Designing for Urban Sustainability and Resiliency in an Era of Climate Change

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Population growth and the migration and concentration of people into urban areas is having a profound impact on the environment. In turn, climate change is threatening the viability and sustainability of these large metropolitan areas, which are mainly located in coastal areas. Planning for urban sustainability and urban/coastal resiliency is increasingly dependent on extensive modeling activities using high-performance computing.

Keywords- urban planning, urban resiliency, urban sustainability, PlaNYC, climate change, Hurricane Sandy, Solar Power, hydrokinetic electric generation

I. THE CITY UNIVERSITY OF NEW YORK

The City University of New York (CUNY) dates to the 1847 founding of the "Free Academy" by Townsend Harris[a], a wealthy businessman and President of the New York City Board. With an inaugural class of 143 students, the Academy set upon a mission to "educate the whole people," in Harris' words, providing access to free higher education based on academic merit alone to children of immigrants and the poor. The "Free Academy" was the first tuition free university in the United States. The Academy quickly grew in enrollment and, as the 20th Century approached, plans were approved for a neo-Gothic campus (Figure 1) at 138th Street and Convent Avenue in Manhattan for what became known as the City College of New York.

Twenty years after the first young men entered the Academy, a separate school for the education of teachers, the Female Normal and High School, later renamed Hunter College in honor of its founder Thomas Hunter, offered the same higher education opportunities to women.

Today, CUNY provides high-quality, accessible education for more than 269,000 degree-credit students and 247,000 adult, continuing and professional education students at 24 campuses across New York City. In keeping with its founding precepts, 41% of its full-time undergraduates are first generation in college, 40% have a native language other than English, and 170 different languages are spoken. Although, since 1974, CUNY is no longer tuition-free, tuition remains affordable: $6,000 per year at the senior colleges with 58% of full-time undergraduates attending tuition-free. It is an integrated system of senior and community colleges, graduate and professional schools, research centers, institutes, and consortia. It provides the City and the Nation with graduates trained for high-demand positions in the sciences, technology, mathematics, teaching, nursing and other fields.

Among its alumni, CUNY counts twelve Nobel Laureates (eleven of which were first generation in college), two winners of the International Medal for Outstanding Discoveries in Mathematics (The "Fields Medal"), and other notables such as Dr. Jonas Salk (polio vaccine), Andy Grove (former CEO of Intel Corp.), and Dr. Robert Kahn, co-inventor of TCP/IP.

Figure 1. Shepard Hall at City College of New York/CUNY

[a] Townsend Harris was a champion of public education and a pioneering diplomat who was the United States' first ambassador to Japan. He negotiated the Treaty of Amity and Commerce (日米修好通商条約), also called "Harris Treaty", between the United States and Japan and is credited as the diplomat who first opened the Empire of Japan to foreign trade and culture in the Edo period.

In 2005, Matthew Goldstein, the Chancellor of CUNY, designated the years 2005 to 2015 the "Decade of Science", renewing the University's commitment to creating a healthy pipeline to science, math, technology, and engineering fields by advancing science at the highest levels, training students to teach in these areas, and encouraging young people, particularly women and minorities, to study in these disciplines. This initiative targeted also several high-priority areas of research. These include Nanoscience, Photonics, Structural Biology, Neuroscience, and the Environmental Sciences. Obviously, a key infrastructure requirement in these research areas is high-performance computing. The rest of this paper will describe the CUNY Interdisciplinary HPC Center (The "Center") and its involvement in supporting critical research initiatives in the environmental sciences.

II. THE CUNY HPC CENTER

The Center beginnings were modest, starting in 2008 with two small clusters totaling 500 cores located in warehouse space. Since then, the warehouse space has been converted to a 2,400 square foot computer room with raised floor and a support infrastructure, which includes a 500 KVA uninterruptible power system, and a 750 KVA diesel generator. Compute resources have increased through the acquisition of three newer systems including a 2,816 core Cray XE6 ("SALK"), a 744 core cluster, and a 1,152 core cluster with 144 NVIDIA Kepler K20 GPUs. There are a number of other, smaller systems also installed. The systems use the Lustre file system for scratch space. A fourth, to-be-announced system, with unique capabilities is to be installed during the third quarter of 2014. The systems also have access to a one-petabyte General Parallel File System for home directories and project files, which is connected by fiber to a remotely located Spectralogic T950 robotic tape system for automated backup and archival purposes. Tivoli Storage Manager is used as the hierarchical storage manager. Fig. 3 is a logical schematic of the systems in the HPC Center.

This is a prelude to the planned construction of 170,000 square foot research facility with 10,000 square feet of raised computer room floor space with appropriately scaled electrical power, cooling, and security systems. The expected completion date for the new facility is 2018.

SALK is the primary CUNY system for environmental science research and hosts the following applications: the Weather Research and Forecasting Code, The ADvanced CIRCulation Model/Spectral Wave Nearshore (ADCIRC/SWAN) [1], The Unstructured Grid Finite Volume Community Ocean Model (FVCOM) [2], Regional Ocean Modeling System (ROMS) [3], NEK5000 [4], Community Earth System Model (CESM) [5], and others. These are used, as described below, to support research on urban resiliency and sustainability, in particular, as well as the broader issues of the impact of climate change on urban life.

Figure 2. CUNY High Performance Computing Center facility

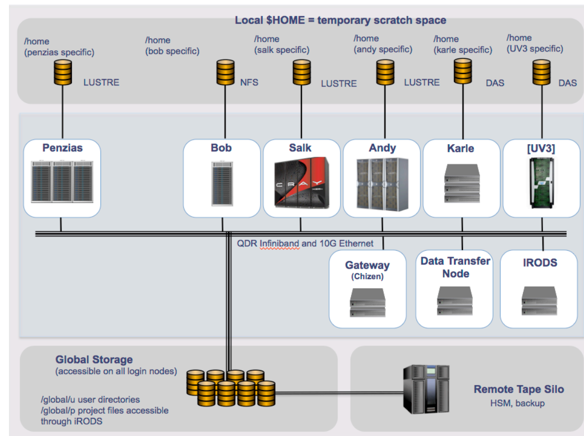

Figure 3. CUNY High Performance Computing Center facility

III. PLANYC

PlaNYC[b] is a plan, initially published in 2007, developed under the direction of former New York City Mayor Michael R. Bloomberg to prepare the City for growth over a 25-year period. The plan focused on ten areas of interest: Housing and Neighborhoods, Parks and Public Spaces, Brownfields, Waterways, Water Supply, Transportation, Energy, Air Quality, Solid Waste, and Climate Change. The goal of PlaNYC was focus efforts on improving the quality of life for New Yorkers, rehabilitating and enhancing infrastructure, providing for a population growth of one million more residents to a total population exceeding nine million, and reducing the City's carbon footprint to 70% of the 2005 level by 2030. PlaNYC is a landmark document in city planning. PlaNYC is now available in Chinese and Japanese. In December 2012, in the aftermath of Hurricane Sandy, Mayor Bloomberg announced the formation of the "Special Initiative for Rebuilding and Resiliency and charged it with producing a plan, "A Stronger, More Resilient New York," [6] to provide additional protection for New York's infrastructure from the impacts of severe weather events and climate change.

In the following section, we describe a number of research projects, many of which are directly related to the Mayor's initiatives. All of the projects described relied on the computational resources of the CUNY HPC Center Systems.

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[b] PlaNYC, its updates, and related documents are available at: http://www.nyc.gov/html/planyc2030/html/publications/publications.shtml

IV. Environmental Sciences Research Using the CUNY HPC Center Systems

Here we describe some CUNY projects in environmental science research that use the resources of the CUNY HPC Center.

A. *The New York Solar Map*

As previously mentioned, one goal of PlaNYC is to reduce the City's carbon footprint by 30%. This goal is difficult to achieve as buildings account for 75 percent of the City's carbon dioxide emissions and 85 percent of the buildings that will exist in 2030 are already built. One possible approach to achieve this reduction is the use of solar power. The Mayor's Office of Long-term Planning and Sustainability and the New York Economic Development Corporation therefore commissioned a study to evaluate this option.

Use of solar power in a city such as New York is complicated. First, the City is a highly developed environment and the solar panels would need to be installed, in most cases, on existing rooftops. Rooftops, however, are not necessarily flat, may be in shadows, may have structures that prevent the installation of solar panels, and have required set-backs for access and/or building code requirements, which need to be considered. Second, there are about one million buildings within the City. Third, the power grid for the City is complex and incorporating solar generated electricity into the grid is complicated. The New York City Solar America City Partnership was formed to address these complex issues.

The Partnership, led by Sustainable CUNY[c], included the Mayor's Office of Long-Term Planning and Sustainability, and the NYC Economic Development Corporation, the Center for Advanced Research of Spatial Information (CARSI)[d] at CUNY's Hunter College. The study was funded in part by the Çity, the United States Department of Energy, and the New York State Energy Research and Development Authority. The National Renewable Energy Laboratory (NREL), and Consolidated Edison provided technical assistance.

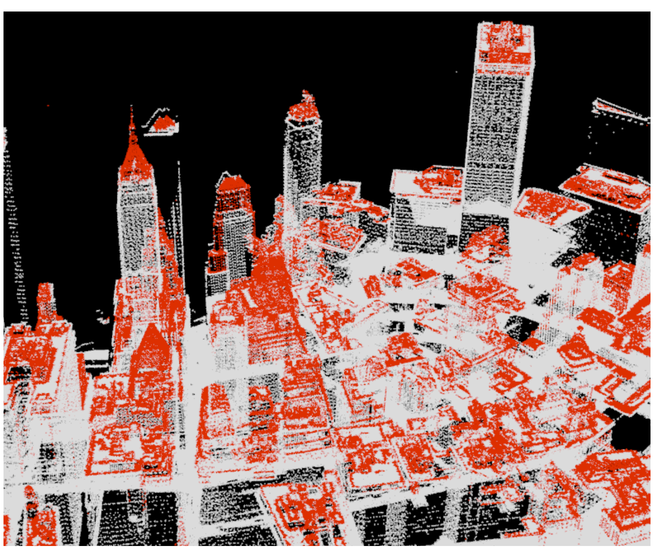

Figure 4a. Separation and Quantification of the Slant Rooftops from a LiDAR Point

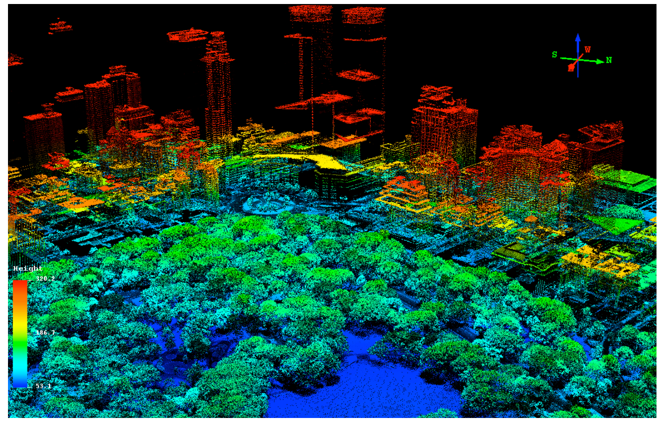

Figure 4b. LiDAR Point Clouds Displayed by Height Coloration

A key part of the study was the creation of a detailed map of the City using airborne LiDAR. The Sanborn Map Company, experts in LiDAR acquisition and mapping, flew a total of 17 missions, crisscrossing 362 square miles of the city. The data collected has a minimum density of 8 points per square meter with an accuracy of 9-10 cm root-mean-square error in LAS format 1.2 with X, Y, Z and intensity information (Figures 4a and 4b) [7]. After the flights were completed, Sanborn turned over 535 GB of raw laser data to CARSI, which created a 3D digital surface model of the entire City (362 square miles) with a one-foot resolution. That model was used to calculate solar insolation data for the entire city, i.e., CARSI calculated how much sunlight was incident on every square meter of every surface of the city. The isolation calculations took into account shading from surrounding buildings and trees, the time of day, the time of year, and even local weather conditions over the last 20 years (Figure 5). NREL and Consolidated Edison evaluated the feasibility of inserting the power generated into New York's electricity grid. The study found that two-thirds of the city's buildings are suitable for solar power installations and could provide up to half the city's power demand in peak periods. Importantly, CARSI also produced the "New York City Solar Map"[e], an interactive map that allows a user to search for any one of the one-million buildings in the City and see the potential annual electrical bill savings, the amount of electricity expected to be produced, the reduction in carbon emissions, and additional

[c] Information on Sustainable CUNY is available at https://www.cuny.edu/about/resources/sustainability/solar-america.html

[d] Information on CARSI is available at http://www.carsilab.org

[e] The NYC Solar Map is available at http://www.nycsolarmap.com/

information related to the installation of solar panels (Figure 5).

The isolation calculations were performed on CUNY HPC Center systems other than the Cray XE6 as they required the use of Matlab™ and we prefer not to run in cluster compatibility mode on Salk.

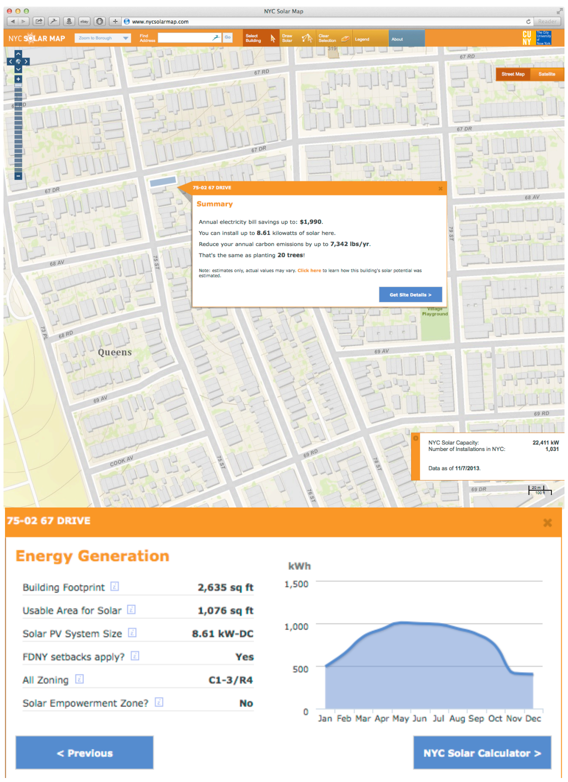

Figure 5. The New York Solar Map allows a user to select a specific building in the City and obtain information on its solar potential.

B. Hydrokinetic electric power generation

Until recently, hydro-electric power generation has generally been limited to generation stations at waterfalls[f] and at dams on rivers, but hydrokinetic electric power generation from tidal energy is potentially a more reliable and more plentiful source of renewable energy. It has global potential second only to solar power. As part of New York City's efforts to reduce it carbon footprint, the Roosevelt Island Tidal Energy (RITE) project was initiated to produce hydrokinetic electric power from turbines placed in New York's East River [8]. At the present time, Verdant Power, Inc. holds a 10-year Hydrokinetic Pilot Project License from FERC and a Water Quality Certification permit from the New York State Department of Environmental Conservation to operate the RITE Project. The RITE Project is the first commercially licensed tidal power project in the United States [9]. A picture of a Verdant Power RITE Project turbine is shown in Figure 6.

[f] Niagara Falls is the largest single electricity producer in New York State, with a generating capacity of 2.4 gigawatts

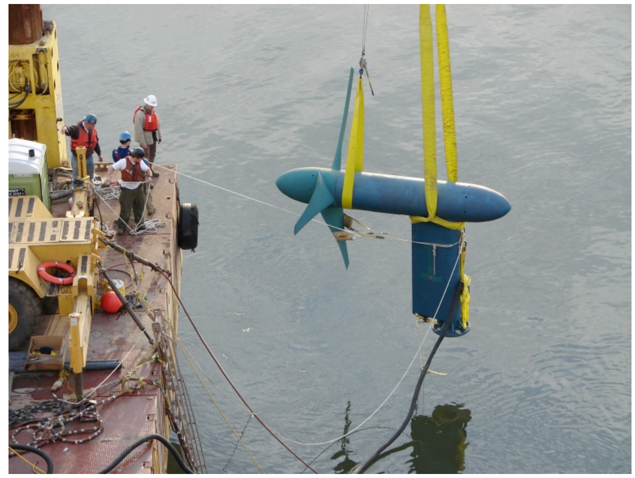

Figure 6. A Verdant Power hydrokinetic turbine being lowered into New York's East River.

Hansong Tang, et al., Associate Professor, of Civil Engineering, City College-CUNY, led a research project, funded by the Bureau of Research, New Jersey Department of Transportation, to study the potential for harnessing tidal energy within the Mid-Atlantic Bight with emphasis on the New Jersey coastline. Issues related to the effect of sea level rise on the potential for hydrokinetic energy generation was also considered [10].

Tang uses the Finite Volume Coastal Ocean Model (FVCOM) to simulate the tidal flows. The mesh used has a 50-meter resolution along the entire New Jersey coast with a local refinement of 10-meters or less to resolve flows within small tributaries and at potential sites for tidal power generation. 50-meter grids also represent some locations distant from the New Jersey coastline, e.g. the south shore of the Long Island Sound and the shoreline of Jamaica Bay. Larger grids are used in other parts of the regions. Overall, the mesh has 3.3 million nodes and 6.3 million elements. This mesh has fine resolution for channels and tributaries to resolve local flows at scales sufficient to provide the calculation of an approximate fluid flow rate to the power generation equipment.

Tang's group primarily used SALK at the CUNY HPC Center for this project and, also, to some extent HOPPER at the Department of Energy's National Energy Research Scientific Computing Center. SALK and HOPPER are both Cray XE6 computers. FVCOM scales linearly on SALK in both 2D and 3D mode. Using 1024 cores, it takes about 2.6 days to finish a 2D model run with a 0.1 second time step on SALK.

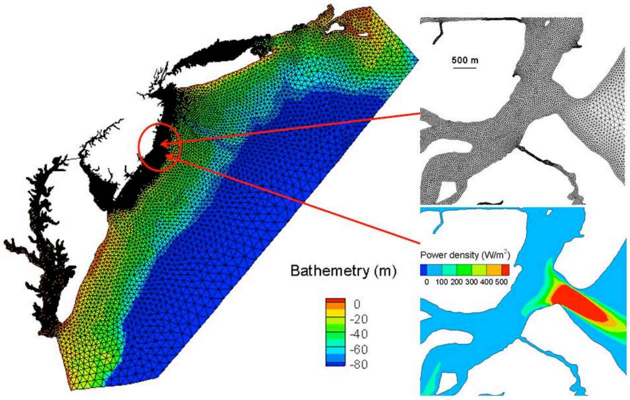

Figure 7. Efficient generation of electricity from tidal flows depends on the careful calculation of flow rates and properly identifying locations for placement of water turbines. To identify potential sites at the accuracy required to assess the feasibility for power generation, high-resolution data for coastlines, bathymetry, and topography was used to create a mesh resolution at 20 meters along the coastline and less than 10 meters for the tributaries. Computer models were used to calculate the tidal flows and the amount of energy that can be harnessed for electrical generation.

C. *Urban Forecasting Model Project*

The Urban Forecasting Model Project[g] is one of a number of environmental science projects conducted under the auspices of the CUNY Cooperative Remote Sensing Science and Technology (CREST) Institute/NOAA-CREST at City College. The Project's goal is the development of a weather prediction model to provide weather forecasting and climate analysis for densely populated urban areas at a fine-scale (1 km) and to evaluate impacts of the urban canopy on the temperature and wind flow in New York City.

The Project has customized WRF to include a multi-layer urban canopy parameterization model [11] and a building energy model (BEM). A building energy parametrization (BEP) [12] takes into account the impact of the buildings in the momentum, energy equations and the turbulent kinetic energy. Turbulence is vertically distributed from the surface to the top of the buildings. The BEM considers the diffusion of heat through walls, roofs and floor; natural ventilation; radiation exchange between indoor surfaces; generation of heat due to occupants and equipment and the consumption due to air conditioning systems. To distinguish it from "standard" WRF, this modified version is alternately referred to as "urbanized WRF" or "μWRF". Fig. 8a and Fig. 8b schematically illustrates the physical and computational models for linking the urban environment's anthropogenic effects into the urban canopy layer.

The heterogeneity of New York's urban landscape is represented using the National Building Statistics Database at 1-kilometer [13]. Three two-way nested domains were constructed with spatial grid resolution of 9, 3, and 1-kilometers with the finer grid covering the five boroughs of the NYC (Manhattan, Brooklyn, Queens, Bronx, and Staten Island). Fifty-one terrain following sigma vertical levels were defined with twenty levels in the first kilometer. The Bougeault-Lacarrere (1989) planetary boundary layer (PBL) scheme was adopted for use with BEP/BEM urban models. The initial and boundary conditions are obtained from the North American Mesoscale model data sets with 12-km resolution at 3-hour intervals with a spin up time of 12-hour. The outputs for 2-meter temperature, 10-meter wind speed and 1-hour rain accumulations are presented at 1-hour intervals for a 72-hour period.

μWRF was validated through comparisons with data obtained from the networks of ground and vertical sensors available in the New York City metropolitan area and collected by the NYCMetNet (Figure 9). A well-documented validation case is the heat wave of summer 2010 [14]. The multilayer parameterization BEP coupled with the BEM schema for estimating the effects of air conditioning systems showed a more accurate representation of the temperature (Figure 6a) and wind fields (Figure 6b) in the urban canopy during this extreme event. Detailed high resolution building information constitutes an important factor to correctly simulate meteorological parameters close to the surface over NYC as anthropogenic heat from air handling systems strongly modifies turbulent kinetic energy mainly in the urban canopy.

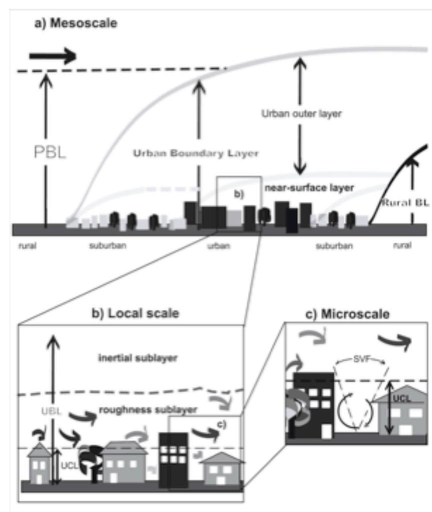

Figure 8a. Schematic illustrating the model physical relationships

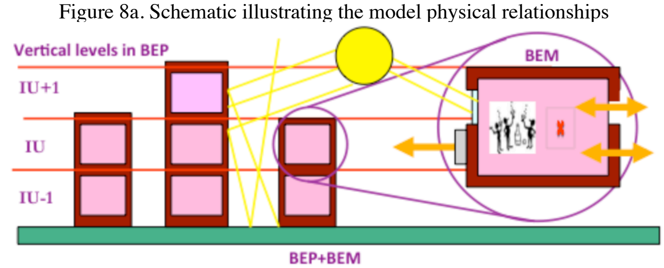

Figure 8b. BEP is a multiple layer urban scheme that permits a direct interaction with the PBL and recognizes three different urban surfaces. BEM is a building energy model, which includes anthropogenic effects. Coupled BEP-BEM provides for the transfer of anthropogenic effects into the urban canopy layer.

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[g] Additional information on CUNY CREST can be found at http://crest.ccny.cuny.edu

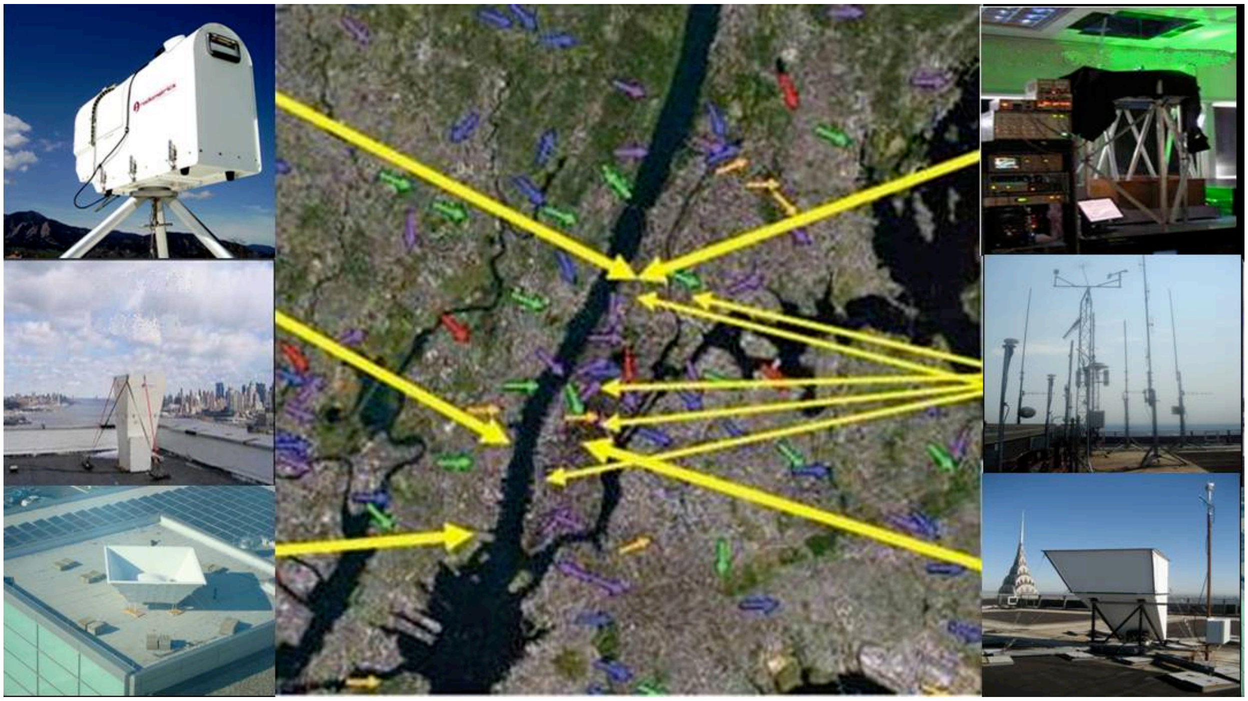

Figure 9. The NYMetNet collects extensive atmospheric data from numerous sensors. Shown (from upper right corner going clockwise) and their relative locations in the City are NYNetMet's Backscatter aerosol Lidar, Met Tower, Sodar to 400 m, Hyperspectral radiometer, Sodar to 300 m, and Radar Wind Profiler. Not shown are approximate 450 ground stations with the City that provide information on air quality and conditions.

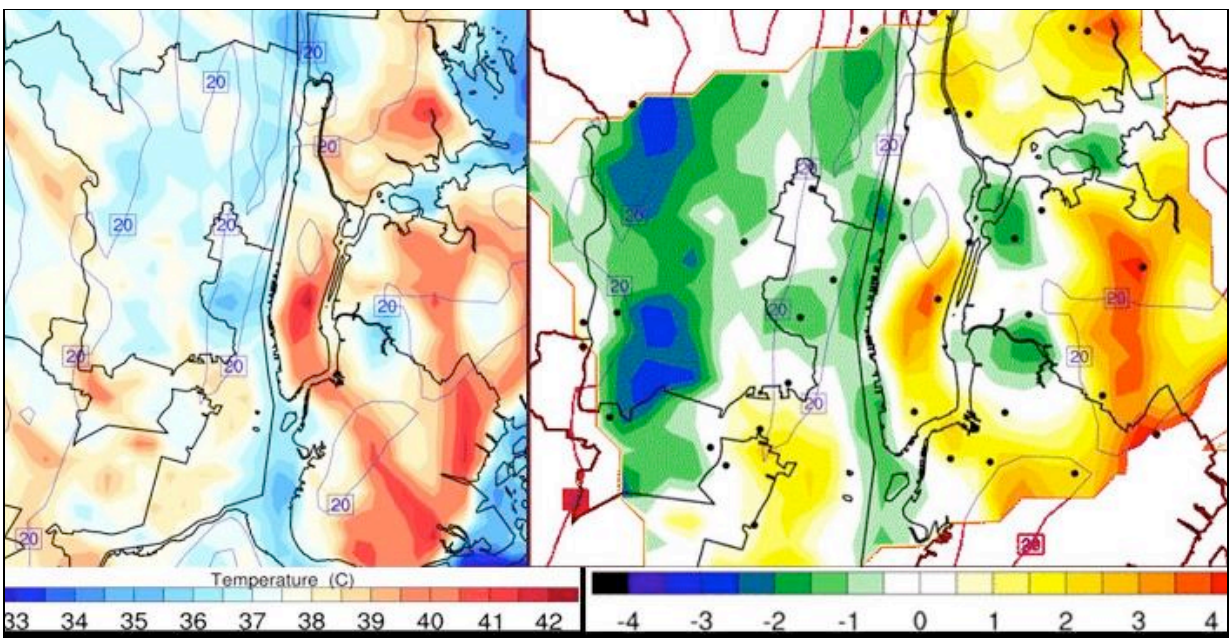

Figure 10. Surface temperature distribution (left) and differences between modeling and observation (right) at 1500 LST July 6th during the heat wave event that took place July 5th-7th, 2010 in NYC Metro Area. The small errors between model and observations in mid- and downtown areas represent a significant improvement over existing modeling capabilities.

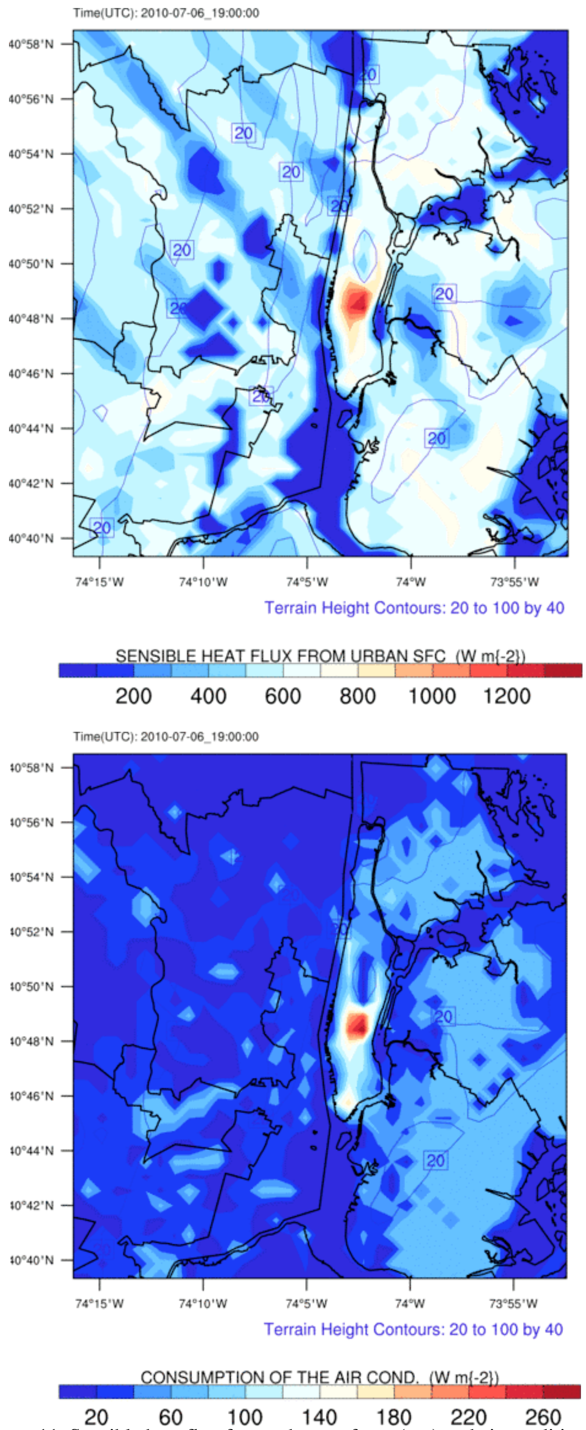

Figure 11. Sensible heat flux from urban surfaces (top) and air conditioning energy consumption (bottom) on July 6th at 1500 LST during the heat wave event that took place July 5th-7th, 2010 in NYC Metro Area.

Presently, using μWRF, the CUNY CREST Institute produces a wind forecast showing hourly wind speeds (3-meters above ground) for the 1-km grid of the New York City. The model, yielding scenarios up to 72 hours in advance, performs the predictive analysis daily. The animated results are available at http://air.ccny.cuny.edu/ws/wrfn/anibmaster.wrfmetnet.php

Additional improvements to the urban parameterization are in progress, including improvements in the latent heat representation in the urban regions by implementing a cooling tower model and evaporation from horizontal urban surfaces after rain events.

D. Hydrodynamic Mapping including the effects of sea level rise

Hurricane Sandy (also referred to as "Superstorm Sandy") was the second-costliest hurricane in United States history. It was the largest North Atlantic Tropical Cyclone (TC) on record (as measured by diameter, with winds spanning 1,800 km). Estimates assess damage to have been over $68 billion, a total surpassed only by Hurricane Katrina. On October 27, Sandy briefly weakened to a tropical storm and then regained strengthen to a Category 1 hurricane. Early on October 29, Sandy curved north-northwest and then moved ashore near Brigantine, New Jersey, just to the northeast of Atlantic City, as a post-tropical cyclone with hurricane-force winds. At The Battery in Lower Manhattan, the water level reached a record 13.88 feet above the average low tide level, which included a surge component of 9.23 feet: an all-time record for the location. Sandy's storm surge caused flooding that exceeded the Federal Emergency Management Agency (FEMA) 100-year floodplain boundaries by 53 percent city-wide.

Sandy caused 43 deaths and $19 billion in losses within the City of New York. More than 443,000 people were living in the areas flooded by Sandy (Figure 12). Critical electrical systems, telecommunication systems, wastewater treatment facilities, hospitals and many elements of the City's transportation network were damaged and put out of commission. Approximately 2 million people were with out electric power. Gas and steam heat distribution systems were disrupted. The storm surge from Sandy flooded two vehicular tunnels, seven subway tunnels (Figure 14), and undermined the subway to the Rockaways in South Queens.

Figure 12. Over 80 homes were lost at Breezy Point in the Rockaways to fire alone caused by downed power lines and salt water.

As previously mentioned, as a result of Sandy, the Mayor created a Special Initiative for Rebuilding and Resiliency (SIRR) and directed a major planning study on enabling New York to better withstand future storms. The SIRR's report was titled, "A Stronger, More Resilient New York" (herein referred to as the SIRR Report). A mandate was to factor in the potential impact of climate change on 100-year and 500-

Figure 13. Manhattan below 34th Street was without electricity for a number of days after Sandy because of damage to major electric facilities.

Figure 14. The subway line tracks to the Rockaways were undermined by Sandy

year storm predictions. Concurrently, Bloomberg also reconvened the New York City Panel on Climate Change (NPCC) to develop climate and sea level scenarios. The NPCC issued a report, titled "New York City Panel on Climate Change: Climate Risk Information 2013 Observations, Climate Change Projections, and Maps[h] and was formally issued concurrent with the SIRR Report.

The SIRR Report is almost 500 pages long; many different organizations and participated in its development. The plan evaluated concepts for regional and local measures for coastal protection, economic recovery, community preparedness and response, and environmental protection and response. Community specific plans evaluated a wide range of critical assets integral in resilient planning for buildings, utilities, liquid fuels, healthcare, telecommunications, transportation, parks, water, and wastewater.

As part of the SIRR, a variety of project alternatives were evaluated based on storm tide, wave and sea level rise mitigation capabilities, cost effectiveness, environmental impacts and benefits, and additional resiliency considerations. Alternatives include engineered structures like sea walls, levees, floodwalls, tide gates, and storm surge barriers, and building with nature measures such as dune restoration, living shorelines, reefs, barrier islands, beach nourishment, and wetlands restoration.

The CUNY HPC Center played an indirect role in the report by providing computational resources and software support on SALK to at least two of the contractors involved in the project. They were the Davidson Laboratory, Stevens Institute of Technology[i] and Arcadis-US[j]. Researchers at the College of Staten Island/CUNY also performed a number of hindcasts of Sandy's effects on the heavily damaged areas of Staten Island. In this paper, we will not address the SIRR Report itself, but rather will present the work of researchers at the Davidson Laboratory, Stevens Institute of Technology in developing flood hazard assessments for future decades.

The Stevens' study [15] had the following objectives:

- Model storm surges using a hydrodynamic ocean model to simulate the dynamically- driven water flows
- Closely reproduce FEMA flood hazard assessments for New York City (in Region 2) – 100-year, 500-year flood zone contours
- Produce similar flood hazard assessments for future decades (2020s, 2050s, 2080s) with NPCC "high-end" (90th-percentile) estimates of sea level rise
- Create contours of the 100- and 500-year flood zone boundary as GIS shape files for the future flood zones.

The primary design standard for coastal flooding from storm surges in the United States is defined by FEMA as the 100-year flood, also known as the 0.01 annual probability or 1% annual flood. This flood height and its spatial boundary both have a 1% chance of being equaled or exceeded in a given year. Similarly, the 500-year flood, 0.002 annual probability or 0.2% annual flood have a 0.2% chance of being equaled or exceeded in a given year. FEMAs standards focus on the Base Flood Elevation, which is the wave crest height and includes both the storm tide and the additional elevation of wave crests above that level.

Stevens' effort was to include sea level rise projections in its analyses and use the same methods and same models currently being used by FEMA in their newest Region 2 (R2) flood hazard assessment [16]. The goal is to produce final flood exceedance curves and flood zones for future decades that are as compatible as possible with the FEMA-R2 study. Stevens used the same storm set, representing the climatology of both TCs and extratropical cyclones (ETCs), and the same statistical techniques for processing the data.

The FEMA-R2 study used the two-dimensional coupled modeling system ADCIRC/SWAN for simulating the coastal flooding and waves for these storms. FEMA adapted an existing grid called Eastcoast 1995 that covers the Northwest Atlantic Ocean from the Gulf of Mexico to Nova Scotia [17] and enhanced it by adding grid nodes on over-land areas for the study area and by refining the resolution around the region's coastal areas. The resulting unstructured grid has

[h] http://www.nyc.gov/html/planyc2030/downloads/pdf/npcc_climate_risk_information_2013_report.pdf

[i] http://www.stevens.edu/ses/davidson

[j] http://www.arcadis-us.com/index.aspx

604,790 nodes and a minimum resolution 70 m (Figure 15). FEMA incorporated detailed land-use data to estimate surface roughness in 12 categories for the air and water flows. No rainfall and river runoff were included as these are typically only a small proportion of water elevation in waterways around New York City [18].

Stevens' approach was to reproduce FEMA's methods as closely as possible, producing final flood exceedance curves and flood zones for future decades that are as compatible as possible with FEMA's study. Stevens used the exact same coupled storm surge model, wave model, model versions, storm sets, and forcing data files (wind, pressure, tide). It also sought to use identical statistical methods, though there are subtle differences that suggest minor differences.

Storm surge simulations with the ADCIRC computer model are computationally intensive, and because the project timetable was six months, it was unrealistic to run 219 storms for each future sea level scenario. As a result, methods were developed for only simulating a subset of storms, yet still utilizing the complete hazard assessment technique that accounts for all the storms. Many of the modeled storms in FEMA's set do not cause over-land flooding in the NYC region, and the non-flooding storms are therefore less valuable for the hazard assessment in this area. Taking advantage of this factor, a subset was objectively determined that covers (1) all the storms that caused substantial overland flooding, indicative of 100-year and 500-year events, and (2) a smaller number of storms that spans the full range of flood heights around NYC.

Storm subsets were 65 storms for the 2050s, 25 storms for the 2020s, and 25 storms for the 2080s. Modeling results for storm tide simulations for these storm subsets were then used to determine basic flood patterns (e.g. typical spatial water elevation gradients) and relationships with flow depth that enabled the synthesis of MAXELE data for the remaining storms.

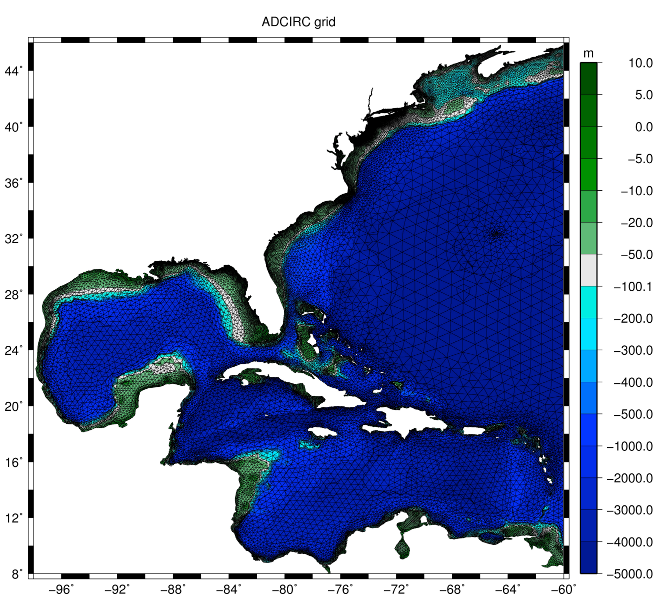

Figure 15. ADCIRC/SWAN model grid for the East and Gulf Coasts of the United States.

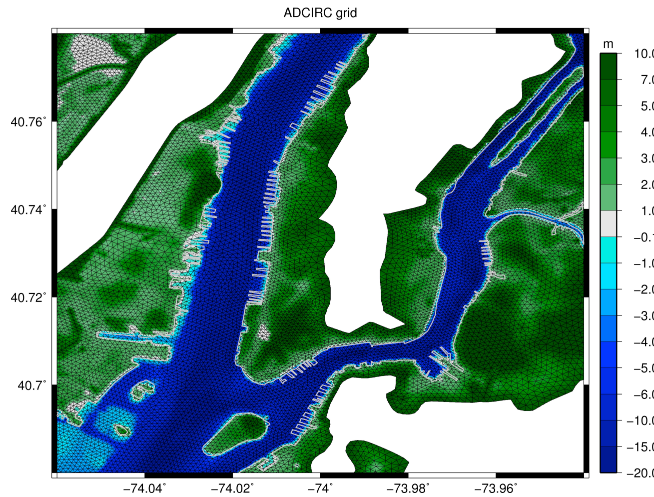

Figure 16. The ADCIRC/SWAN model grid for Manhattan, Upper New York, and the Hudson and East Rivers

As with the FEMA study, the ADCIRC/SWAN coupled modeling system (Version 49) was utilized for simulating water elevations and waves. The approach for simulating sea level rise was to enable the 'geoid offset' parameter in ADCIRC, which facilitates introduction of the sea level rise (SLR) over the entire domain in ADCIRC/SWAN. For each SLR scenario (see Table 1), a sequence of tidal runs needs to be run—up to 159 runs for the TC storms and up to 60 runs for ETC storms, each sequence starting from the cold state (no motion), and continuously ramping up tidal motions driven by eight tidal constituents.

The parallel ADCIRC/SWAN Version 49 is running on a dedicated queue on Cray system SALK at the CUNY HPC Center on the College of Staten Island. Wall time may vary with an overall load on the system, but using 256 processors for parallel processing, one typical TC storm run takes about 4.5 hours, and one ETC storm takes about 8 hours. The full tidal sequence for each scenario usually takes up to 1.5 days, with a first tidal run being the longest (up to 10 hours).

The most important outcome of each storm run that is relevant to this particular study is a two-dimensional gridded field of maximal elevations representing the peak sea level that was reached at each grid node, the MAXELE dataset.

TABLE 1. THE FEMA REGION

Epoch	SLR relative to base case in cm	SLR relative to base case, whole inches	Number of TC runs	Number of ETC runs
1983-2001	0	0	56	9
2020s	31	12	16	9
2050s	82	32	61/159*	9/60
2080s	150	59	16	9
Total completed storm runs			**149**	**36**
Total completed tide runs			**159 x 3= 477**	**40 x 3 = 120**
Overall number of completed runs			**782**	
* The full set of storm runs will be for the 2050s scenario to quantify the error from subsetting storms				

Additional diagnostics includes time series of sea level at pre-selected locations, along with 3-dimensional elevation (gridded fields changing with time). The post-processing is done on a shared multiprocessor computer, KARLE, in the CUNY HPC Center by transferring the production and creating the maps of maximal elevations, time series plots, and sea level animations with the use of MATLAB and FigureGen tools.

Over a 4-month period, Stevens completed 782 model runs consisting of the base set (0 cm SLR, 2000's epoch), 31 cm SLR scenario (2020's epoch), and 150 cm SLR scenario (2080's epoch), along with all required tidal spin-ups. For the 82 cm SLR scenario (2050's epoch), Stevens plans to run all available TC and ETC storms (219) and all the required tidal spinups.

E. Analysis of short-term dune reconstruction efforts on Staten Island

New York City's Borough of Staten Island was hard hit by Hurricane Sandy. The 23 deaths on Staten Island caused by Sandy amounted to over 50 percent of the deaths in New York City. Nineteen of those 23 deaths were in the Midland Beach area (including South Beach and Oakwood), which lies just south of the Verrazano Bridge. This area faces to the Southeast and forms one of the legs of an approximate 120 degree angle with New York Harbor at the apex and the other leg being the 120 mile Long Island coast line, which runs approximately West to East. Consequently, this area is particularly susceptible to storm surge from TCs that hit the New York area.

The Midland Beach area's 4-mile long shoreline for this area falls primarily under the jurisdiction of the City of New York's Department of Parks and Recreation, except for approximately a 1,200 foot stretch along Miller Field, which is part of the Gateway National Recreation Area and is managed by the National Park Service.

Fig. 17a is a Google map of the area around Lower New York Bay and the Midland Beach area. Fig. 17b is a hindcast of Sandy using ADCIRC/SWAN and the FEMA-R2 grid. A comparison of the map and an ADCIRC/SWAN generated Sandy hindcast shows the extent of flooding along Staten Island's eastern shore.

After Sandy, New York City moved to rebuild the dunes along the Northeastern shore of Staten Island to a height of 13 to 14 feet. The City, however, did not restore the dunes along the 1,200 foot stretch of Miller Field as that beach is under the jurisdiction of the Federal Government. Unfortunately, that gap in the dunes leaves the communities in and around the Midland Beach area vulnerable to storms with characteristics similar to that of Sandy. Fig. 18a shows areas of potential flooding assuming that a Sandy-type storm with the dunes in their present configuration. While flooding is somewhat reduced, a substantial exposure appears to remain. Figure 18b shows that restoring the dune in the area of Miller Field, could provide a significant reduction in exposure. The grid for the simulations shown in Figures 18a and 18b used the FEMA-R2 grid modified to include a 13 to 14-feet dune in the respective areas. The modifications to the grid have limitations. At the same time, the simulation based on these modifications is effective in illustrating what can be done now to potentially reduce flooding if a similar storm was to hit the New York Area in the near future. At the present time, the United States Geological Survey is conducting more accurate topological surveys of the Staten Island coastal areas. This is important to develop higher resolution grids to better model the impact of storms on the area and evaluate longer-term solutions.

The simulations shown in Figure 18a and Figure 18b do not consider the effect of erosion of the dunes caused by wave action or storm surge [20].

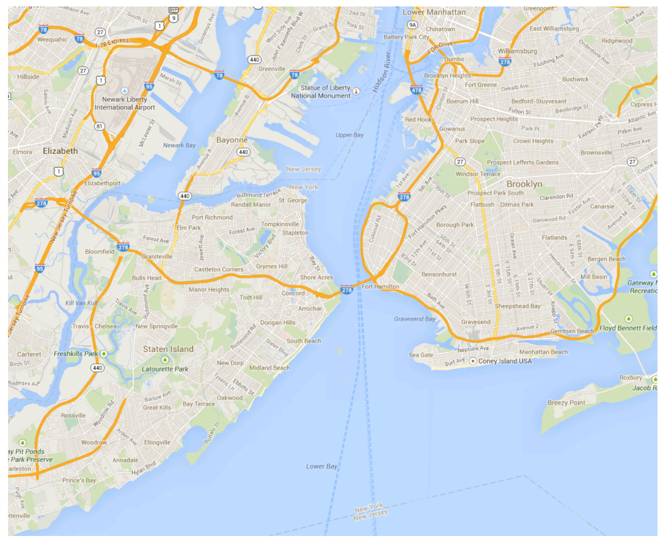

Figure 17a. Staten Island, Brooklyn, and New York Harbor. The area of interest extends from the Verrazano Bridge to the southwest for 4 miles. (Map courtesy of Google).

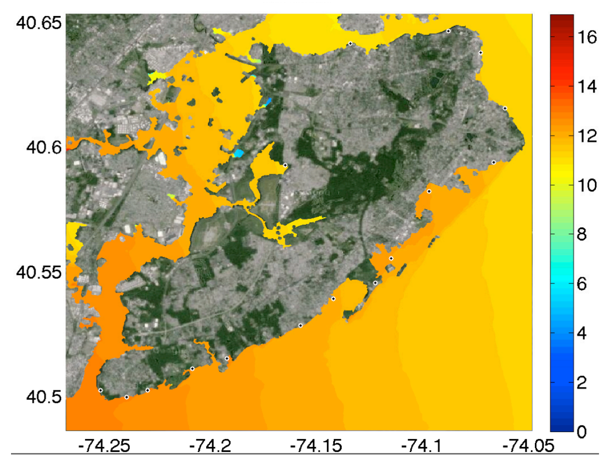

Figure 17a. The ADCIRC hindcast of the storm surge had good agreement with the actual field measurements. As can be seen by comparing Figures a and b, a large are of the coast between the Verrazano and Great Kills was flooded. The color scale shows the height of the storm surge in feet.

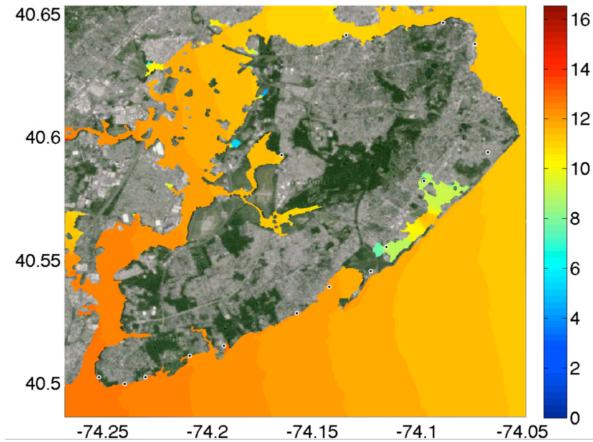

Figure 18a. (top) This ADCRIC/SWAN hindcast of Sandy using the REMA-R2 grid updated to include the new sand dunes created by the City, shows that flooding would likely still occur in the Midland Beach area because of the lack of a dune in front of Miller Field.

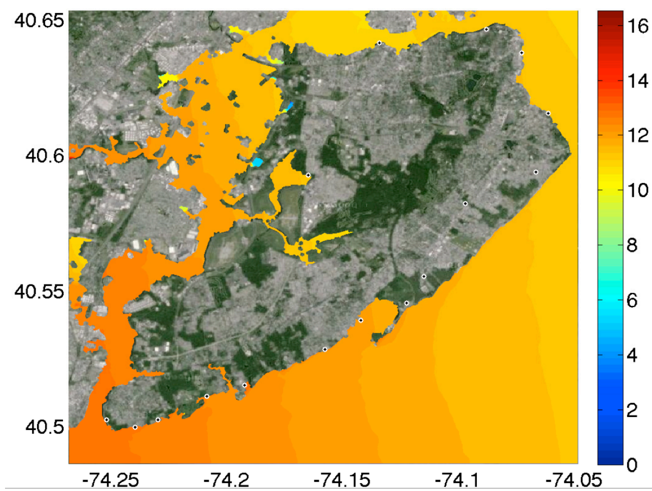

Figure 18b. The above hindcast assumes that a dune comparable to that created by the City was in place by Miller Field. In this instance, it appears that flooding will not occur. The model does not provide for dune erosion caused by waves and storm surge. The color scale shows the height of the storm surge in feet.

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REFERENCES

[1] ADCIRC, https://adcirc.org, accessed 29 April 2014

[2] The Unstructured Grid Finite Volume Community Ocean Model (FVCOM), http://fvcom.smast.umassd.edu/fvcom/, accessed 29 April 2014

[3] Regional Ocean Modeling System (ROMS), http://www.myroms.org, accessed 29 April 2014

[4] Welcome to Nek5000 Project, http://nek5000.mcs.anl.gov/index.php/Main_Page accessed 29 April 2014

[5] Community Earth System Model (CESM), http://www2.cesm.ucar.edu, accessed 29 April 2014

[6] PlaNYC: A Stronger, More Resilient New York, http://www.nyc.gov/html/sirr/html/report/report.shtml

[7] Ahearn, Sean C., CARSI-Hunter College-CUNY, Presentation titled, “Solar NYC”, given at the NGAC Meeting, September 23, 2010, www.fgdc.gov/ngac/meetings/september-2010/index_html, accessed 22 April 2014.

[8] "New York: Leading the Way in Tidal Power - Danish Architecture Centre. http://www.dac.dk/en/dac-cities/sustainable-cities/all-cases/energy/new-york-leading-the-way-in-tidal-power/

[9] "Regulatory & Permitting." *Verdant Power*. http://www.verdantpower.com/regulatory--permitting.html

[10] Tang, H. S., Kraatz, S., Qu, K., Chen, G. Q.Chen, Aboobaker, N., Jiang, C. B., “High-resolution survey of tidal energy towards power generation and influence of sea-level-rise: A case study at coast of New Jersey, USA, Renewable and Sustainable Energy reviews 32 (2014) 960-982.

[11] Martilli A., Clappier A., and Rotach M., 2002: An urban surface exchange parameterization for mesoscale models. Bound.-Layer Meteor., 104 , 261–304.

[12] Salamanca, F., and A. Martilli, 2009: A new Building Energy Model coupled with an Urban Canopy Parameterization for urban climate simulations. Part II: Validation with one dimension off-line simulations'. Theor Appl Climatol. 99, 345-356.

[13] Burian S., Augustus N., Jeyachandran I., and Brown M., 2008. Final Report for the National Building Statistics Database. LA-UR-08-1921 April 4, 2008.

[14] E. Gutierrez, J.E. González, M. Arend, A. Martilli, and R. Bornstein. A new modeling approach to forecast building energy demands during extreme heat events in complex cities. J. of Solar Energy Engineering, 135, DOI: 10.1115/1.4025510

[15] Orton, P., Vingradov, S., Blumberg, A., Georgas, N., “Final project report submitted to New York City: Hydrodynamic Mapping of Future Coastal Flood Hazards for New York City”, Davidson Laboratory, Stevens Institute of Technology, November 30, 2013.

[16] FEMA (2013), Redefinition of the Coastal Flood Hazard Zones in FEMA Region II: Analysis of the Coastal Storm Surge Flood Frequencies, Fairfax, VA.

[17] Westerink, J., R. Luettich, and J. Muccino, (1994) Modelling tides in the western North Atlantic using unstructured graded grids, Tellus A, 46(2), 178-199.

[18] Orton, P., N. Georgas, A. Blumberg, and J. Pullen (2012), Detailed Modeling of Recent Severe Storm Tides in Estuaries of the New York City Region, J. Geophys. Res., 117, C09030, DOI:10.1029/2012JC008220.

[19] FEMA (2013), Region II Storm Surge Model Calibration and Validation Report, Prepared by Risk Assessment, Mapping, and Planning Partners (RAMPP), Washington, DC.

[20] Presentation by Yauheni Dzedzits, Michael Kress, and Alan Benimoff, College of Staten Island/CUNY and Brian Blanton, Renaissance Computing Institute, University of North Carolina, at a US Geological Survey Workshop held at the College of Staten Island/CUNY on 22-23 April 2014.