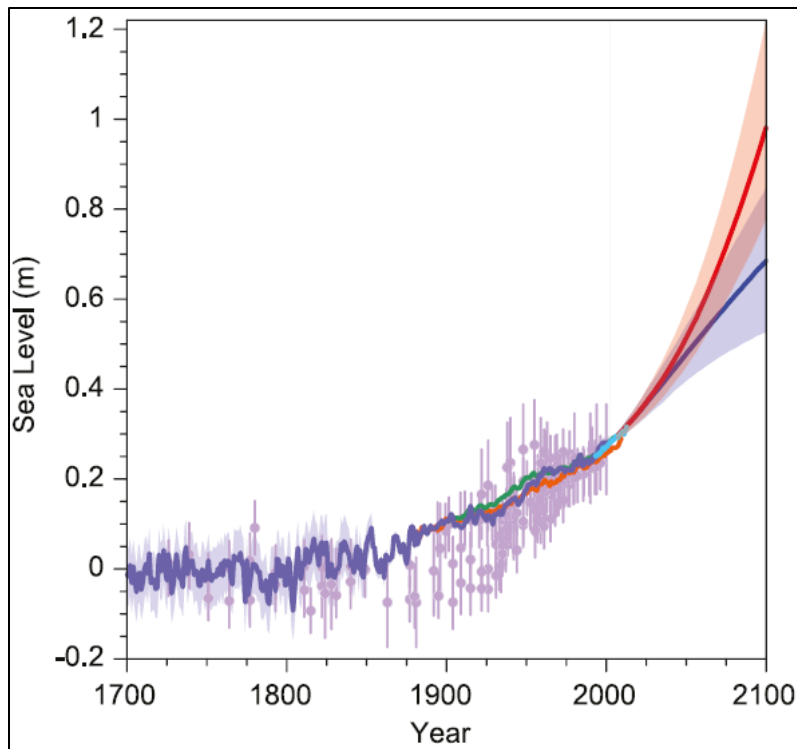


Figure 2 – Compilation of past and future sea-level rise consisting of paleo sea level data (purple), tide gauge data (blue, orange and green), *altimetry* data (light blue) and central estimates and likely ranges for projections of global mean sea level rise from the extreme scenarios of various global climate models, all relative to pre-industrial values (Stocker et al. 2013).

Vertical Datums

Vertical datums have traditionally come in two categories, those based on a form of mean sea level, called *geodetic datums* and those based on tidally derived surfaces of high or low water, called *tidal datums*. To avoid misinterpreting surge elevations, vertical datums must be consistent when comparing water level observations (i.e. from tide gauges) with forecasts or model data. Figure 3, shows many different datums water level data can be referenced to. The NWS typically conveys coastal flooding potential referenced to *Mean Lower Low Water (MLLW)* for extratropical cyclones.

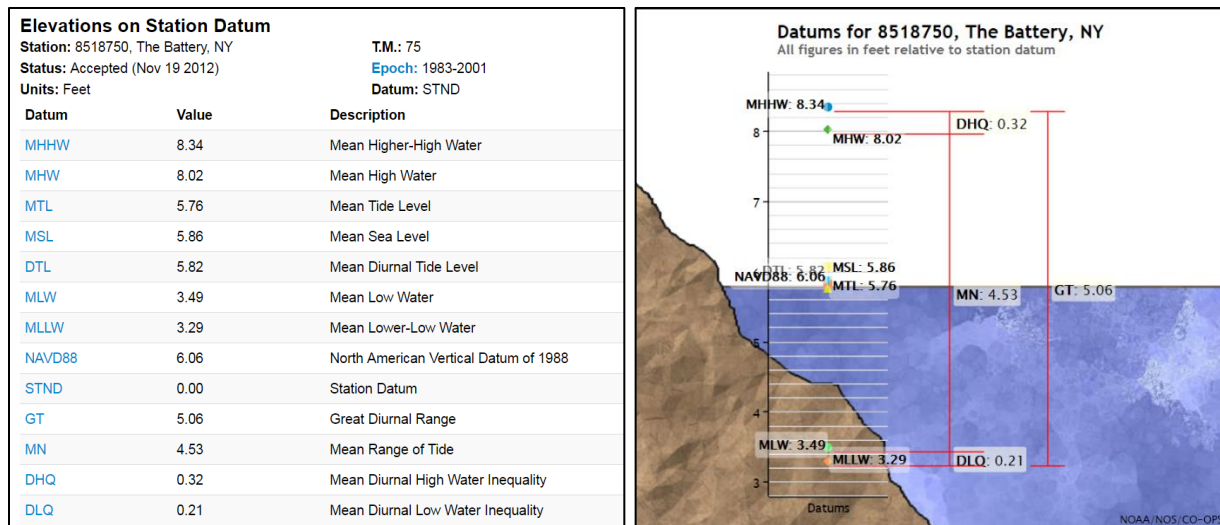


Figure 3 – List of vertical datums water level data at The Battery, NYC can be referenced to (National Ocean Service 2017a).

Risk Communication and Visualization

Risk communication is the process of developing and delivering a message from the risk expert to the general public (Cutter 1993). Effective communication between experts, decision makers and the general public is vital when there is a threat to a community’s livelihood. Visualization techniques can help the risk assessor better understand underlying factors and generate better risk maps, thus communicating a clearer message (Husdal 2001). Buckley, Gahegan, and Clarke (2000) explain that, “The human visual system is the most powerful processing system known. By combining technologies such as image processing, computer graphics, animation, simulation, multimedia, and virtual reality, computers can help present information in a new way so that patterns can be found, greater understanding can be developed, and problems can be solved.” There is also evidence suggesting that (interactive) visualization may often be better suited to communicate risks than mere text or print media (Hahn et al. 2007). Additionally, Coppock (1995) noted visualization as important not only in the development of GIS generally, but also as a tool to improve reliability of hazard assessment, thus decision support, and also to improve the ability of non-experts to take advantage of the information presented.

One of the earliest examples of graphical visualization/communication tool developed by the NWS in the mid 1990’s was the illustration of a hurricane track and its associated “cone of uncertainty” that encompasses the regions most likely to be at risk from tropical cyclones over the next 3 days (American Meteorological Society 1996). The agency has come a long way since then, implementing many more graphical visualization tools to convey weather information, some of which will be discussed later. However, the need for a visualization tool to communicate extratropical storm surge risk is still lacking.

Hurricanes Irene and Sandy

Although the storm surge forecasts for Hurricanes Irene and Sandy were accurate, NOAA's Service Assessment Team (SAT) found that conveying storm surge/storm tide forecast information was one of the most difficult challenges faced by the NWS, EMs and the media. There were several comments received by the team after Irene indicating that the forecasts were "sometimes perceived as being insufficient, confusing and conflicting" (Lubchenco and Furgione 2012).

One Meteorologist-In-Charge responsible for a coastal NWS field office said "EM's don't understand or remember how to use/interpret the SLOSH software. Outside of a few coastal flood savvy EMs and local officials, there is considerable confusion on their part on what the datums mean in terms of real world impacts" (Lubchenco and Furgione 2012).

The Weather Channel staff commented on the lack of visualization tools, "The storm surge forecast was excellent but we are missing the ability to communicate it more visually" (Lubchenco and Furgione 2012).

The most common comment about forecasts heard from government officials, NWS forecasters, and media was that the text forecasts are insufficient and that NWS needs simplified, graphical, impact-based coastal inundation forecast maps. The New York City Office of Emergency Management (NYCOEM) Commissioner stated:

"Mayor Bloomberg asked me every time, 'If I walk out of my door, how far will the water be up on my legs' ...He doesn't want to know 12 feet, 8 feet, etc... The more you can give me about the impact of surge by area—that would be helpful. Graphical inundation forecasts would be helpful" (Lubchenco and Furgione 2012).

Similar statements were made in the wake of Sandy. One media representative commented:

"There were forecasts, but there were no details about what the predicted surges would cause. There was no wording in the warning like, 'Most of lower Manhattan will be under water at a certain point' or 'Staten Island will flood up to Beach Street'" (Sullivan and Uccellini 2013).

An important finding by the SAT was that storm surge terminology, including reference datums and the description of impacts, was confusing. In addition, coastal flood forecasting is difficult and time consuming due to the fact that the data have to be processed in a number of formats and reference datums. The team recommended that the NWS "should present storm surge forecasts in a single, consistent datum and adopt a unified format and language for products describing impacts from storm surge" (Sullivan and Uccellini 2013).

Visualization tools for Tropical Cyclones

NHC has developed several graphical tools that provide storm surge and storm tide information for tropical cyclones, such as the Sea, Lake and Overland Surges from Hurricanes (SLOSH), Probabilistic Surge (P-Surge), and Probabilistic Hurricane Inundation Surge Height (PHISH).

Sea Lake and Overland Surges from Hurricanes (SLOSH)

SLOSH is a numerical model that estimates storm surge heights in thirty-one predefined basins (Figure 4) across the U.S. Atlantic and Gulf of Mexico coastlines, Hawaii, Puerto Rico, Virgin Islands and the Bahamas, from historical, hypothetical, or predicted hurricanes, by taking into account the atmospheric pressure, size, forward speed, and track data. These parameters are used to create a model of the wind field which drives the storm surge (National Hurricane Center 2017b). All SLOSH basins in the contiguous U.S. have recently been updated to NAVD88 from NGVD29. The graphical SLOSH output (Figure 5) can simulate the effects of overland flooding (i.e. inundation) and can be displayed with reference to NAVD88, or feet above ground level, although the differing sizes of the grid cells (Figure 6) indicate that the resolution varies across the basin. Since SLOSH contains a historical database it can be used for a worst-case scenario forecast of storm surge. It is typically used when there is the potential for a tropical cyclone to impact an area in a time beyond 48 hours.

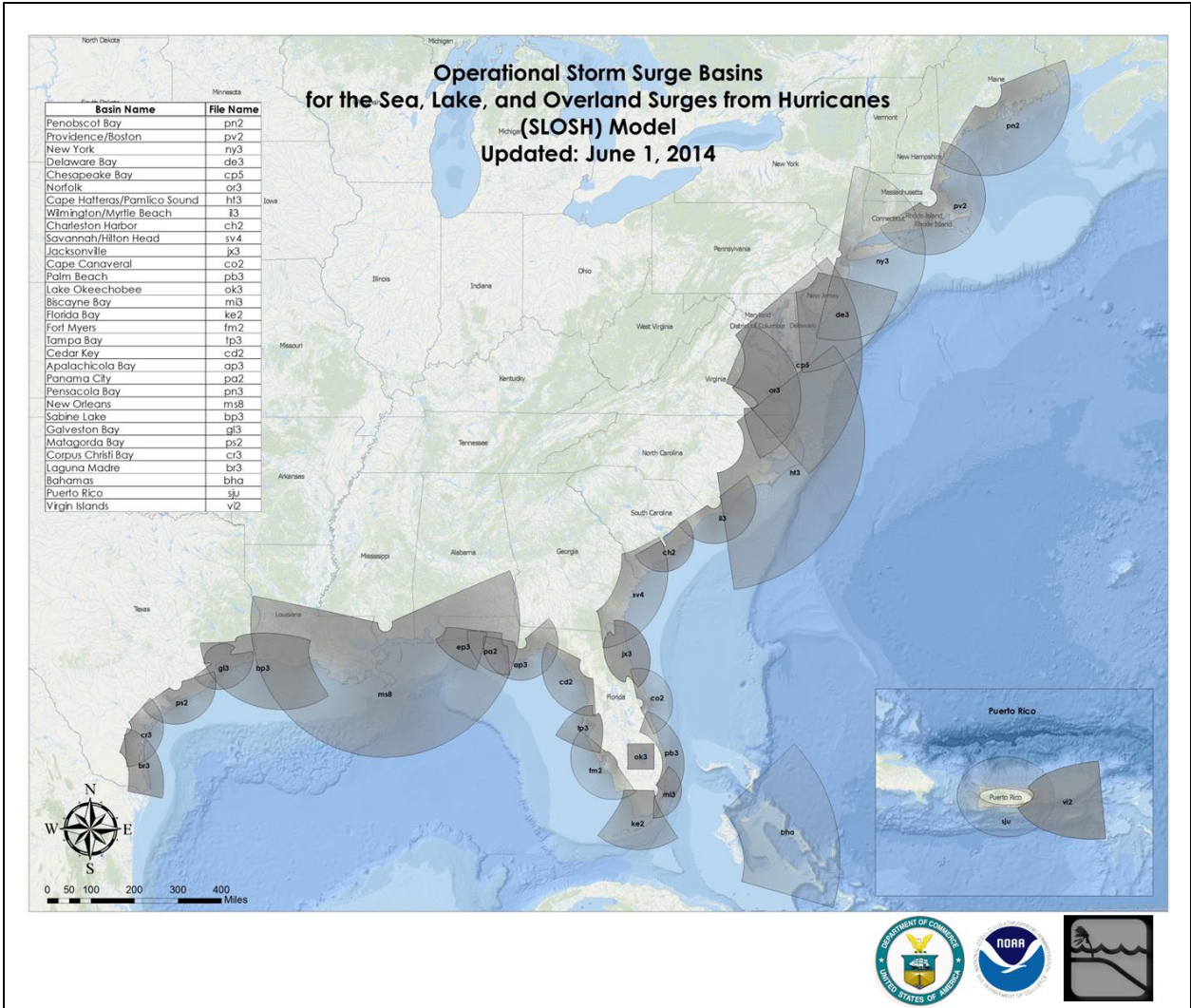


Figure 4 – Thirty-one operational storm surge basins for the SLOSH model (National Hurricane Center 2017b).

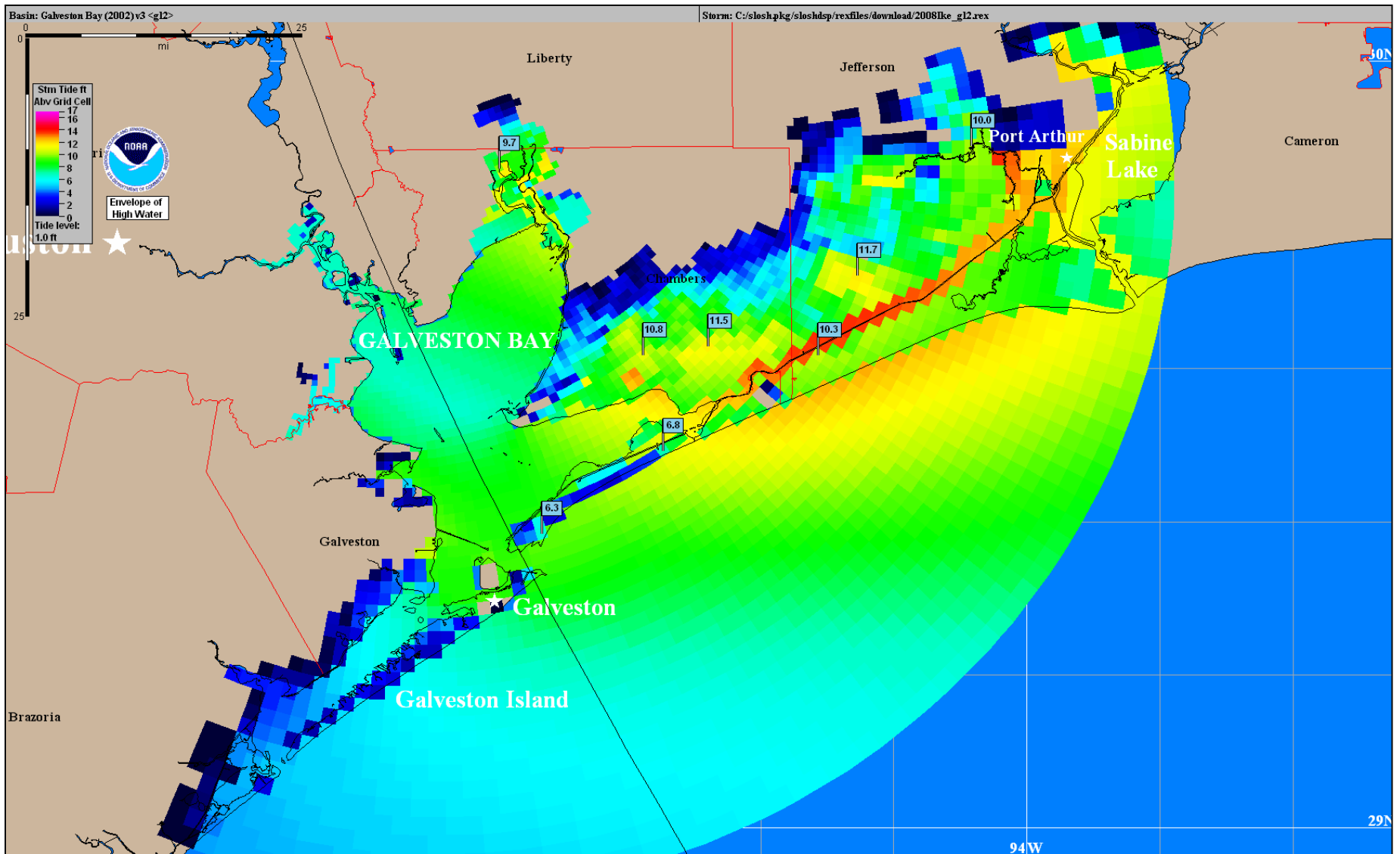


Figure 5 – A sample output of the SLOSH model from Hurricane Ike that affected communities in and around Galveston, TX in 2008. The flagged values are predicted storm tide values in ft. above grid cell based on the National Hurricane Centers forecasted track of Ike through Galveston Bay (National Oceanic and Atmospheric Administration 2017b).

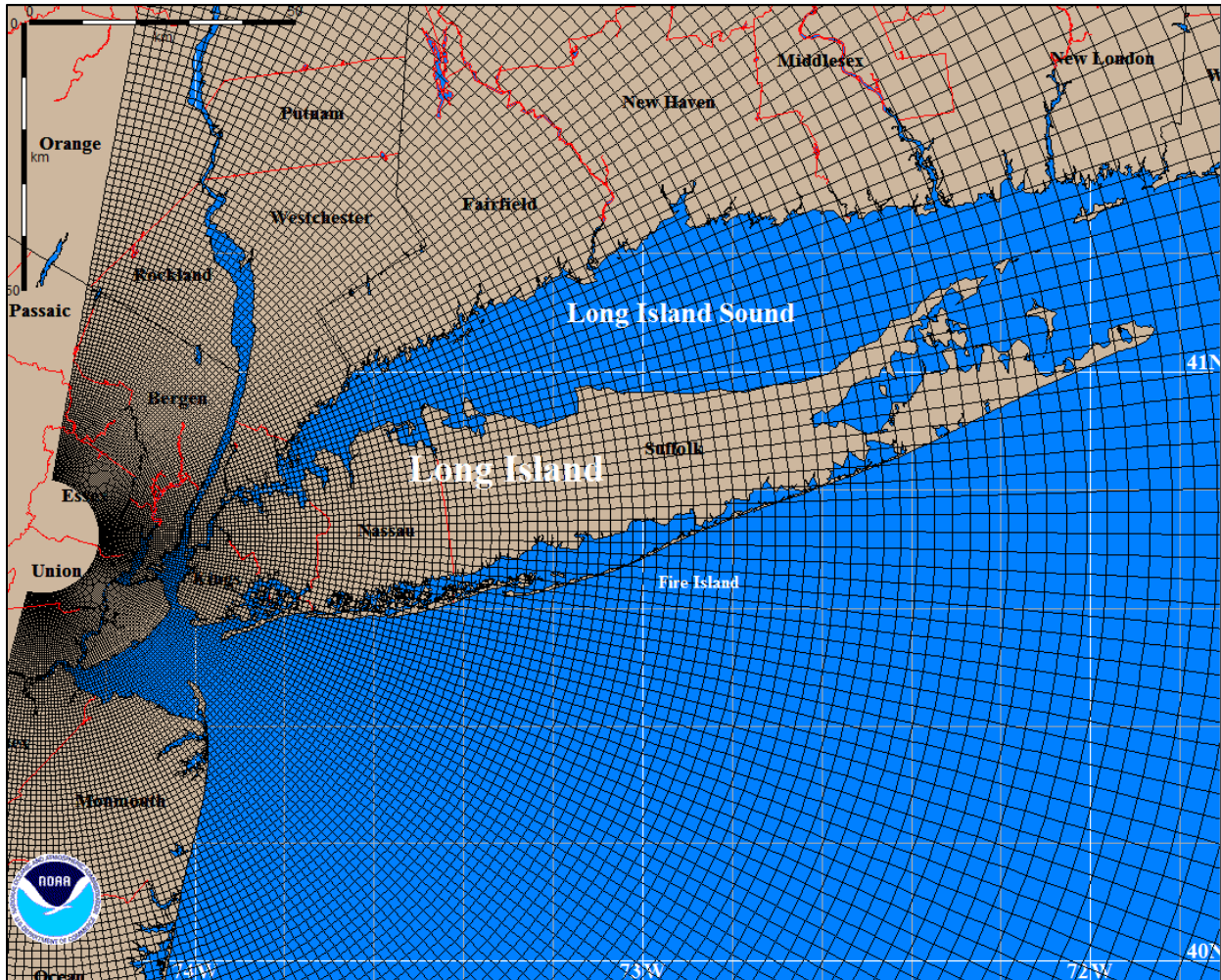


Figure 6 – NYv3 SLOSH basin. The varying sizes of grid boxes are indicative of varying horizontal resolution across the basin (Taylor 2015).

Probabilistic Surge (P-Surge) and Probabilistic Hurricane Inundation Surge Height (PHISH)

P-Surge was developed to enhance SLOSH by quantifying the likelihood of an area exceeding a specified storm surge threshold. However, it is only available from NHC when a watch or warning is issued for a tropical cyclone. P-Surge is an *ensemble forecast* model based on SLOSH that takes the hurricane forecast from NHC and uses error statistics from past hurricane forecasts to create many statistically probable storms. P-Surge then computes the possible storms surge from each of these and combines them together to get a better idea of the probable storms surge (National Weather Service Meteorological Development Laboratory 2017b). P-Surge is issued in two formats; the first displays a graphic of the range of surge heights for a specified probability. The second displays a graphic of the probability of reaching a specified surge height. For example, Figure 7 is an example of the first format and indicates that surge in Western Long Island Sound and New York Harbor have

a 50 percent chance of exceeding 5-7 feet above the NGVD29 datum. Figure 8 is an example of the second format which indicates the probabilities of portions of the east coast exceeding 2 ft. surge, again above NGVD29.

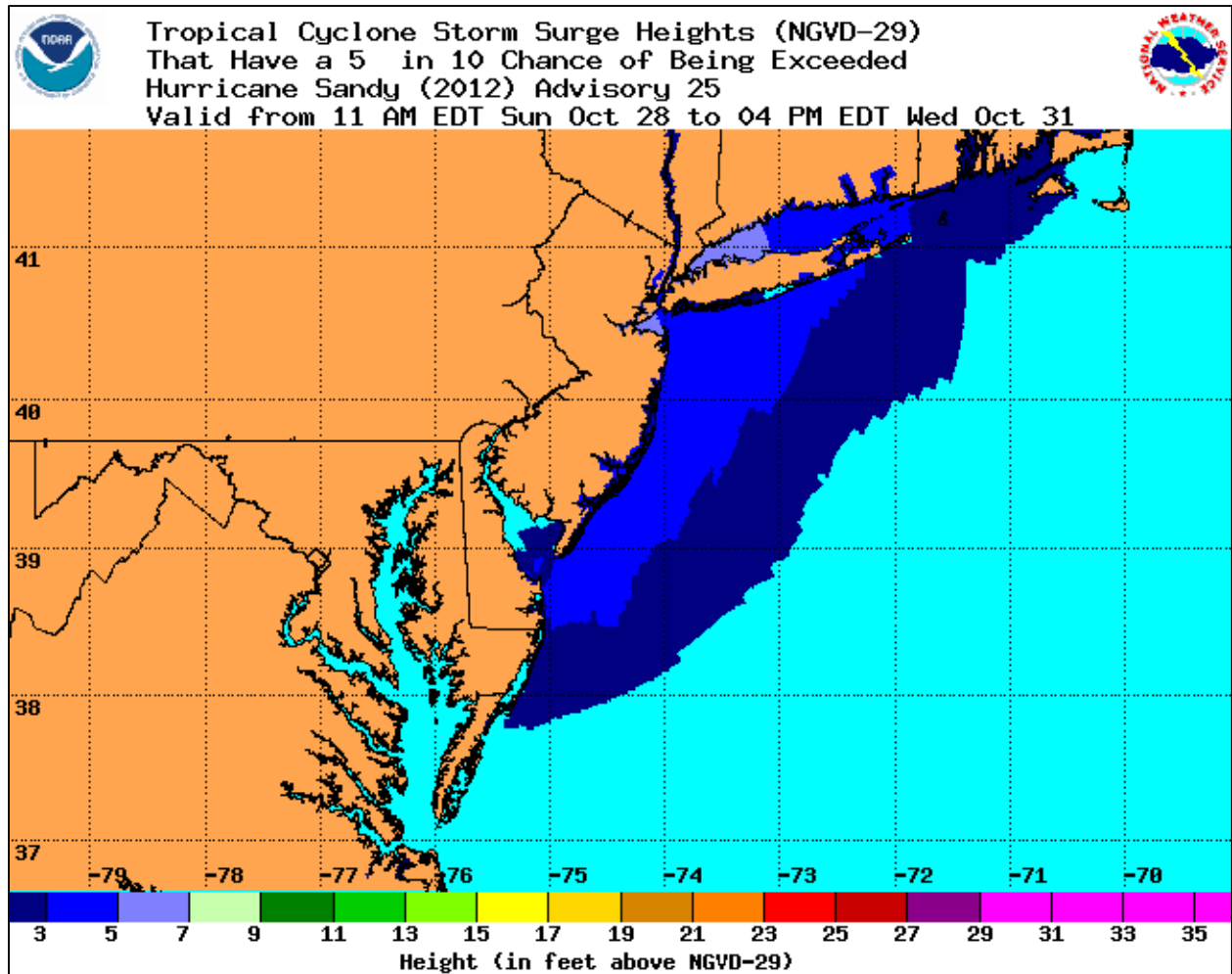
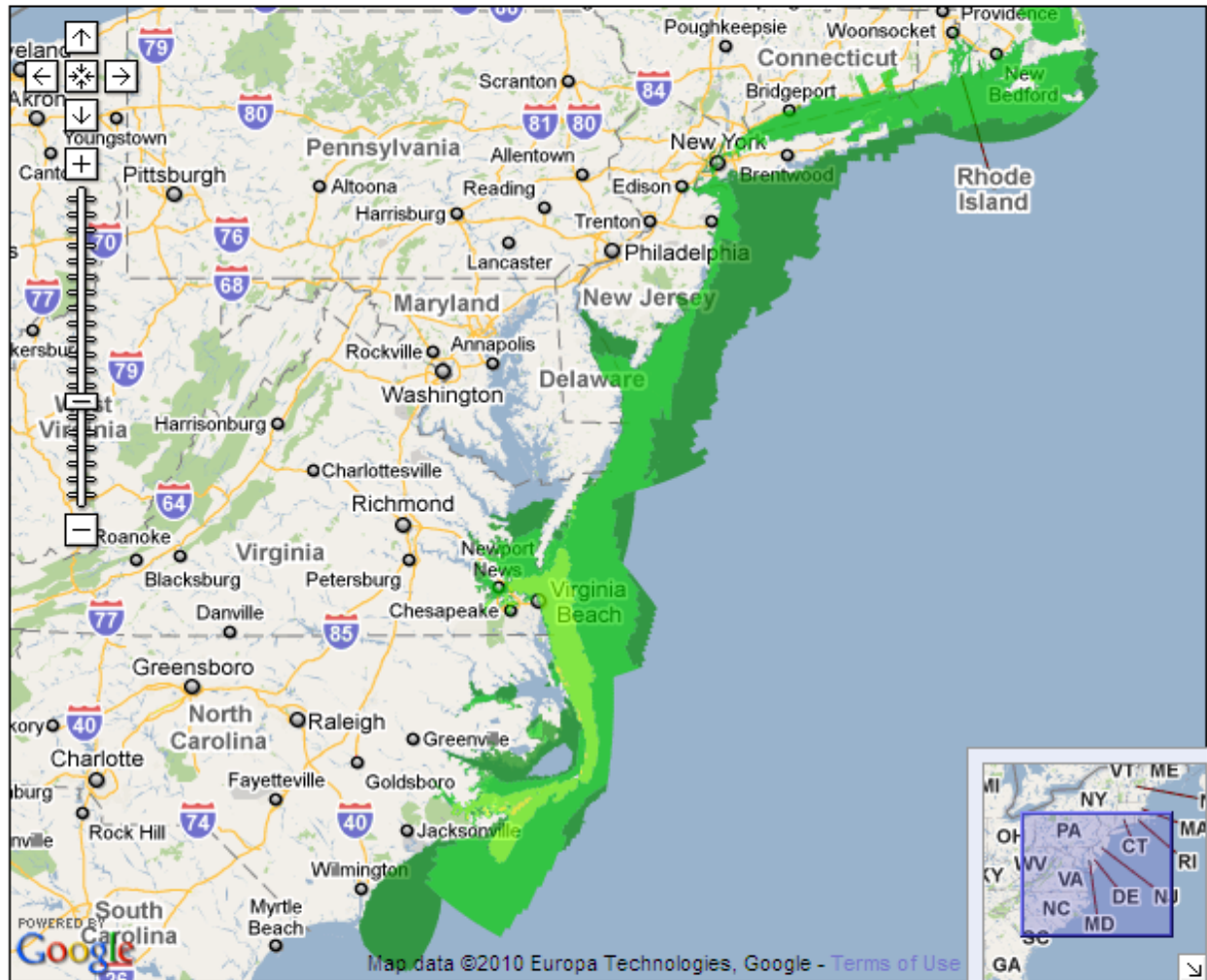


Figure 7 – P-Surge exceedance heights in NGVD29 from Hurricane Sandy Advisory 25 (National Weather Service Meteorological Development Laboratory 2017c).

Tropical Cyclone Storm Surge Probabilities
Chance of Storm Surge \geq 2 feet (NGVD-1929) at individual locations
Hurricane Earl (2010) Advisory 28
For the 77 hours from 05 AM EDT Wed Sep 01 to 10 AM EDT Sat Sep 04

Select Level:



Legend

Probability		
5% - < 10%	40% - < 50%	80% - < 90%
10% - < 20%	50% - < 60%	90% - 100%
20% - < 30%	60% - < 70%	
30% - < 40%	70% - < 80%	

Disclaimer



Historical Data:
 NHC this storm
 NHC all storms
 MDL

Figure 8 – Example of 2 ft. Storm Surge Probabilities in NGVD29 during Hurricane Earl in 2010 (National Hurricane Center 2017d).

To address the communication issue when referencing storm surge/tide above a datum, the NWS developed the Probabilistic Hurricane Inundation Surge Height (PHISH) in 2013. Figure 9 shows the difference between P-Surge and PHISH. PHISH's output shows storm surge inundation which uses the ground as its reference point instead of a datum. This is ideal since it reduces the need for additional calculations to determine what areas will flood. Since P-Surge and PHISH utilize SLOSH grids as inputs, the resolution of both model outputs will vary across the area. However, an interpolation algorithm is used to display the resulting outputs (Figure 10) onto a uniform 625 x 625 meter sub grid to conform with dissemination requirements dictated in NWS policy (National Weather Service 2017c).

While the NHC has been addressing the storm surge communication issues for tropical cyclones by providing probabilistic and exceedance height information through the PHISH product, the resolution is very coarse.

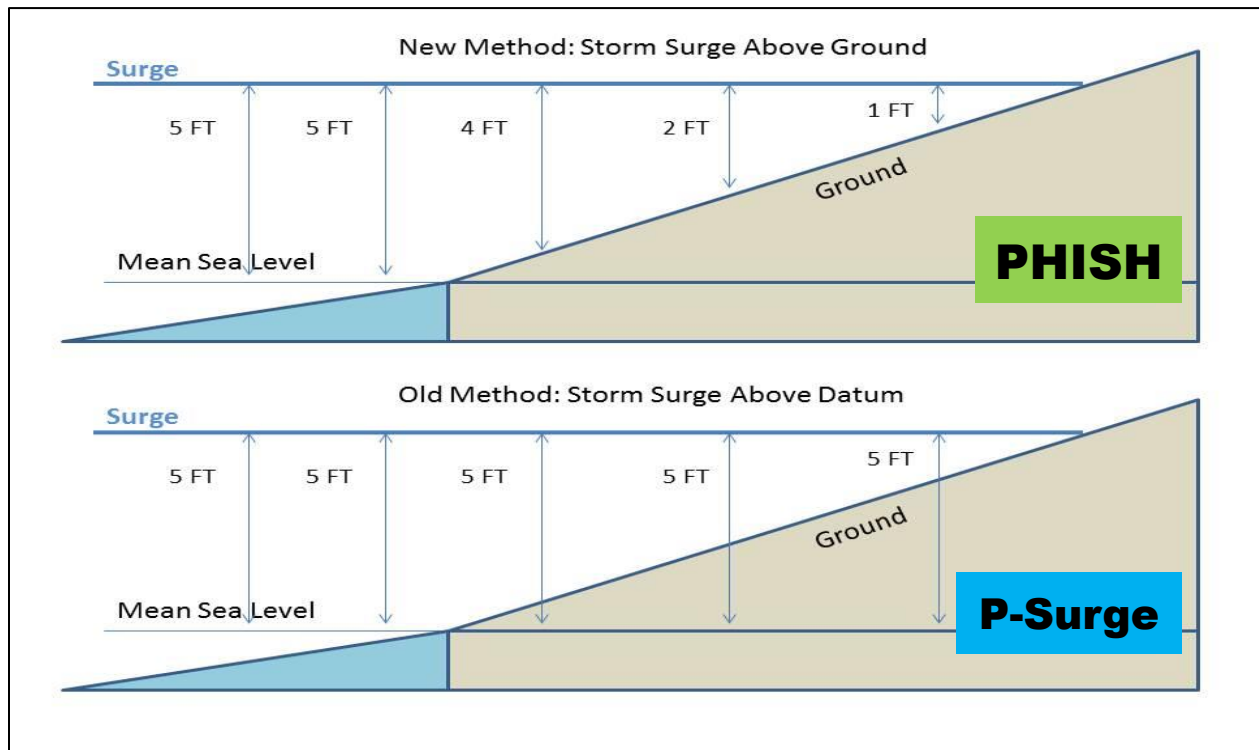


Figure 9 – Two methods the NWS uses to reference storm surge. P-Surge is referenced above a vertical datum while PHISH is referenced to ground level (National Weather Service Meteorological Development Laboratory 2017b).



Figure 10 – Output from PHISH in the New Orleans area. Values in the balloon box indicate the range in feet between which the storm tide is forecasted to reach in the corresponding grid cell (Gibbs 2013).

Visualization Tools for Extratropical Cyclones

Extratropical Storm Surge (ETSS)

Extratropical cyclones can also cause life threatening storm surge. For example, the 1993 Superstorm produced a storm surge of 9 to 12 feet in Florida that killed 11 people. This amount of fatalities were more than what resulted from the surges from Hurricanes Hugo and Andrew combined (National Oceanic and Atmospheric Administration 2017a).

ETSS Storm Surge Model Guidance is used to forecast storm surge associated with extratropical cyclones and is derived from the winds and pressures of the NWS's Global Forecast System (GFS) atmospheric model. It is strictly a forecast of storm surge that ends at the coastline. It does not simulate tides, waves, river effects or overland flooding. Figure 11 is one graphical format example

of this data which is in reference to MSL with a horizontal resolution of 5 km. Another format of the ETSS guidance will be shown later.

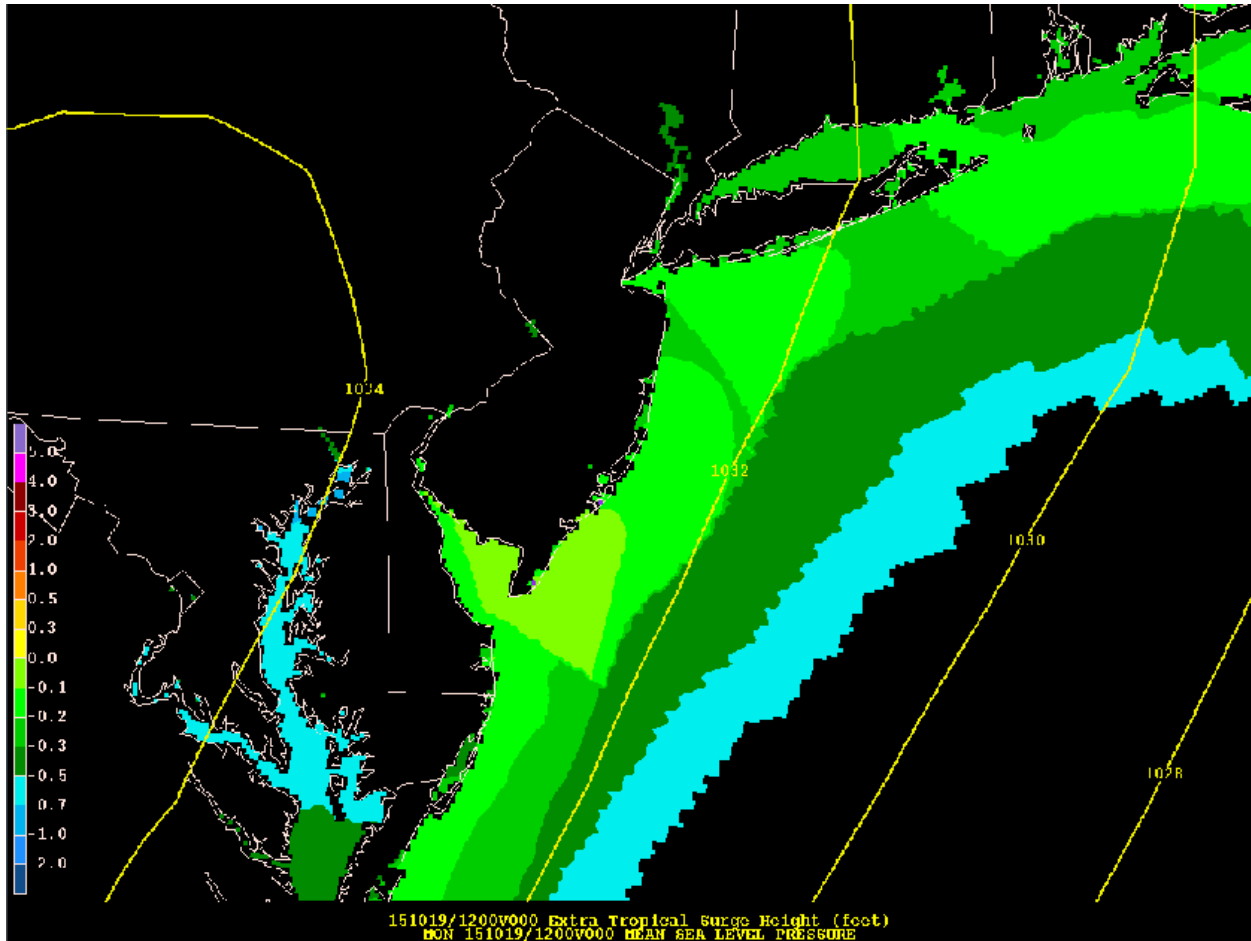


Figure 11 – Graphical ETSS guidance for portions of the U.S. Mid-Atlantic Region (Ocean Prediction Center 2017b).

Extratropical Surge and Tide Operational Forecast System (ESTOFS)

ESTOFS guidance (Figure 12) is also used to forecast storm surge associated with extratropical cyclones. It is derived from the Advanced Circulation (ADCIRC) Model, a hydrodynamic modeling technology that conducts short- and long-term simulations of tide and storm surge elevations and velocities in deep-ocean, continental shelves, coastal seas, and small-scale estuarine systems (US Army Corps of Engineers 2017). ESTOFS are produced at half the resolution as the ETSS, 2.5 km, and incorporates tidal information into its solutions, therefore is a forecast of storm tide above MSL. However, like the ETSS, it does not simulate waves, river effects or overland flooding.

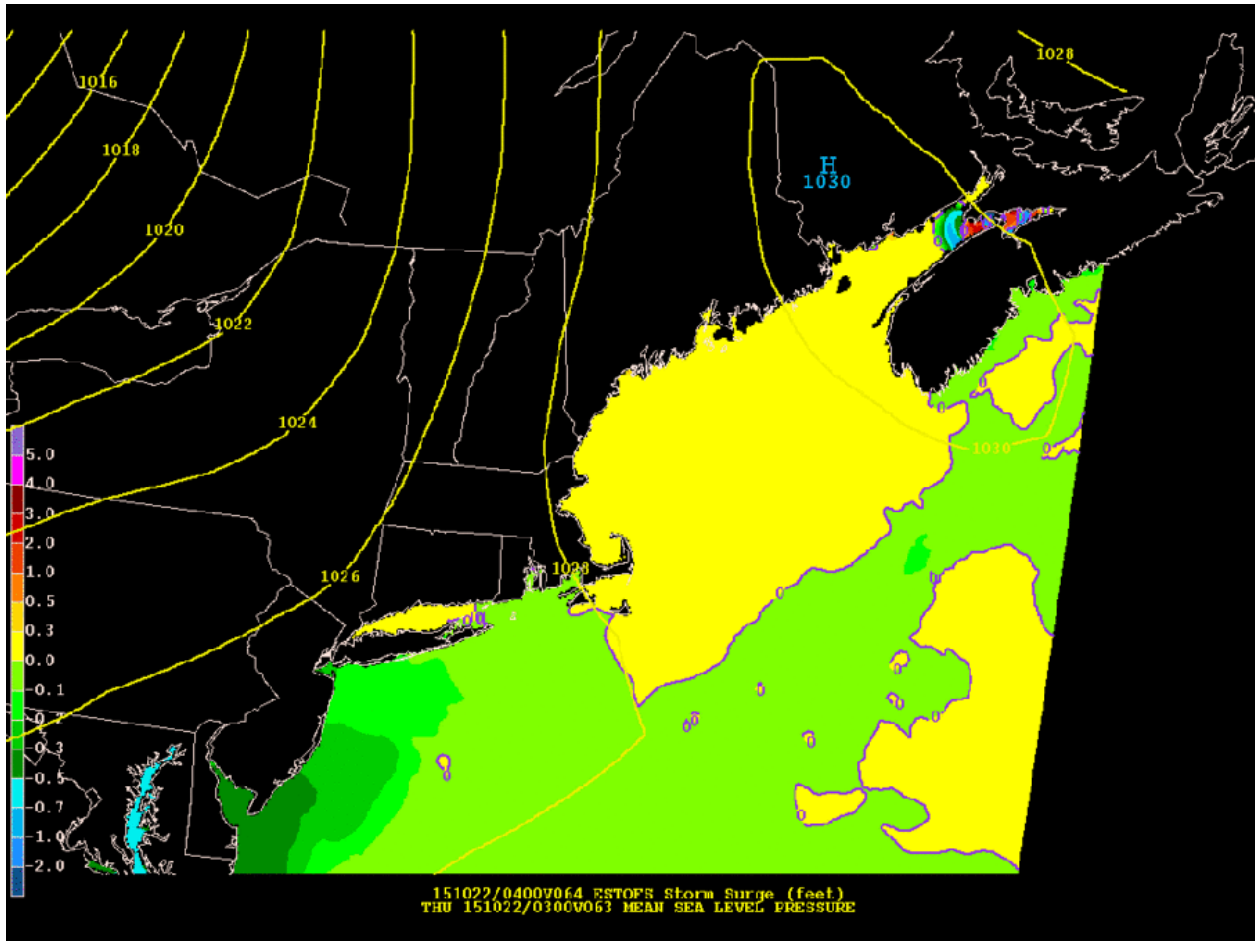


Figure 12 – A graphical representation of ESTOFS guidance for the coastlines of New England and portions of the Mid-Atlantic region (Ocean Prediction Center 2017a).

Extratropical Storm Surge Products Provided to the Emergency Management Community by NWS NY, NY

The NWS New York City Weather Forecast Office conducts webinars for the EM community whenever there is the potential for a widespread severe weather event, to convey the potential risks their respective jurisdictions could be facing. While the ETSS and ESTOFS graphical guidance shown above is available, the fact that the surge is expressed above MSL is not ideal. The EM's are most familiar with MLLW and NGVD29 although this is still not optimal since they have to refer to other information or make additional calculations to determine what areas will be inundated and potentially evacuated.

Many NWS field offices currently use a combination of graphical and text products to convey the threat of coastal flooding to its customers and partners during extratropical events. Figure 13 is an example of what the NWS New York City office provides to EMs during decision support briefings/webinars prior to a significant coastal flooding event. This graph has a lot of useful information in it, but decision makers need something that is elementary and does not take a lot of

explaining or analysis. Figure 14 is an example of a text product issued by NWS NYC prior to the April 16, 2010 Nor'easter. The total water levels (i.e. storm tide) are provided, however it is only available for select locations. It is difficult to visualize what this means in terms of overland flood inundation and extent not only at these locations, but also between locations.

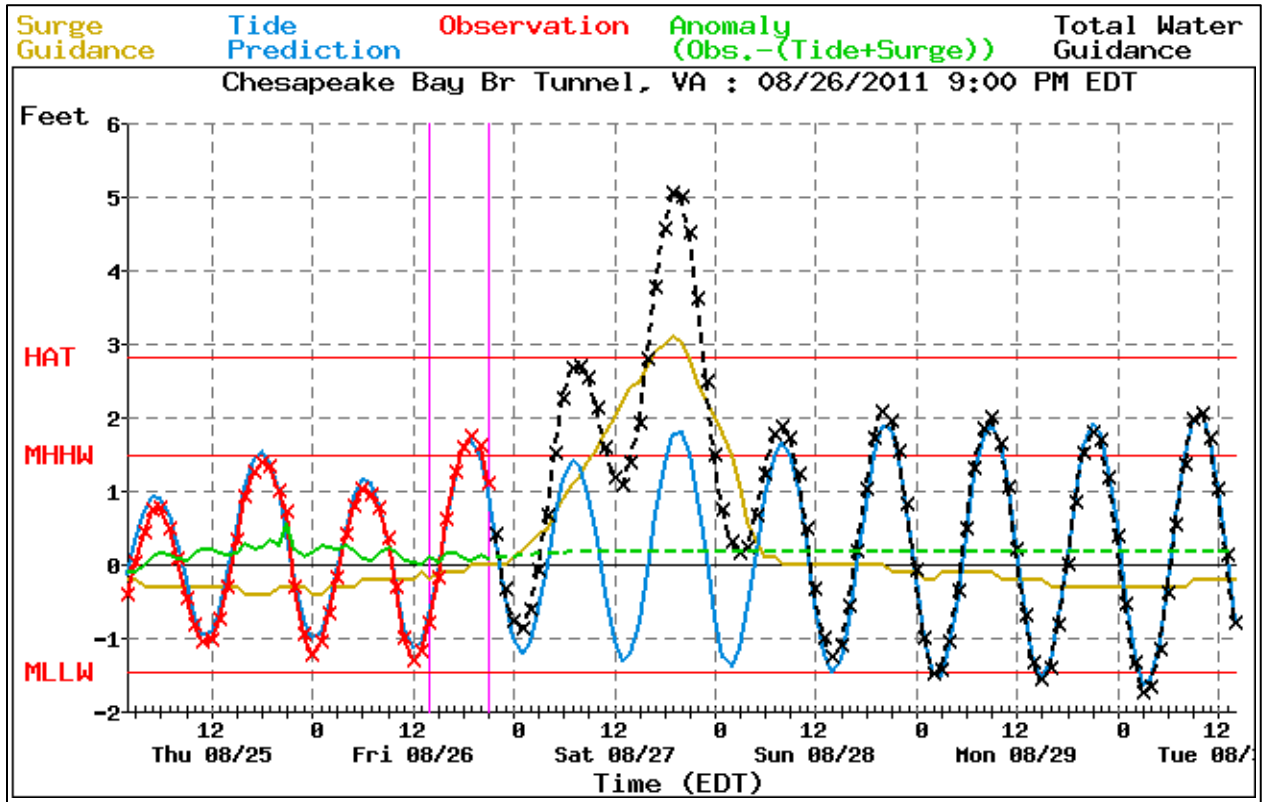


Figure 13 – Graphical ETSS surge above MSL for Chesapeake Bay Br. Tunnel, VA displaying astronomical tide levels, storm surge forecast, observed data, anomaly and total water levels for Hurricane Irene (National Weather Service Meteorological Development Laboratory 2017a).

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HIGH TIDE CYCLES THIS MORNING
...LONG ISLAND SOUND...
.....TIME OF.....FORECAST TOTAL.....FLOOD.....
LOCATION.....HIGH TIDE.....WATER LEVEL (FT).....CATEGORY..
.....(MLLW).....
BRIDGEPORT.....940 AM.....8.9.....MINOR.....
STAMFORD.....943 AM.....10.0.....MINOR.....
KINGS POINT.....1014 AM.....10.0.....N/A.....
LATTINGTOWN.....952 AM.....9.7.....MINOR.....

...NEW YORK HARBOR...
.....TIME OF.....FORECAST TOTAL.....FLOOD.....
LOCATION.....HIGH TIDE.....WATER LEVEL (FT).....CATEGORY..
.....(MLLW).....
BATTERY.....642 AM.....6.5.....NONE.....
BERGEN POINT.....644 AM.....6.9.....N/A.....

HIGH TIDE CYCLES THIS EVENING
...LONG ISLAND SOUND...
.....TIME OF.....FORECAST TOTAL.....FLOOD.....
LOCATION.....HIGH TIDE.....WATER LEVEL (FT).....CATEGORY..
.....(MLLW).....
BRIDGEPORT.....1000 PM.....10.7.....MODERATE...
STAMFORD.....1003 PM.....10.9.....MINOR.....
KINGS POINT.....1032 PM.....11.6.....MODERATE...
LATTINGTOWN.....1010 PM.....10.8.....MODERATE...

...NEW YORK HARBOR...
.....TIME OF.....FORECAST TOTAL.....FLOOD.....
LOCATION.....HIGH TIDE.....WATER LEVEL (FT).....CATEGORY..
.....(MLLW).....
BATTERY.....642 PM.....7.7.....MINOR.....
BERGEN POINT.....644 PM.....8.3.....N/A.....

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Figure 14 – A portion of a Coastal Hazard Message issued by the National Weather Service New York, NY Forecast Office indicating forecasted storm tide and corresponding flood categories for select locations (National Weather Service New York NY 2010).

Methodology

The case study chosen for this project was Hurricane Sandy. Although it could be argued that Sandy was a tropical system (even though she was officially classified as extratropical before landfall), and this tool is meant to be used for extratropical storm systems in the future, it is used as the case study since it was an extreme event and a lot of impact data was received which was used to verify the analysis. The output raster will provide inundation AGL for extratropical cyclones within the study area (Figure 15) with a 3-meter horizontal resolution.



Figure 15 – Study area: National Weather Service New York, NY County Warning Area. Initial validation of results will focus on the area in the bottom left inset (*ArcGIS* (version 10.4) 2016).

Data

A digital elevation model (DEM) and a water surface constitute the core data inputs for the analysis. The DEM chosen for this project was developed by NOAA’s National Centers for Environmental Information (NCEI) with a 1/9 arc second (approximately 3m) spatial resolution and is referenced horizontally to the North American Datum of 1983 (NAD83) and vertically to the North American Vertical Datum of 1988 (NAVD88) in units of meters (National Centers for Environmental Information 2017a).

The water surface was extracted from the *Graphical Forecast Editor* (GFE) contained in the Common Advanced Weather Interactive Processing System (AWIPS) Visualization Environment (CAVE), the software forecasters in the NWS use to develop weather forecasts. GFE contains a temporally gridded database consisting of various weather elements such as temperature, winds, sky cover, etc. (Figure 16). Storm surge and astronomical tide grids are also included in GFE. These datasets were used to create a Storm Tide grid, also known as Total Water Level (TWL), and exported from GFE to a Network

Common Data Form (NetCDF) file. The TWL dataset has a 2.5 km. spatial resolution and is referenced horizontally to a customized Lambert Conic Conformal (LCC) projection and vertically to the MLLW tidal datum in units of feet.

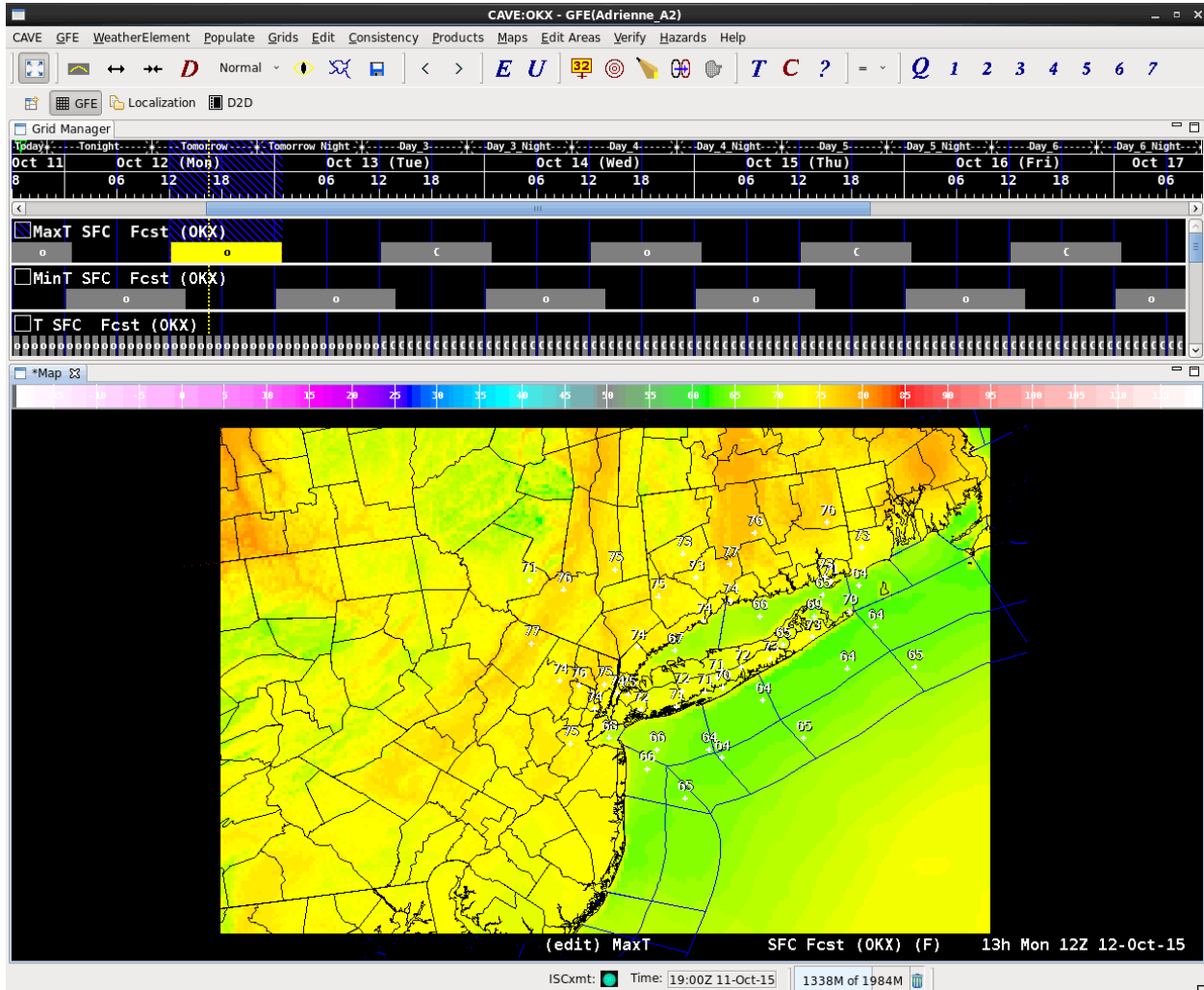


Figure 16 – The Graphical Forecast Editor contained within the CAVE system utilized throughout the NWS to create forecasts (Common AWIPS Visualization Environment (version 14.4.2-5) 2015).

ArcGIS

Esri recently added a multidimensional toolset to the ArcGIS toolbox to aid in importing scientific data for analysis, as long as the metadata complies with the Climate and Forecast (CF) metadata convention. Since the NetCDF file was extracted from an internal database, it couldn't readily be displayed in ArcGIS using the multidimensional toolset because it did not write the metadata in such a way that complies with the CF convention. Thus, the Geospatial Data Abstraction Library (GDAL) was employed to convert the dataset into a readable format.

and the TWL raster is in MLLW (feet). Since Esri is still working on adding tidal datums to their vertical transformation toolset in ArcGIS, another solution is required. This solution involves using NOAA's Vertical Datum Transformation (VDatum) tool, which converts elevation values between different vertical datums based on a locations geographic coordinates, but requires a bit of work.

VDatum requires a tabular dataset, so first the TWL raster has to be converted to point data. The attribute table of this point data is then exported from ArcGIS as a database file and converted into a comma delimited file using Microsoft Excel. The comma delimited file is then run through VDatum with the source and target data configured (Figure 18).

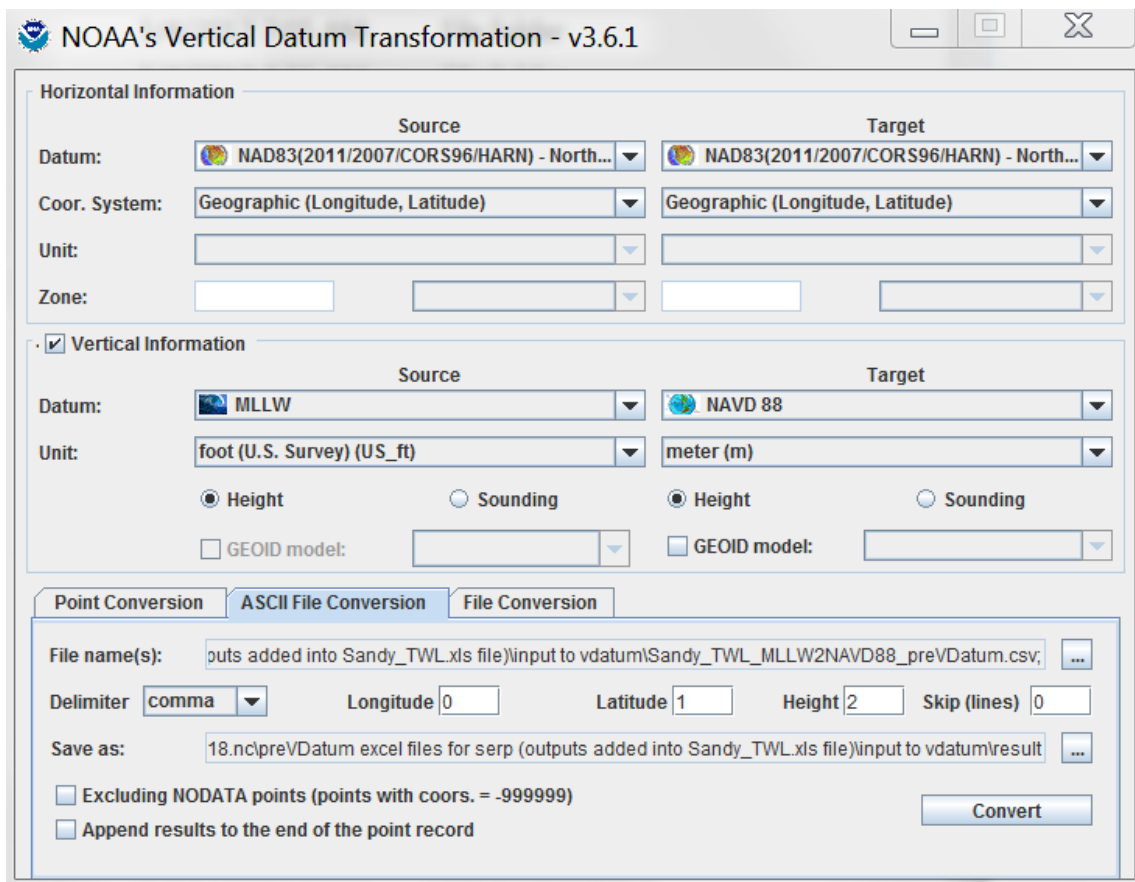


Figure 18 – Interface of the VDatum tool (*Vertical Datum Transformation (VDatum)* (version 3.6.1). 2016).

The output file from VDatum now contains the dataset in NAVD88 (meters). This tabular data is then imported back into ArcGIS, saved as a point data feature class and then converted back to a raster. As a result of running the dataset through VDatum, a lot of points became undefined (dark blue areas) and thus have “NoData” in them (Figure 19).

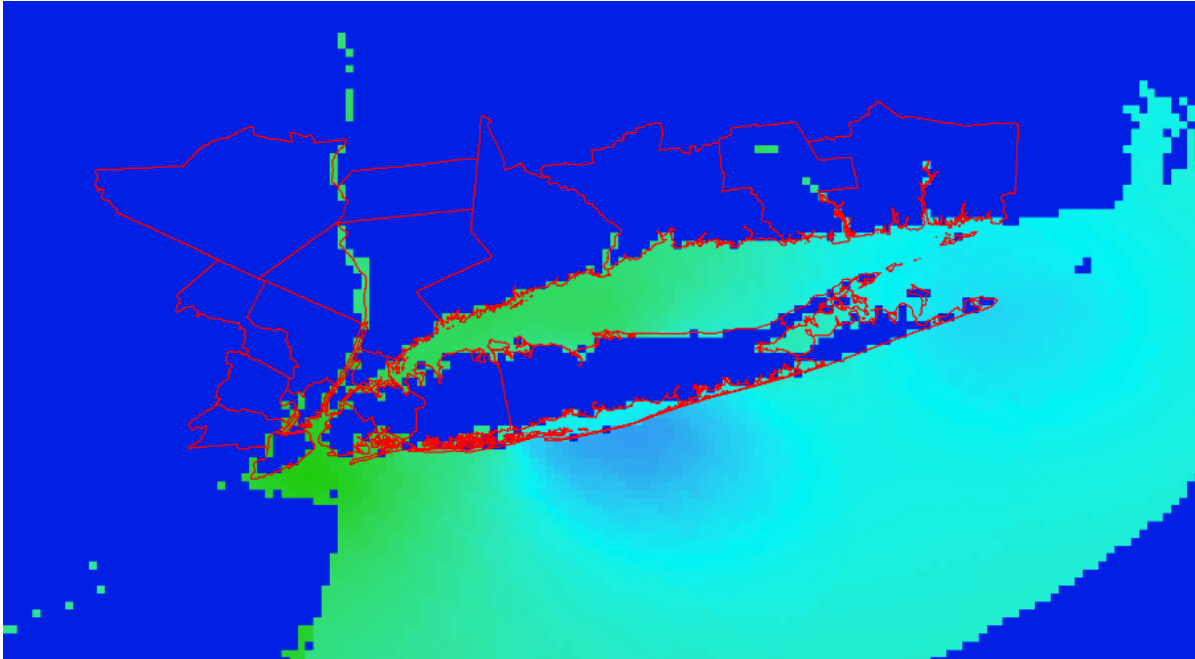


Figure 19 – Raster dataset post-VDatum (ArcGIS (version 10.4) 2016).

Since there is data right at the coastline, the Euclidean Allocation (EA) tool can be used to extrapolate it inland. A hydrodynamic model containing an overland water surface would be the most ideal for this project, but such a dataset doesn't exist, so the EA tool is the next best option. The EA tool creates a raster where "NoData" cells have been extrapolated to contain values based on their Euclidean, or straight line, distance to the nearest cell containing a real value.

After running the EA tool, the raster is resampled to match the horizontal resolution of the DEM to obtain a high-resolution inundation raster. Since both the water surface and the DEM are in the same vertical and horizontal coordinate systems (NAVD88 and NAD83 respectively), and have the same units (meters) and horizontal resolution (1/9 arc second), we can now calculate inundation.

To calculate inundation, the raster calculator is used to subtract the resampled raster from the DEM wherever the raster's water level values are greater than the DEM's elevation. Finally, the resulting inundation raster values were converted from meters to feet using the raster calculator tool in the spatial analyst toolset.

Results

Figure 20 shows the inundation raster across the study area indicating the potential inundation areas from Sandy. Deeper areas of inundation are shown as darker shades of blue. Although there is inundation indicated along major tidally driven rivers, this information should be used with caution since

the data does not account for tidal influence up the rivers. Additional analysis needs to be conducted to determine the accuracy of this.

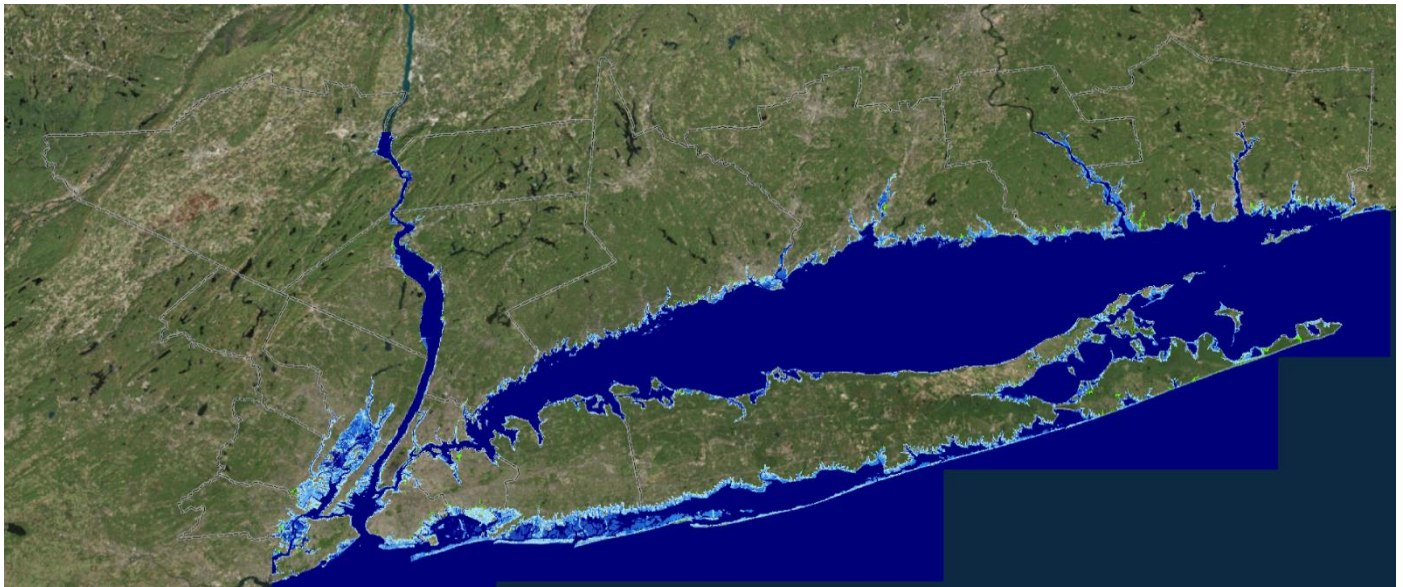


Figure 20 – Inundation raster across the study area. Inundated areas are in various shades of blue along coastal regions and large tidally driven rivers (ArcGIS (version 10.4) 2016).

In order to verify the validity of the data, impact data received from EM’s that correlated with the water levels recorded at the tidal gauge at The Battery in NYC were used. These impacts consisted of locations that experienced coastal flooding during the event. The latitude and longitude of the locations were found and plotted in ArcGIS. The intersect tool was then used to determine if these areas fell within the inundation area calculated. Green points indicate a positive result, while red points fall outside of the inundation raster (Figure 21). As you can see there is only one location out of nineteen that did not overlap, but upon closer inspection, it was only forty feet beyond the inundated area. There are a total of twenty-two tidal gages across the study area. Additional verification will be performed at these locations in the same manner as at The Battery to validate the entire dataset.

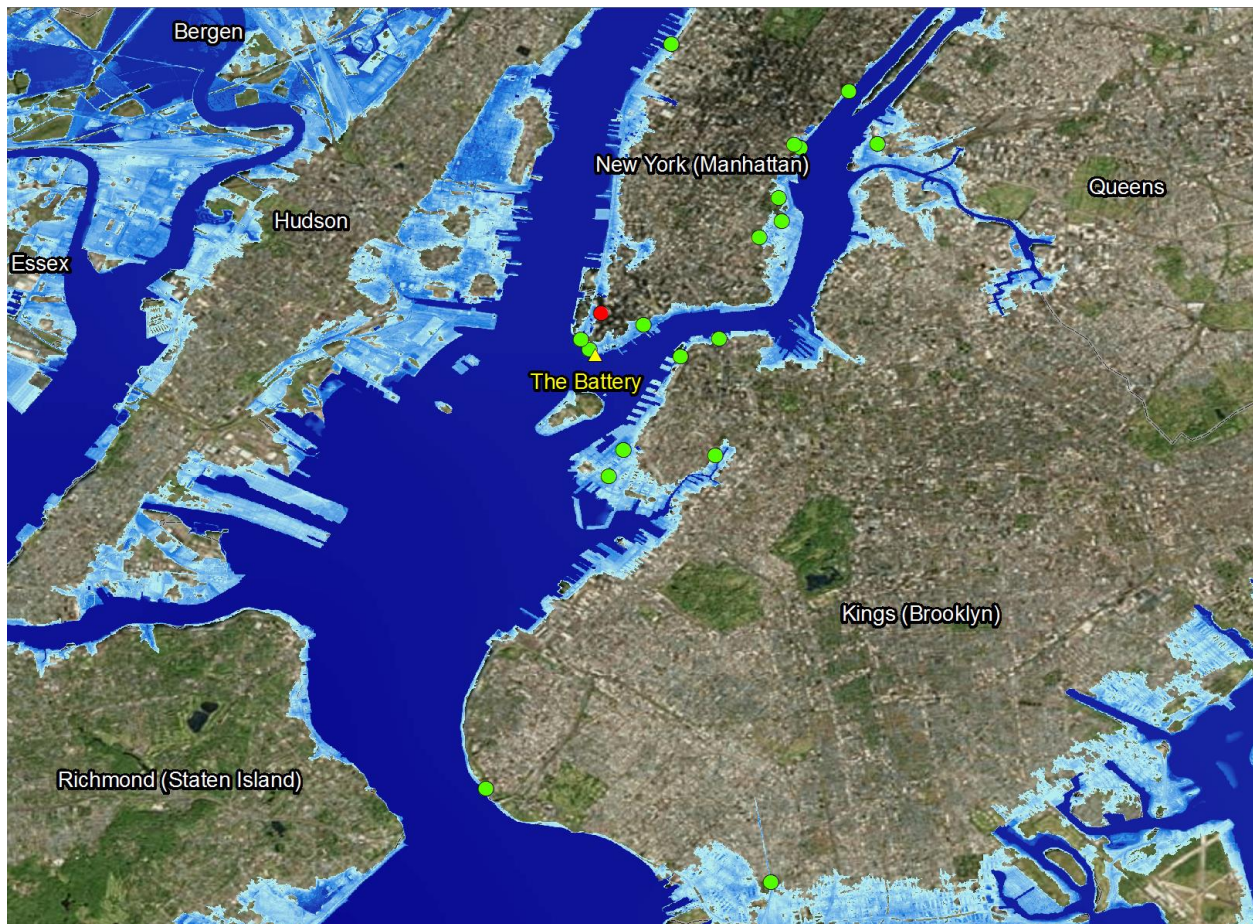


Figure 21 – Validated areas of inundation near the tidal gage (yellow triangle) located in The Battery, NY (ArcGIS (version 10.4) 2016).

Summary

Geospatial technology can be used to analyze and solve many problems faced across the globe. A visual representation of coastal inundation associated with extratropical cyclones is just another example of exploiting this technology. This project has improved upon the products already being produced by the NWS by extrapolating the water level data overland and providing the output as inundation at a higher resolution.

Graphical visualization products provided by the NHC for tropical cyclones have been improving in resolution over the past decade due to faster central processing units, but they are still very coarse at 625 meters. More importantly, conveying the storm surge threat is much easier with the implementation of PHISH, although none of the storm surge products associated with tropical cyclones are available until a watch or warning is issued.

The resolution of ETSS model guidance is better than tropical surge guidance at 2.5 km and 5 km, however the data does not currently extend overland and is still referencing its output to a vertical datum.

Appendix A – Glossary

Altimetry – a technique for measuring the height of the Earth’s surface with respect to the geocenter of the Earth within a defined terrestrial reference frame (geocentric sea level) (IPCC 2013).

Coastal Inundation – the flooding of normally dry, low-lying coastal land, primarily caused by severe weather events along the coasts, estuaries, and adjoining rivers (National Oceanic and Atmospheric Administration 2017c).

Ensemble – a collection of numerical model results that show slightly different possible outcomes (National Weather Service 2017a).

Ensemble Forecast – multiple predictions from an ensemble of slightly different initial conditions and/or various versions of models. The objectives are to improve the accuracy of the forecast through averaging the various forecasts, which eliminates non-predictable components, and to provide reliable information on forecast uncertainties from the diversity amongst ensemble members. Forecasters use this tool to measure the likelihood of a forecast (National Weather Service 2017a).

Extratropical Cyclone – a cyclone whose primary energy source results from the temperature contrast between warm and cold airmasses (National Hurricane Center 2017a).

Geodetic Datum – an abstract coordinate system with a reference surface (such as sea level) that serves to provide known locations to begin surveys and create maps (National Ocean Service 2017d).

Great Diurnal Range (GT) – the difference in height between mean higher high water and mean lower low water (National Ocean Service 2017b).

Hurricane – a tropical cyclone in the Atlantic, Caribbean Sea, Gulf of Mexico, or eastern Pacific, which the maximum 1-minute sustained surface wind is 64 knots (74 mph) or greater (National Weather Service 2017a).

Mean Diurnal High Water Inequality (DHQ) – the difference in height of the two high waters of each tidal day for a mixed or semidiurnal tide (National Ocean Service 2017b).

Mean Diurnal Low Water Inequality (DLQ) – the difference in height of the two low waters of each tidal day for a mixed or semidiurnal tide (National Ocean Service 2017b).

Mean Diurnal Tide Level (DTL) – the arithmetic mean of mean higher high water and mean lower low water (National Ocean Service 2017b).

Mean High Water (MHW) – the average of all the high-water heights observed over the National Tidal Datum Epoch. For stations with shorter series, comparison of simultaneous observations with a control tide station is made in order to derive the equivalent datum of the National Tidal Datum Epoch (National Ocean Service 2017b).

Mean Higher High Water (MHHW*) – the average of the higher high-water height of each tidal day observed over the *National Tidal Datum Epoch*. For stations with shorter series, comparison of simultaneous observations with a control tide station is made in order to derive the equivalent datum of the National Tidal Datum Epoch (National Ocean Service 2017b).

Mean Low Water (MLW) – the average of all the low water heights observed over the National Tidal Datum Epoch. For stations with shorter series, comparison of simultaneous observations with a control tide station is made in order to derive the equivalent datum of the National Tidal Datum Epoch (National Ocean Service 2017b).

Mean Lower Low Water (MLLW*) – the average of the lower low water height of each tidal day observed over the National Tidal Datum Epoch. For stations with shorter series, comparison of simultaneous observations with a control tide station is made in order to derive the equivalent datum of the National Tidal Datum Epoch (National Ocean Service 2017b).

Mean Range of Tide (MN) – the difference in height between mean high water and mean low water (National Ocean Service 2017b).

Mean Sea Level (MSL) – the arithmetic mean of hourly heights observed over the National Tidal Datum Epoch. Shorter series are specified in the name; e.g. monthly mean sea level and yearly mean sea level (National Ocean Service 2017b).

Mean Tide Level (MTL) – the arithmetic mean of mean high water and mean low water (National Ocean Service 2017b).

National Tidal Datum Epoch – The specific 19-year period adopted by the National Ocean Service as the official time segment over which tide observations are taken and reduced to obtain mean values (e.g., mean lower low water, etc.) for tidal datums. It is necessary for standardization because of periodic and apparent secular trends in sea level. The present NTDE is 1983 through 2001 and is actively considered for revision every 20-25 years. Tidal datums in certain regions with anomalous sea level changes (Alaska, Gulf of Mexico) are calculated on a Modified 5-Year Epoch (National Ocean Service 2017b).

Nor'easter – a strong low-pressure system that affects the Mid-Atlantic and New England States. It can form over land or over the coastal waters. These weather events are notorious for producing heavy snow, rain, and tremendous waves that crash onto Atlantic beaches, often causing beach erosion and structural damage. Wind gusts associated with these storms can exceed hurricane force in intensity. A nor'easter gets its name from the continuously strong northeasterly winds blowing in from the ocean ahead of the storm and over the coastal areas (National Weather Service 2017a).

North American Vertical Datum of 1988 (NAVD88) – a leveling network on the North American Continent, ranging from Alaska, through Canada, across the United States, affixed to a single origin point on the continent (National Geodetic Survey 2017):

- Tide Station & Location = Pointe-au-Pere, Rimouski, Quebec, Canada
- PID = TY5255
- GSD* Designation = 54L071
- Bench Mark = 1250 G
- Ht above LMSL(Meters) = 6.271

Post-tropical Cyclone – A former tropical cyclone. This generic term describes a cyclone that no longer possesses sufficient tropical characteristics to be considered a tropical cyclone. Post-tropical cyclones can continue carrying heavy rains and high winds. Note that former tropical cyclones that have become fully extratropical, as well as remnant lows, are two classes of post-tropical cyclones (National Hurricane Center 2017a).

Proxy Data – data that paleoclimatologists gather from natural recorders of climate variability, such as tree rings, ice cores, fossil pollen, ocean sediments, coral and historical data (National Centers for Environmental Information 2017b).

Station Datum – a fixed base elevation at a tide station to which all water level measurements are referred. The datum is unique to each station and is established at a lower elevation than the water is ever expected to reach. It is referenced to the primary bench mark at the station and is held constant regardless of changes to the water level gauge or tide staff (National Ocean Service 2017b).

Storm Surge – an abnormal rise in sea level accompanying a hurricane or other intense storm, whose height is the difference between the observed level of the sea surface and the level that would have occurred in the absence of the cyclone. Storm surge is usually estimated by subtracting the normal or astronomic tide from the observed storm tide. (National Weather Service 2017a).

Storm Tide – the actual level of sea water resulting from the astronomic tide combined with the storm surge. Most NWS flood statements, watches, or warnings quantifying above-normal tides will report the Storm Tide (National Weather Service 2017a).

Tropical Cyclone – a warm-core non-frontal synoptic scale cyclone, originating over tropical or subtropical waters, with organized deep convection and a closed surface wind circulation about a well-defined center (National Hurricane Center 2017a).

Tidal Datum – a type of vertical datum that is based on tidally-derived surfaces of high or low water (National Ocean Service 2017c).

Vertical Datum - a surface of zero elevation to which heights of various points are referred in order that those heights be in a consistent system (National Geodetic Survey 2017).

*Some locations have diurnal tides--one high tide and one low tide per day. At most locations, there are semidiurnal tides--the tide cycles through a high and low twice each day, with one of the two high tides being higher than the other and one of the two low tides being lower than the other.

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