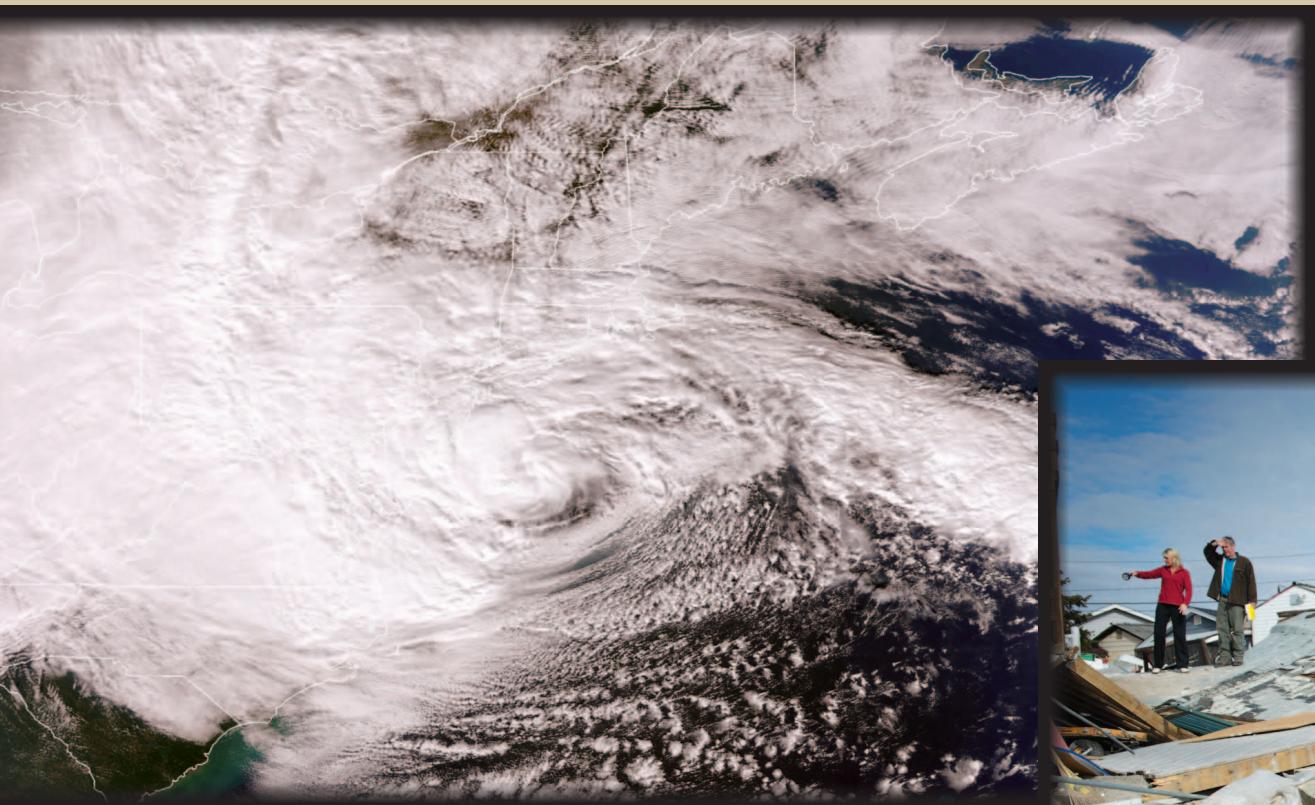


Stormy Weather



NASA/NOAA

Assessing Climate Change Hazards
to Electric Power Infrastructure:
A Sandy Case Study



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POWER SYSTEM INFRASTRUCTURE IS SUBJECT to damage from a wide range of extreme weather events, including hurricanes, tornadoes, lightning storms, snow and ice storms, floods, storm tides, heat waves, droughts, and more (see Figure 1). As climate change occurs, scientists expect extreme events to become even more severe in some locations, resulting in more intense precipitation; longer, hotter heat waves; higher-intensity hurricanes; higher storm tides; more ice storms; and so on.

The increased severity of extreme weather events will subject the electric grid to higher levels of risk. Enhanced understanding of these risks can help utility executives and regulators make better decisions regarding the levels of risk that are tolerable and the measures and financial resources required to manage risk to acceptable levels. In this article, we discuss a case study undertaken to evaluate how future climate change might impact the electricity delivery system on Long Island, New York. The study used a scenario-based approach to examine how warmer atmospheric, soil, and sea surface temperatures would affect the evolution and impact of a Superstorm Sandy-like storm in the future.

This work brought together researchers and practitioners in the atmospheric and environmental sciences, risk analysis, and the electric power sector to explore ways of integrating their respective disciplines to consider how climate change science can be introduced as a design input for electric infrastructure analysis. Given the long-lived nature of electricity infrastructure investments, it is judicious to consider how climate change may affect the future efficacy of measures taken to increase grid resilience today.

Climate scientists need to be involved early on in the process. They ensure the required capability in weather and climate modeling using the fundamental laws of physics, and they know the strengths and limitations of weather forecasts and climate projections. Knowledge of the electric power system is also critical to understanding the consequences of extreme weather. The ability to identify system vulnerabilities and thresholds of failure and to assess and evaluate the types and magnitudes of outages is fundamental. In between the domains of the atmospheric sciences and electrical power systems reside experts who translate information from weather models into the actual hazard that damages the electric system, such as high winds, storm surge and flooding. Coordination among the various experts and stakeholders is needed to ensure the ideal transfer of information across these different domains. In this work, scientists from the National Center for Atmospheric Research (NCAR) teamed up with engineers and risk analysts from DNV GL to explore how climate science can better inform hazard and impact analysis, ultimately serving weather-related risk management and storm hardening programs under current and future climate conditions.

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As climate change occurs, scientists expect extreme events to become even more severe in some locations, resulting in more intense precipitation.

Our analysis focused on surface winds and their impact on storm surges and on precipitation and the associated flooding throughout the region after landfall. These objectives were achieved by simulating, in detail, Superstorm Sandy as it occurred and under future climate conditions and then using modeling output to conduct hazard and impact analysis (see “Sandy: A Storm to Remember”). Increased understanding and advanced computer simulation that integrates state-of-the-art weather, impact, and damage models will help in societal and economic analyses for improved storm hardening, enhancing preparedness, and planning emergency responses. We demonstrate our forward-looking approach, which takes advantage of such integration, to explore how climate change can be incorporated in decision making with respect to storm hardening. Further, we show how such integration relies on a close collaboration among experts in different domains. The resulting case study explores the impacts that Superstorm Sandy had on the coastal electrical infrastructure of Long Island due to storm surges and flooding, how such impacts may differ if fundamental climate and environmental parameters change in the future, and how the integration of the various models can inform decisions about electric infrastructure resilience measures.

Superstorm Sandy exhibited unusual and unprecedented characteristics, and it is within this context that we 1) explored the ability of NCAR’s regional weather research

and forecasting (WRF) model to accurately simulate Sandy’s key features (e.g., landfall timing and location and associated surface wind intensity and extent; precipitation amounts and spatial distributions; and partitioning between snow and rain); 2) investigated how Superstorm Sandy might be different in a future, warmer world, where the surface ocean temperatures are higher and the atmosphere is warmer and holds more moisture; 3) utilized the outcomes of WRF to drive storm surge and flooding models and assess the changes in impacts between the actual Sandy event and future scenarios; and 4) integrated the impact assessment with system specifics of the electric infrastructure onto a common GIS platform, thus enabling analysis of geographically informed, risk-based strategies to adapt to future climate threats.

Superstorm Sandy

Superstorm Sandy made continental U.S. landfall at approximately 8 p.m. EDT on 29 October 2012 (00:00 UTC 30 October 2012) near Brigantine, New Jersey, with winds of 80 mi/h (130 km/h) spanning a 1,800-km path (see Figure 2). It was the largest Atlantic hurricane on record, taking 286 lives and causing more than US\$68 billion in property damage—the second-costliest hurricane in U.S. history. The widespread damage caused by the storm, as well as its unusual merging with a frontal system, resulted in its being nicknamed “Superstorm Sandy” by media outlets and U.S. government agencies. Sandy was a Category 3 storm when it made landfall in Cuba at 05:25 UTC on 25 October. After Sandy passed across Cuba, the storm weakened and turned to the north-northwest, toward the Bahamas, eventually reintensifying into a hurricane with a redeveloped eye.

When moving north, Atlantic hurricanes typically move in a northeasterly direction and thus away from the coast, due to the jet stream’s prevailing westerly winds. In late October of 2012, however, the polar jet stream dipped sharply into the eastern United States, giving rise to a midlatitude trough of low pressure. There was also a mass of



figure 1. Electric power infrastructure damage associated with Superstorm Sandy. (©iStockimages.com.)

high pressure centered in Greenland that partially blocked Sandy's path. These ingredients came together to steer Sandy westward, into the densely populated eastern seaboard of the United States. While moving northeast, Sandy underwent extratropical transition, and a vast wind field emerged with hurricane-force winds along the small, central core of the storm and with outer wind bands moving into Long Island and New York City and winds nearing 90 mi/h as far north as Rhode Island.

Superstorm Sandy also made landfall during high tide, making it even more catastrophic. The extreme winds combined with the high tide created some of the greatest sea-level heights ever recorded in many regions along the coast. The storm surge levels measured at the Battery in lower Manhattan were the highest ever recorded at that location, nearly five feet above any previously measured value. This storm surge meant that a considerable amount of electric infrastructure near the coast was

Sandy: A Storm to Remember

Superstorm Sandy was considered a "hybrid" storm, since it pulled together a variety of familiar meteorological ingredients, including its main tropical hurricane component, a cold front from the northwest, and a ridge of high pressure over Greenland. Combined, these aspects of the storm prevented it from following a path that would traditionally have carried it out over the Atlantic.

Sandy's impacts and damages on Long Island were unprecedented, highlighting the fragility of current systems relative to extreme weather events and emphasizing the need for a risk-based approach for evaluating what measures should be taken to enhance resilience to uncertain events.

We need to understand the atmospheric underpinnings of how and why severe storms such as Superstorm Sandy develop and evolve and then demonstrate that our advanced weather models can simulate these dynamical processes with skill and precision. This understanding can then be used to project how variations brought about by climate change might influence the evolution and impacts of severe storms in the future.

The vulnerability of the New York area and other coastal cities highlights the need for accurate information on the timing and effects of storm surge flooding. As the mean sea level continues to rise over, flooding problems will only be aggravated, and this analysis shows that substations may also be subjected to higher storm tides.



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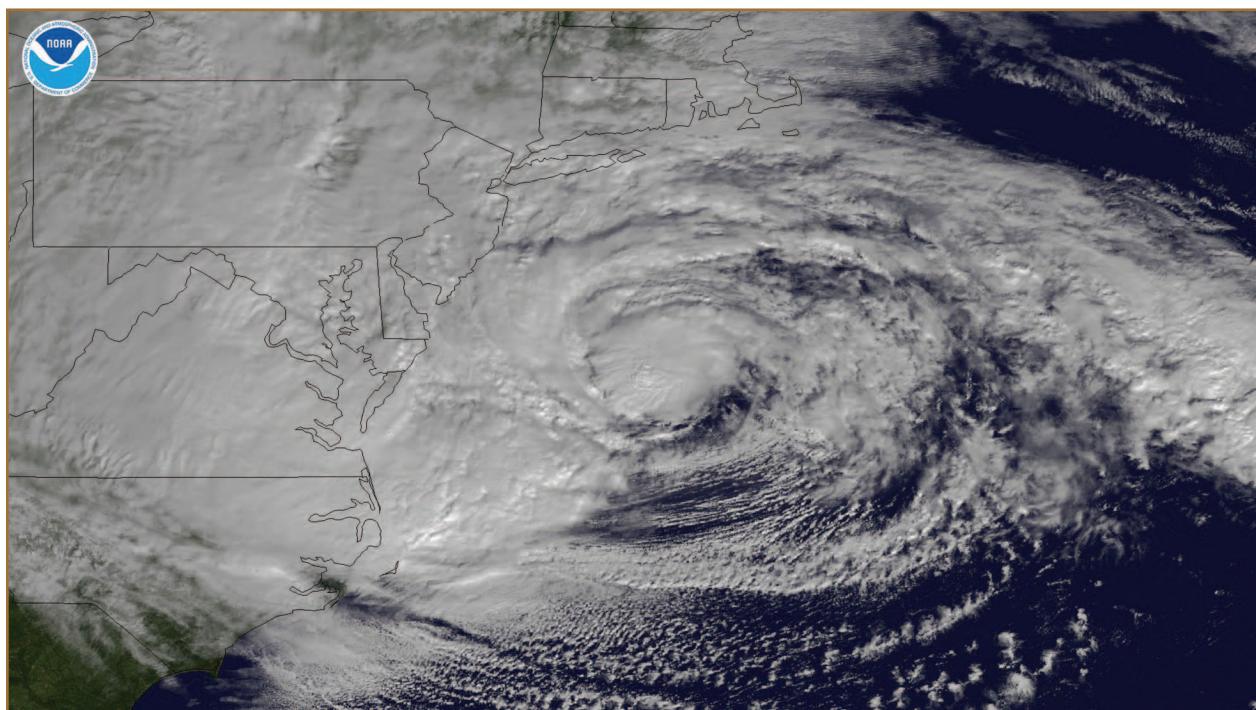


figure 2. A satellite image of Superstorm Sandy before landfall on the continental United States. (Image used with permission from the National Oceanic and Atmospheric Administration.)

inundated; inland, high precipitation in the form of both rain and snow wreaked havoc on the power distribution system.

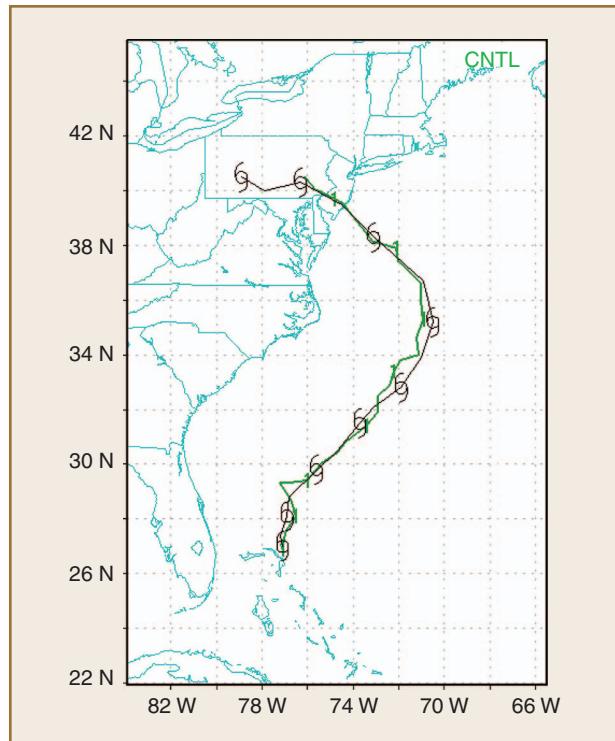


figure 3. A comparison of the WRF-simulated Superstorm Sandy track (in green) with NOAA National Hurricane Center data (in black) at 6-h time intervals, starting at 18:00 UTC on 26 October 2012. (Image used with permission from NCAR.)

Impact on the Long Island Electrical Infrastructure

Hurricane Sandy was a devastating storm, affecting the entire Atlantic coastline of the United States from Florida to Maine and spreading into the mid-Atlantic, Ohio Valley, and Great Lakes states. At least 159 people were killed in the United States. Among coastal states, 69 power plants and 102 electric substations were located in areas flooded due to storm tides. In the service territory of the Long Island Power Authority (LIPA), the subject of the study discussed here, damage occurred to 51 substations (12 were flooded); nearly 2,500 transformers were repaired or replaced, more than 4,400 distribution poles were repaired or replaced, and more than 400 mi of wire was repaired or replaced. This damage caused a loss of electric service to more than 90% of LIPA's 1.1 million customers, and it took days and in some cases weeks or longer to restore their power. LIPA's repair costs in the days and weeks following Sandy approached US\$1 billion.

The response of public officials and electric utilities to the damage inflicted by Sandy has included both near-term and longer-term measures to increase the resilience of the utility infrastructure in the affected areas. For example, in October 2013, Governor Andrew M. Cuomo of New York announced that approximately US\$72 million in federal funding would be dedicated to helping Long Island's electric grid become more resilient in the event of major coastal flooding or severe storms by elevating as many as 32 coastal substations in flood-prone areas. Utilities in the hardest-hit areas have identified several billion U.S. dollars' worth of investments that will be made to harden the grid and increase its resilience to future storms.

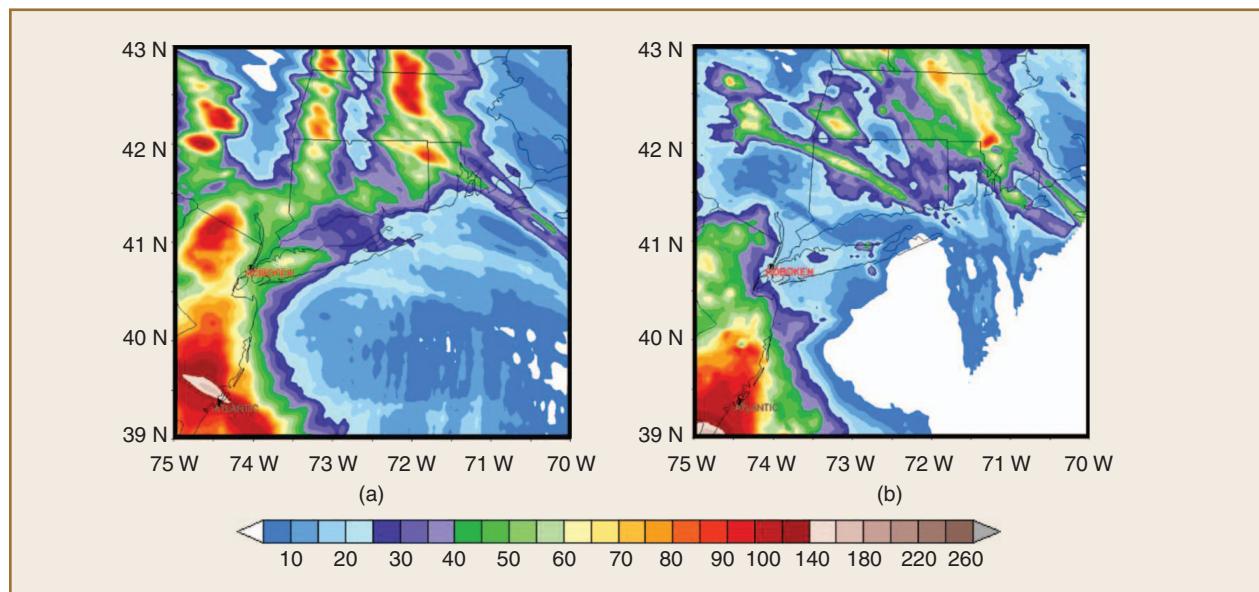


figure 4. The 24-h (ending at 12:00 UTC on 30 October 2012) accumulated precipitation (a) as derived through WRF control simulation from the 3-km domain (mm) and (b) from the actual National Centers for Environmental Prediction (NCEP) 4-km Stage IV observations. (Image used with permission from NCAR.)

Our analysis focused on surface winds and their impact on storm surges and on precipitation and the associated flooding throughout the region after landfall.

table 1. The WRF numerical experiment design (changes in air and soil temperature and sea surface temperature are relative to the control simulation).

Numerical Experiments	Initial and Boundary Conditions		
	Air Temperature	Deep Soil Temperature	Sea Surface Temperature
F2020: a climate-warming scenario for 2020	+ 1 °C	+ 1 °C	+ 0.3 °C
F2050: three 2050 climate-warming scenarios	A + 2 °C	+ 2 °C	+ 0.6 °C
	B + 2 °C	+ 2 °C	+ 0.9 °C
	C + 2 °C	+ 2 °C	+ 1.2 °C
F2090: a climate-warming scenario for 2090	+ 4 °C	+ 4 °C	+ 1.8 °C

Understanding Superstorm Sandy Through Weather Modeling

We used the advanced research version of the WRF model as our primary atmospheric modeling tool. The WRF model was developed jointly by NCAR, a number of government agencies, and the university research community. To conduct the numerical studies of Superstorm Sandy, the WRF model was configured as two nested domains: a coarse modeling domain with 15-km horizontal grid spacing and a high-resolution domain with 3-km grid spacing.

Two types of WRF simulations were performed. The first was a simulation of Superstorm Sandy under current climatic conditions (the control, or CNTL, simulation). The second type consisted of scenario-based simulations of Superstorm Sandy for future climatic conditions that included warmer initial and boundary conditions. The first day of model simulation began at 18:00 UTC on 26 October 2012, and the final time of simulation was at 00:00 UTC on 31 October 2012, about 24 h after landfall in the United States.

Control Simulation

Figure 3 shows the control simulation storm track (green) compared with the track from the National Hurricane Center (NHC) observations (black). Although the WRF-predicted location of Superstorm Sandy is slightly westward of its actual track during the second intensification phase (the 12-h period beginning at approximately 60 h into the forecast), the overall evolution of the observed track—especially the timing and location of landfall—was well reproduced by the WRF model, as were the maximum surface-wind speed (about

80 kn) and storm intensity as measured by surface pressure, where a lower value reflects greater intensity (about 940 mb).

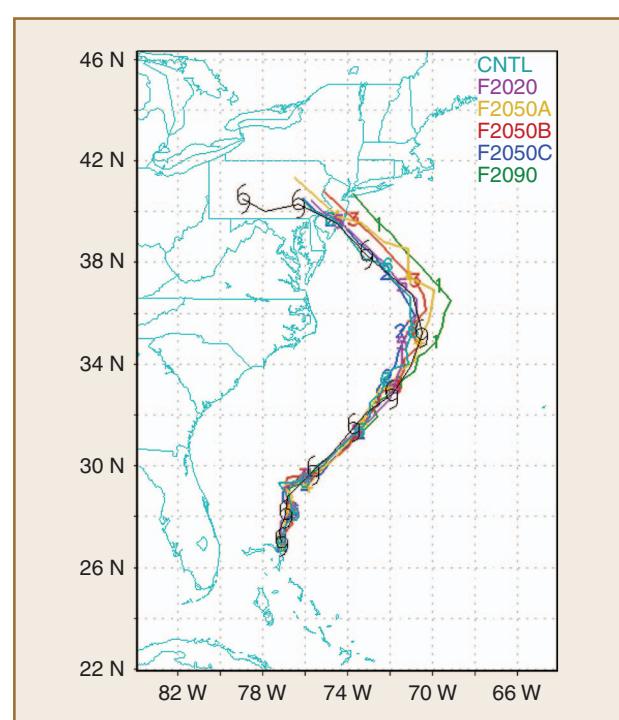


figure 5. A simulated Hurricane Sandy track in CNTL (cyan), F2020 (purple), F2050A (gold), F2050B (red), F2050C (blue), and F2090 (green) simulations. (Image used with permission from NCAR.)

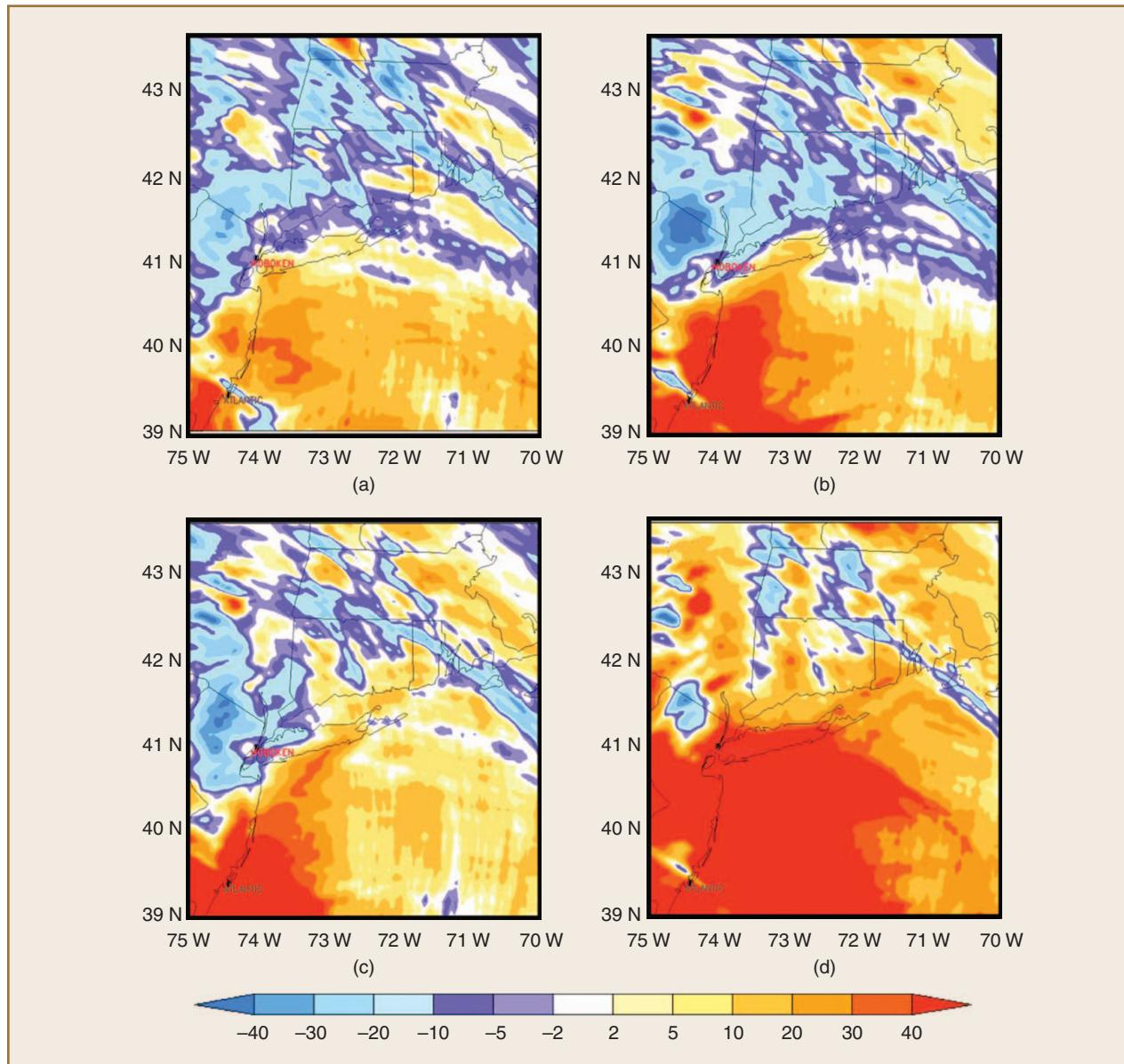


figure 6. A comparison of 24-h accumulated precipitation (mm) from 12:00 UTC 29 October to 12:00 UTC 30 October in the future scenarios with that in the CNTL simulation, for (a) F2020, (b) F2050A, (c) F2050B, and (d) F2090. (Image used with permission from NCAR.)

Despite some differences in the northern portion of the domain, the spatial distribution of 24-h rainfall in New Jersey and in the lower portion of New York State forecast by the WRF model is notably similar to observations (see Figure 4). Moreover, the maximum amount of rainfall near Atlantic City, New Jersey, was well predicted.

The data handshake between the atmospheric science and hazard impacts teams required close cooperation, as the WRF outputs need to be compatible with the required inputs for the surge and flood models. The WRF model, when run at such fine resolution over such a large domain, can generate terabytes of data, so modelers are selective in the output fields generated and the time intervals over which they

are saved. For example, typical outputs from WRF include three-hourly wind speeds at the hour, but the impacts models required subhourly wind speeds and their maximum values. The WRF output fields were modified to generate the maximum wind speed, the wind direction, and the radius of maximum winds from the storm center over each 15-min interval. These data were then passed from the atmospheric modeling team to the hazards modeling team for use in storm surge, flooding, and inundation modeling.

Future Scenarios

The WRF simulations for the future, warmer conditions followed a perturbation method where the surface-air

table 2. Sandy's landfall characteristics in the various future simulations.

Simulation	Landfall (UTC)	Latitude	Longitude	Min Pressure	Intensity Max Wind
CNTL	00:00 30 October	39.49° N	74.13° W	940 mb	30 m/s ⁻¹
F2020	02:45 30 October	39.65° N	74.22° W	938 mb	30 m/s ⁻¹
F2050A	05:15 30 October	39.81° N	74.23° W	940 mb	28 m/s ⁻¹
F2050B	05:30 30 October	40.08° N	74.16° W	942 mb	28 m/s ⁻¹
F2050C	01:30 30 October	39.76° N	74.35° W	942 mb	28 m/s ⁻¹
F2090	05:30 30 October	40.67° N	73.64° W	938 mb	28 m/s ⁻¹



figure 7. A simulation of flooding extent during Superstorm Sandy. (Image used with permission from DNV GL.)



figure 8. A simulation of flooding extent under the 2090 scenario. (Image used with permission from DNV GL.)

When moving north, Atlantic hurricanes typically move in a northeasterly direction and thus away from the coast, due to the jet stream's prevailing westerly winds.

temperature, sea surface temperature (SST), and soil temperatures were uniformly increased. The initial and boundary conditions were thus modified for each of the future climate scenarios given as summarized in Table 1. Simulations were conducted for future warming conditions in which the degree of temperature warming was taken from estimates provided by the *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC) for a future climate scenario around 2020 (F2020), three 2050 scenarios (F2050A–C), and a 2090 scenario (F2090). For instance, in the F2020 simulation, the air temperature was increased by 1 °C at all vertical levels in the atmosphere, the sea surface temperature and soil temperature were increased by 0.3 °C, and the deep soil temperature was increased by 1 °C (see Table 1).

Simulated Sandy tracks for current and future conditions are shown in Figure 5. The tracks shift slightly to the north in the future simulations; while the 2020 scenario shows a minimal shift, the 2090 scenario makes landfall in western Long Island. As illustrated in table 2, the simulated future storm landfall shifts north by 20–100 km, and the landfall time is delayed by 2–5.5 h in simulations with future climatic conditions. Notably, the intensity of future storms at landfall, in terms of minimum pressure and maximum wind speed, is within 5% of the control simulation.

Along the coastlines in New Jersey and New York, the future Sandy simulations produce more precipitation than the control simulation (see Figure 6)—approximately 15–40 mm more for the 24-h period. Increasing temperatures, and therefore more water vapor in the atmosphere, result in larger rainfall amounts in the general landfall areas. The most extreme case (the 2090 scenario, with the highest temperature increase) produces the greatest and most widespread rainfall, especially

in western Long Island, where it is increased by more than 40 mm for the 24-h period.

Storm Surge Analysis and Flooding of Substations

Based on the WRF Sandy runs for present and future scenarios, a storm surge analysis identified surge heights and the spatial extent of water on land, water depths, and the final inundation extent. The data transfer between the atmospheric and storm surge model plays an important role, as it ensures the consistent representation of the physical processes across the various models employed. For this analysis the track location in time, maximum wind speed, pressure drop, and the radius of maximum wind were the primary variables from the atmospheric model used in the storm surge assessment. Furthermore, future sea level rise for 2050 and 2090 were also accounted for, following estimates provided by IPCC, in the form of constant vertical shifts of the mean sea level relative to the present sea level.

The storm surge was simulated with a hydrodynamic model driven by the WRF-simulated hurricane track with a time-varying grid. The model was used to simulate the Superstorm Sandy event (CNTL), and the results were validated against National Oceanic and Atmospheric Administration (NOAA) buoy measurements. Once validated, the surge model was run using the results from the future Superstorm Sandy scenarios from the WRF model (see Tables 1 and 2). The resulting maximum water levels computed for the future simulations of Sandy are significantly higher than the actual levels recorded in some areas of the New Jersey and Long Island coasts, due to changes in the local characteristics of the storm at landfall—primarily, location and, secondarily, the storm's pressure and wind profiles.

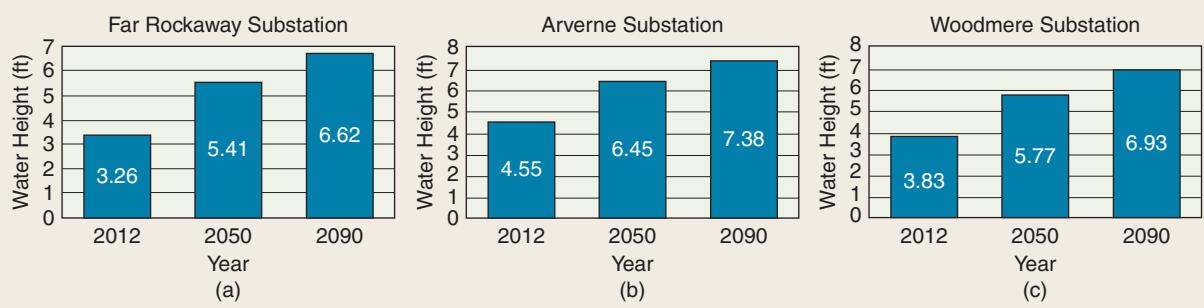


figure 9. Modeled and projected flooding heights for the (a) Arverne, (b) Far Rockaway, and (c) Woodmere substations. (Image used with permission from DNV GL.)

The flooding extent was simulated from the values obtained at each grid cell using the output of the storm surge model.

The flooding extent was simulated from the values obtained at each grid cell using the output of the storm surge model. The flooding assessment was performed using a 20-m digital terrain model of the unconfined floodplain. As the flood wave moved over the floodplain, effects such as flow over adverse slopes, attenuation, ponding, and backwater effects were also simulated. Using the simulated surge for the historic Superstorm Sandy case (CNTL), the simulated flooding extent compared well with actual observations on Long Island provided by FEMA.

Based on this simulation and on geographical data about substations within the counties of Nassau and Suffolk, we were able to identify the substations that reported flooding in these counties during Sandy, identified by the red dots in Figure 7. The yellow dots in the figure indicate substations that did not report flood impacts, and the simulated flood correlates well with these also.

Running the same flooding model with the storm surge simulated for the future scenarios, it is estimated that 27 substations would potentially be affected by flooding under the 2050B scenario and 30 under the 2090 scenario (see the yellow dots in Figure 8). Under these scenarios, more than twice as many substations would be affected as were flooded in 2012.

Three substations—Arverne, Far Rockaway, and Woodmere—were selected to help illustrate the flood elevations during Sandy and under the climate change scenarios. These substations were chosen based on their proximity to the estimated landfall of future Sandy tracks and the damage they suffered during the actual storm in 2012. Figure 9 shows the height of floodwater at these substation locations from the 2012 simulation, the 2050B scenario, and the 2090 scenario. Given the long-lived nature of investments in substation infrastructure, these projections show the importance of taking the potential effects of future climate change into account when considering measures to enhance the resilience of the electric grid.

Insights and Lessons Learned

A number of insights were gained and lessons learned during the course of this study. From the outset, a mutual understanding and knowledge sharing among the different parties and disciplines were of paramount importance. The expertise of power system engineers was fundamental in directing the climate analysis toward the types of hazards and events that needed to be modeled while ensuring that the climatic information was useful for system-specific decision making. In this respect, the spatial scale of the climate assessment played a crucial role, as the information required is often highly localized. Furthermore,

compatibility among the climate, hazard, and impact models was also important. One example was the characterization of surface winds needed for assessing their impacts on the electric network. We needed to ensure that wind estimates obtained from the climate model followed the requirements of the environmental and electrical engineering analysis. In the context of the present analysis, we have highlighted the case of coupling an atmospheric model with a storm surge model; similar considerations apply for wind impacts on poles and overhead lines and the standards according to which these are designed. One further insight we gained regards the time line of the analysis, the choice of which must take the design lifetime of the components of the network into account. For storm hardening, the lead time of the analysis must reflect the expected lifetime of the most capital-intensive and long-lived components of the network, plus possible lifetime extensions.

For Further Reading

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