

Final Project Report

**RAPID: Collection of Data on Flood and Hydrodynamic Impact on  
Coastal Infrastructure in the New York City Metropolitan Region  
during the Hurricane Sandy**

Grant Dates: January 15, 2013 -- December 31, 2014

NSF Award Number: CMMI # 1313877

Grant Amount: \$35,000

Project manager: Kishor C. Mehta

Hansong Tang (PI), Anil Agrawal (co-PI)

Dept. of Civil Eng., City College

The City University of New York

138th Street & Convent Avenue

New York, NY 10031

March 31, 2015

## **Acknowledgment**

We sincerely acknowledge the contribution of Damian Okon, Yan Fei Luo, Ananth Niraula, Rianna Marishka Yuen, Jon Rosen, Chris Santana, Joseph Muller, Rifat Hussain, Ke Qu, Yalong Cai, and Mohsen Amjadian in field data collection, analysis, and documentation. This project is sponsored by Natural Science Foundation (award number CMMI # 1313877). The PIs are grateful to the project manager Dr. Kishor Mehta for his valuable suggestion during this project. We thank Mr. Krish Kramalingam, project manager of Applied Research Program in New York City Department of Environmental Protection, Ms. Bridget McKenna, chief operating officer of New Jersey Valley Sewerage Commission, and Mr. John Hinge, assistant facility engineer of MTA Bridges and Tunnels, for their help on data collection. Support of Dr. Henry Perahia, former deputy commissioner of New York City Department of Transportation, in accessing field data on bridges in New York City area is acknowledged.

## Contents

Summary	4
1. Motivation and objective	5
2. Plan and approach	6
3. Collected data and discussion	6
4. Computer modeling of storm surge in Hudson River	13
5. Deliverables	15
6. Concluding remarks	15
References	16

## Summary

While Hurricane Sandy has significantly impacted the metropolitan New York City (NYC) region, it also left behind rich, unique, and valuable data on its trace in the form of water marks, damage and destruction to infrastructure, etc. In this project, perishable field data on flood, wind, and consequent damage to coastal facilities and infrastructure, such as high water marks, damaged residential houses, and fallen trees, has been collected through extensive site visits and discussions with stakeholders. The regions of data collection cover several zones in the New York City metropolitan area such as Manhattan, Queens, Staten Island as well as a few zones in New York and New Jersey. The data indicates that while there was extensive damage to coastal houses and wooden components, there has been no apparent damage to bridges, ports, and other major infrastructure because of hydrodynamic impact. A website integrated with a Google Earth file has been created to disseminate the collected data. Preliminary computer modeling has been made to numerically simulate the storm surge in Hudson River during Sandy, and the simulation has been compared to collected data. It is anticipated that the collected data will be very useful in study and prediction of future hurricane wind field, storm surge, and coastal flooding and plan development for mitigation of their damage to infrastructure.

## **I. Motivation and Objective**

Measurement records indicate that frequency of strong hurricanes, e.g., the number of category IV and V storms, along with the ocean temperature, has greatly increased over past 35 years [1]. In addition, due to global warming and climate change, sea level is rising at an alarming speed, and this speed has been twice as fast along the Northeastern U.S. coastline as compared to the global average rate [2]. A severe consequence of the increase in frequency of strong hurricanes and the sea level is a significant increase in the risk of catastrophic flooding along coastlines. Therefore, it is crucial to collect field data on storm surges during hurricanes and damage because of such flooding to coastal infrastructure and communities. These field data can be used to develop reliable methods to predict future events and develop effective plans to mitigate consequent damage to our coastal built infrastructure.

While Hurricane Sandy has significantly impacted the metropolitan New York City (NYC) area by causing catastrophic damage to residential and commercial facilities, and transportation, and other infrastructure, it also left behind rich, unique, and valuable data on its path and intensity in the form of damage and water marks. Since Hurricane Sandy struck the NYC metropolitan area on October 29, 2012, a number of efforts have been made to collect perishable data on storm surge and damage during this event. The collected data include satellite images, tidal gage records, aerial surveys, ground examination, etc. [3-6]. For instance, USGS has collected a variety of information on tides and floods during Hurricane Sandy and has produced a database on the USGS website for public use [4,5].

The objective of this NSF RAPID project is to collect field data, especially perishable data, of flooding, wind, and infrastructure damage in the metropolitan NYC region during Hurricane Sandy, and produce a database and a preliminary analysis for future scientific studies and management use. Besides supplementing to the efforts of other teams and agencies, this project also targets data with information on wind and coastal flood, dynamic loads, as well the process of structural damage (e.g., displacement, deformation, destruction). Such data will be useful for validation of computer models for damage to facilities and structures during similar future events. Special effort has been made to ensure that the data resolution, i.e., the distance between two adjacent sites for data collection, is 50 m or less.

The objective of the project has been realized through the following three tasks:

- 1) Collection of wind and flood information, such as high water marks on coastal infrastructure, and if possible, data on wind and flood speed and their evolution.
- 2) Identification of damaged structures, including damaged houses and coastal infrastructure
- 3) Preliminary analysis of the collected data and creation of a database.

The time of the recorded data spans from October 29, 2012, right after the Hurricane Sandy, to February of 2015.

## 2. Plan and Approach

On the basis of information on Hurricane Sandy and damage reported in news media, computer modeling, interview of residents, etc., a number of local zones within the metropolitan NYC region were selected for field data collection. Fig. 1 illustrates one of such zone for data collection. A particularly useful source of such information has been the USGS database [4]. We have also contacted agencies, such as New York City Department of Transportation, New York State Department of Transportation, MTA, etc. for the availability of data.

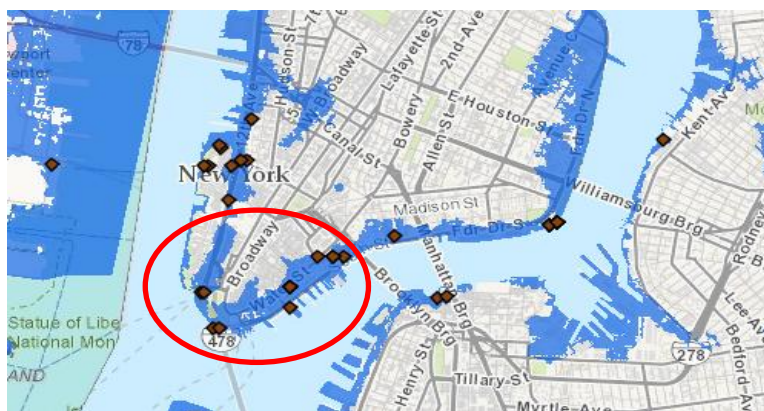


Figure 1. A sample zone for data collection. The map is from USGS database [4]. In the map, blue color indicates area flooded by the storm surge, and red diamonds represent sites with collected data. The red circle denotes a zone for field data collection, which is at the southern tip of Manhattan. Field trips have been made to collect data in zones like this.

Several teams of students, each consisting of 2-3 people, were formed and sent to the selected local zones for data collection with necessary tools and documents (e.g., GPS, cell phone, camera, rulers, a data collection form, etc.). Many of these students live in regions affected by the Hurricane Sandy. During the trips for data collection, they interviewed residents and field workers, measured data, took pictures, and wrote notes. Computer modeling was also made to simulate storm surge within the Hudson River during Hurricane Sandy. Results of computer models have been compared with available field data.

## 3. Collected Data and Discussion

The waterfront of the New York City metropolitan area was severely impacted because of flooding and damage to built environment. In this project, data collection was carried out at

many waterfront locations, such as Long Beach, Rockaway, Howard Beach, Manhattan, Long Island, Inwood, etc. Data on high water marks were recorded at residential structures and other infrastructure. At each of the sites, besides the measurement for the high water marks, at least two photographs showing water marks and surrounding environment were taken. Fig. 2 shows an example of water mark on a wall next to an open channel in Howard Beach. Fig. 3 presents a water mark on the garage gate of a family house in Cross Bay. Fig. 4 shows flood mark at the East Coast Memorial in Manhattan.



Figure 2. High water mark record in Howard Beach, Queens.



Figure 3. Water mark on a house in Cross Bay, Queens.



Figure 4. High water mark at East Coast Memorial in Manhattan. The high water mark indicates a flood of 1.6 ft.

Information on flooding due to Hurricane Sandy was collected not only from high water marks but also in other types of data. For example, Fig. 4 shows that water trace indicated by dead grass on the ground caused by salty water during the flooding. At some locations, either water marks were not present or they disappeared shortly after the flood. Information on these water marks was collected by interviewing people who witnessed the flooding. For instance, a parking lot of a marina in Long Island, shown in Fig. 6, was completely flooded. According to witnesses, water depth was at least waist high. This information from witness was also recorded.



Figure 5. Dead grass due to salt water from the sea in Inwood, Queens.





Figure 6. A flooded region in Long Island (based on interview of a Marina Officer).

Data on dynamic processes of storm surge and flood are extremely useful but difficult to obtain. Evidence and possible clues on such processes were also recorded. Sediment transport is an important process associated with flooding caused by storm surge. Fig. 7 presents a site where sediment deposition was observed. At a farm in Manhattan, as shown in Fig. 8, severe erosion took place. This area was completely flooded by 3 -- 4 ft of water. However, water dispersed away after about 6 hrs. The soil had to be replenished because of the excess of salt content. A table of the measured content of the soil was collected.



Figure 7. Sand deposited by flood in Inwood, NY



Figure 8. Erosion of soil at Battery Urban Farm in Manhattan.

Efforts were also made to collect data on structural damage caused by the Hurricane Sandy. A large number of houses near water fronts, especially in Long Beach, Rockaway, Howard Beach, were damaged, and a good amount of data on such houses were collected. Fig. 9 shows one of such sites for data collection. At this site, there are three houses next to each other. The one in the middle was damaged, while the other two remained in a good shape. The data for this site presents an interesting and very useful example of houses that can sustain damage and the ones that are vulnerable to damage. Fig. 10 shows an example of damage to boardwalk at waterfronts.



Figure 9. Comparison of damaged and undamaged houses in Long Beach, NY. In the figure, the damaged one, house B, has been raised for repairing.





Figure 10. Damaged marine infrastructure in Staten Island.

Data for other types of damage were also collected. Fig. 11 shows a fallen tree in New Jersey. The owner of the house where the tree fell provided detailed information on uprooting of the tree and wind condition at that time: “The tree fell on the house approximately around 10:30 to 11:00 PM. I think the wind was blowing East to West based on the orientation of the house and the manner in which the tree fell. A very strong wind gust is what caused the tree to fall. I was standing in front of the bedroom window looking outside when it happened”.



Figure 11. Wind damage in Westfield, NJ (Courtesy of the owner of the house).

Besides first hand of data collected during our field trip, field data of Sandy has been collected from agencies that experienced flooding and damage, or, were involved in recovery. A partial map collected at a wastewater treatment plant in Newark in Fig. 12 shows flood evolution at the plant during the Hurricane Sandy. Fig. 13 is from New York City Department of Transportation, which shows the flooding into the Brooklyn Battery Tunnel.

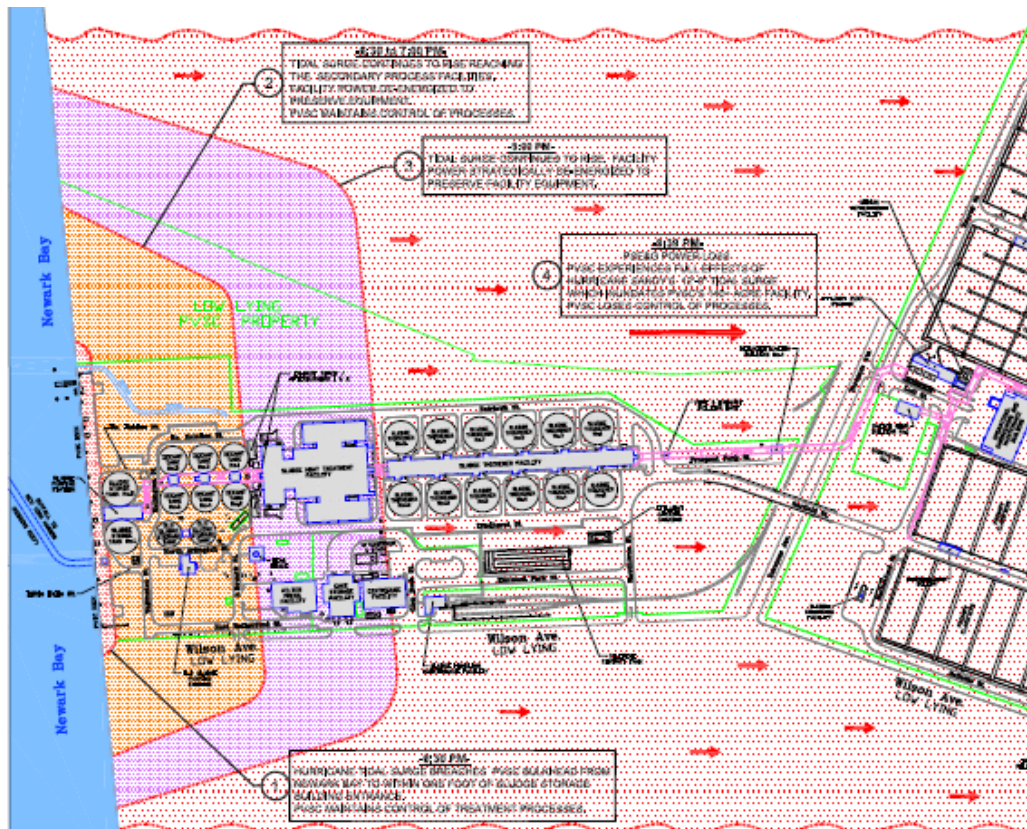


Figure 12. A high water mark on a wall of the wastewater treatment plant in Oakwood Beach, Staten Island (Courtesy of New Jersey Valley Sewerage Commission).

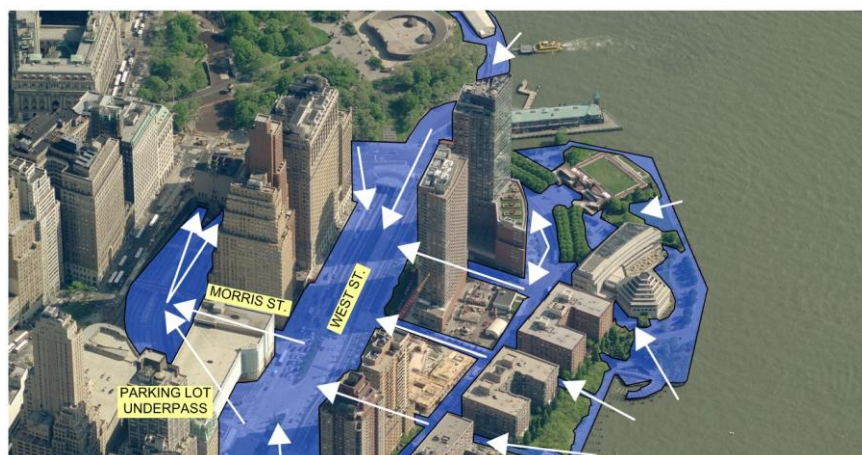


Figure 13. Route of flooding into the Brooklyn Battery Tunnel (Courtesy of MTA Bridges and Tunnels).

During the field trips, we also investigated damage to infrastructure such as bridges, major ports, etc. While there has been extensive damage to coastal houses and wooden components,

such as boardwalk on beachside, there has been no apparent damage to bridges, ports, and other major infrastructure, except tunnels of subways that underwent significant damage because of water penetration and flooding. Bridges in the path of Hurricane Sandy were inspected immediately after the hurricane to allow movement of traffic. We also contacted transportation agencies such as New York State Department of Transportation about the inspection of bridges. These agencies found no major damage to bridge components. At few locations, components, such as wooden embankments, slope protection measures (permanent topsoil, jute mesh and seeding), steel security fencing, light poles, were damaged and were needed to be repaired.

#### 4. Computer Modeling of Strom Surge in Hudson River

During Hurricane Sandy, storm surge took place in the Hudson River, and it propagated upstream up to as far as Albany. In order to better understand the storm surge and also demonstrate the usage of collected data, a preliminary computer modeling of the involved flow has been made using the SIFOM-FVCOM modeling system we recently developed [7]. In this simulation, bathymetry data for the Hudson River is from NOAA NGDC, and NOAA's VDATUM is used to convert all of the bathymetry data to the common vertical datum NAVD88 [8,9]. The river boundaries are specified by the NOAA high-resolution composite vector shorelines [10]. Water surface elevation observed at the Battery station of NOAA NDBC and the Albany station of USGS during Oct. 29<sup>th</sup>, 2012 to Nov. 1<sup>st</sup>, 2012 are respectively used as boundary conditions to drive the simulation, as shown in Fig. 13, which shows that the evolution of elevation in time at the Albany station is about four hours later than that at the Battery station during the Hurricane Sandy.

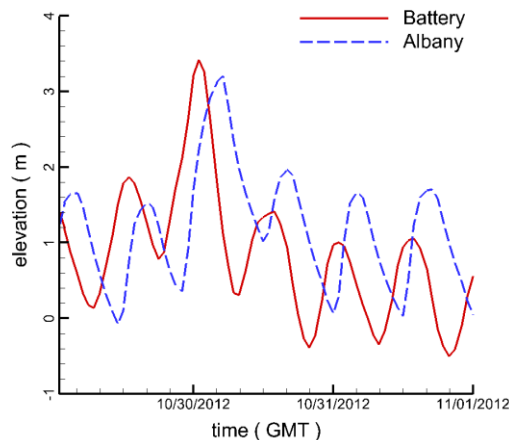


Figure 14. Temporal evolution of water elevation observed at the stations of Battery and Albany [11,12].



The simulated all-time highest elevations of water along the centerline of the river, together with that of the highest water marks measured at its two banks, are plotted in Fig. 14a. One of the water marks was obtained from this project, and its elevation was estimated with aid of a website tool [14]. In this figure, the distance starts from at the Battery station located at the downstream boundary of the computational domain, and is measured in the upstream direction. Since the computational mesh is relatively coarse in the lateral direction, it is anticipated that the model cannot appropriately resolve the difference of water surface elevation at the two banks. It is seen that overall the simulation agrees with the measurement reasonably with regard to the trends of water surface. They compare well in the range of distance from zero up to 75 miles, but deviate more within a section after that location. This deviation is attributed to the fact that data used in the modeling lacks enough resolution for bathymetry and river bank in that section. In addition, simulated non-hydrostatic force in the north direction on a circular pier located in the river is presented in Fig. 14b. and Fig.14c. More details of the modeling have been presented in [15]. This simulation for the surge flow illustrates the usefulness of collected field data in prediction of future events similar to the Hurricane Sandy.

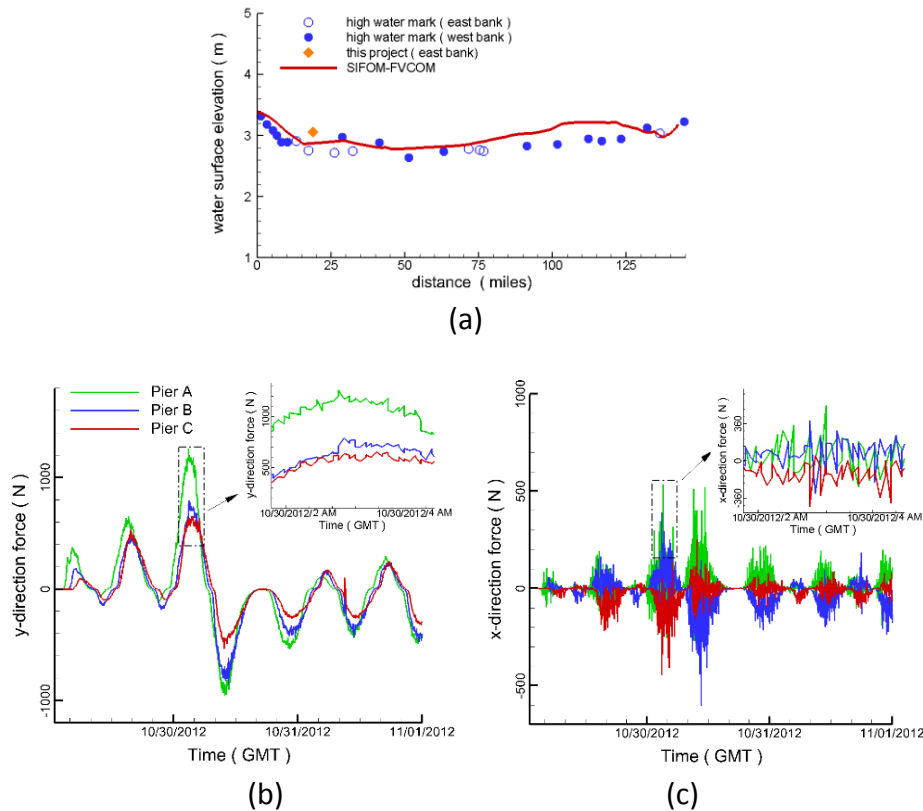


Figure 15. (a) Computed water surface elevation, together with measurement in [13], in circles and circular dots, and of this project, in diamond. (b),(c) Computed non-hydrostatic force on a pier within the Hudson River in the north-south and the east-west direction, respectively.

## 5. Deliverables

The deliverables of this project include the following items:

1. A final project report (this document)
2. A website on the project at  
<http://www-ce.ccny.cuny.edu/cfd/sandydata.html>  
All collected data are presented in a Google Earth file at this website.
3. Presentations and publications:
  - a) Tang and Qu, A Hybrid geophysical fluid dynamics and fully 3D fluid dynamics approach to simulate multiphysics coastal flows. Poster, AGU Fall Meeting, 15-19 December, 2014, San Francisco, California.
  - b) Qu and Tang. Numerical Study on a Hybrid Fully 3D Fluid Dynamics and Geophysical Fluid Dynamics Modeling System for Multiphysics Coastal Ocean Flows. Poster, 7th Int. Conf. Mesoscopic Method in Eng. and Sci., New York City, USA, July 14-18, 2014. New York, NY, USA .
  - c) Tang and Agrawal, Collection of data on coastal flood and structure damage in the New York City Metropolitan region during the Hurricane Sandy. Oral presentation, DIMACS/CCICADA Workshop on S&T Innovations in Hurricane Sandy Research, Rutgers University, Oct. 22, 2014.
  - d) Tang and Agrawal, Collection of data on flood and hydrodynamic impact on coastal infrastructure in the New York City Metropolitan region during Hurricane Sandy. Oral presentation, DIMACS/CCICADA Workshop on S&T Innovations in Hurricane Sandy Research, Rutgers University, June 5, 2013.

## 6. Concluding Remarks

In this project, we carried out an extensive survey in the NYC metropolitan area after the Hurricane Sandy and collect perishable field data on flood, wind, and damage to coastal facilities, homes, and other infrastructure. The collected data include information such as high water marks, damage to houses, sedimentation, land erosion, and fallen trees, and they come from 177 sites, among which, 130, or 73.4%, bear high water marks. While there has been extensive damage to coastal houses and wooden components, there was no apparent damage to bridges, ports, and other major infrastructure due to hydrodynamic impact. A preliminary modeling has been made to simulate the storm surge in the Hudson River. Comparison between the simulation results and collected data shows a good agreement between them. All collected data have been presented at a website in a Google Earth file. The results of this

research have also been presented during several conferences. It is expected that the collected data will be useful for study of future coastal flooding due to hurricanes and resulting damage.

A strong motivation in data collection of this project is to identify and gather information that can be used to extract and recover dynamic processes of wind, flood, dynamic impact, and structural response during the hurricane. In general, the data collected in this project, such as high water marks and fallen trees, do not directly reflect such processes. Careful and detailed analysis is necessary for recovery of the involved dynamic processes, which can be used for future development of models that are able to predict such processes. Such analysis will be significant and the focus of our research in the future. In addition, examination is necessary for data accuracy, such as latitude and longitude of the position of a site measured by a GPS or a cell phone.

It is mentioned that the current Google Earth file contains data for 177 sites. However, we may continue our data collection through outreach with numerous agencies in the City that have vast amount of filed data on water marks in the form of photographs. One of the challenges dealing with these agencies is their requirement for confidential agreement to access their report, which also contains future plans to deal with future events like Hurricane Sandy. We will continue to update our Google Earth file and the website as we received further data from agencies in the NYC metropolitan region.

## References

- [1] NOAA NRDC 2012, The consequences of global warming on weather patterns.  
<http://www.nrdc.org/globalwarming/fcons/fcons1.asp>.
- [2] Yin et al. (2009). Model projections of rapid sea-level rise on the northeast coast of the United States. Nature Geoscience, March 15, 2009; DOI: 10.1038
- [3] Lillibridge J, Lin MS, Shum CK. (2013). Hurricane Sandy Storm Surge Measured by Satellite Altimetry Oceanography, 26, SI, 8-9
- [4] USGS, Hurricane Sandy Storm Tide mapper.  
<http://54.243.149.253/home/webmap/viewer.html?webmap=c07fae08c20c4117bdb8e92e3239837e>.
- [5] USGS, Hurricane Sandy Monitoring  
<http://ga.water.usgs.gov/flood/hurricane/sandy/sites/hwm/HWM-NY-QUE-730.html>.
- [6] NOAA National Ocean Service, Aerial Photos of Hurricane Sandy Damage from NOAA's National Geodetic Survey. <http://oceanservice.noaa.gov/news/weeklynews/nov12/ngs-sandy-imagery.html>.
- [7] H. S. Tang, K. Qu, and X. G. Wu, An overset grid method for integration of fully 3D fluid dynamics and geophysics fluid dynamics models to simulate multiphysics coastal ocean flows. J. Comput. Phys., 273(2014), 548-571
- [8] NOAA NGDC, <http://www.ngdc.noaa.gov/>.
- [9] NOAA VDATUM, <http://vdatum.noaa.gov/>.
- [10] NOAA Coastal Services Center. NOAA composite coastline,  
<http://shoreline.noaa.gov/data/datasheets/composite.html>.
- [11] NOAA NDBC, <http://www.ndbc.noaa.gov/>.



- [12] USGS Water, <http://water.usgs.gov/wateralert/>.
- [13] USGS NY Water, <http://ny.water.usgs.gov/flood/HudsonSandy.JPG>.
- [14] Free Map Tool. <http://www.freemaptools.com/elevation-finder.htm>.
- [15] K. Qu and H. S. Tang. Numerical Study on a Hybrid Fully 3D Fluid Dynamics and Geophysical Fluid Dynamics Modeling System for Multiphysics Coastal Ocean Flows. Oral presentation. 7<sup>th</sup> Int. Conf. Mesoscopic Method in Eng. and Sci., New York City, USA, July 14-18, 2014.