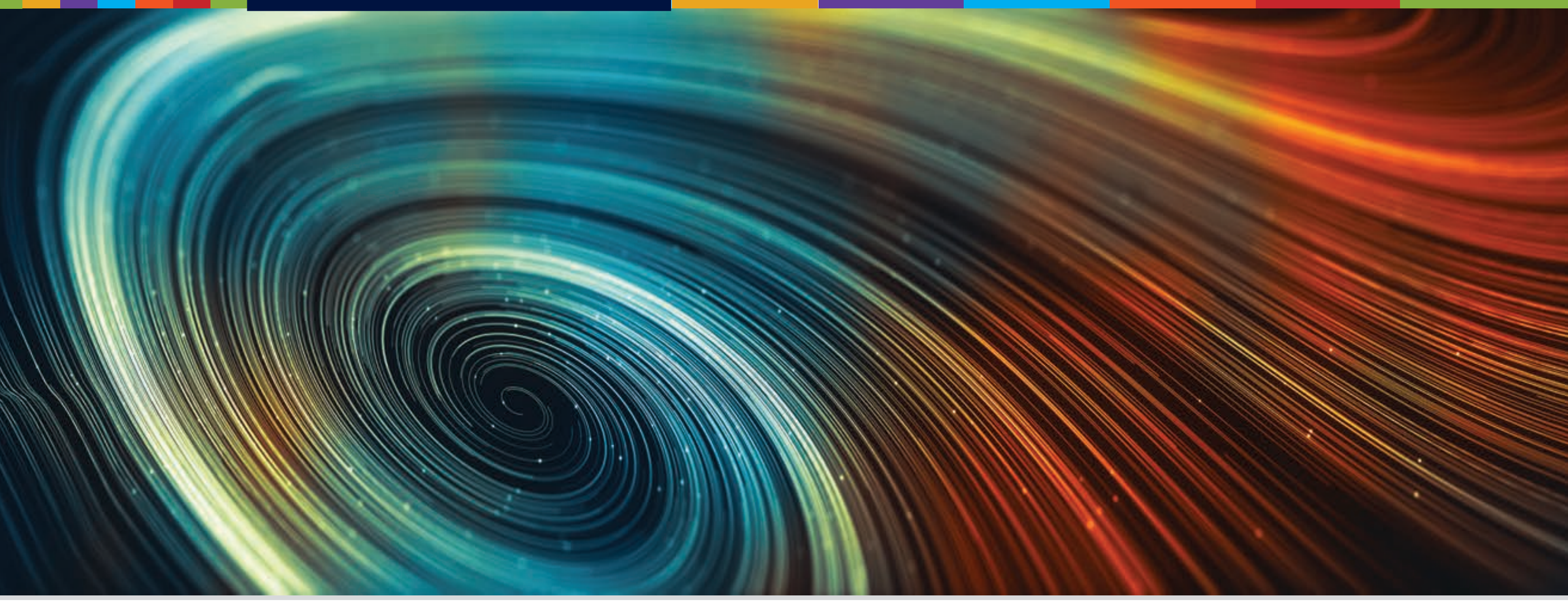
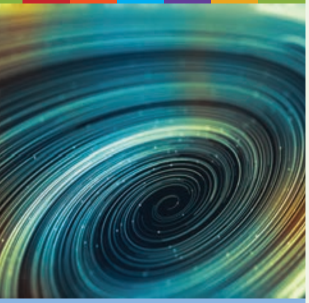
# Annual Report

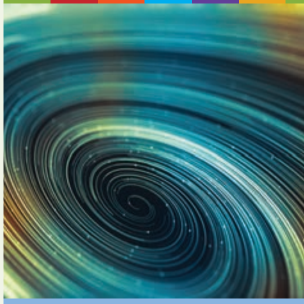
EVERSOURCE
**ENERGY CENTER**
A utility-university partnership at UConn

**2020**



# Contents





**Dear Friends,**

Like everyone else, the Eversource Energy Center faced the unprecedented challenges posed in 2020 by COVID-19. Despite them, we maintained firmly our focus on promoting innovative research that fulfills our commitment to delivering new knowledge and high-quality technologies to the electric utility sector and concomitant industries and stakeholders.

In the past year, we completed 14 research projects and initiated 22 new projects, strategically aligned into six thematic areas: Outage Prediction Modeling and Emergency Response, Resilience System Modeling and Economic Effects, Vegetation Management, Outreach, and Forest Science, Renewable Energy and Grid Integration, Cyber and Physical Security, and Offshore Wind Energy.

Among the several milestones highlighted in this report is the expansion of our operational outage prediction model to account for new vegetation and drought variables. This expansion will improve significantly the model's prediction accuracy for such extreme events as tropical storm Isaias, which caused widespread outages in the northeastern United States last August. We also marked in the fall of 2020 the kickoff of our power grid modernization graduate certificate program and welcomed three new faculty members with expertise in, respectively, weather-impact modeling, power engineering, and the energy-biodiversity nexus. Our funding is stronger than ever, with active research grants totaling $9 million (total to date $20 million) and pending grants of $22 million.

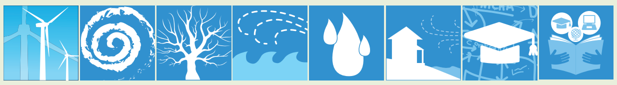
We have also developed new regional partnerships. With the University of Albany's Atmospheric Sciences Research Center, we proposed a National Science Foundation Industry-University Research Partnership Center for Weather Innovation and Smart Energy and Resilience (WISER). This center will bring together power utilities and industry across the country to support innovative research that will provide state-of-the-art weather and climate information to strengthen and safeguard the energy industry of the future. In collaboration with the Electric Power Research Institute, we are developing a tool to quantify how often power disruptions occur as a result of storms and track trends brought about by climate change. This tool will guide policymakers and the utility industry on ways to improve power grid performance by focusing their efforts on its reliability and resiliency.

We invite you to take a look at the research summaries and other information in this report and hope you will find it both enlightening and useful. We are open to broadening our collaboration with representatives of academia and industry who wish to participate in our research, activities, and initiatives. Our proven consortium method will produce the next generation of technologies and software, leading to transformative commercial products and services and advances in storm preparedness, grid resilience, and grid modernization. Our exceptional partnerships are driving innovation, and we invite you to join us in building the grid of the future, today.

**Emmanouil Anagnostou**
**Director, Eversource Energy Center**

**April 30, 2021**

**The Eversource Energy Center** is the leading partnership between an energy utility and a university in the United States. A trusted source of energy expertise, the Center is striving to advance new research and technologies to ensure reliable power during extreme weather and security events. Our Center's consortium approach is to create partnerships, develop next-generation technology and software, and collaborate to meet current and future reliability and energy needs



## We Are a hub for innovative and progressive thinking to build the electric grid of the future, today.

# Our Team

## Principal Investigators

### Department of Civil and Environmental Engineering
**Emmanouil N. Anagnostou,** *Board of Trustees Distinguished Professor, Eversource Energy Endowed Chair in Environmental Engineering, Director of the Eversource Energy Center*
**Marina Astitha,** *Assistant Professor, Forecasting Team Lead*
**Amvrossios Bagtzoglou,** *Professor, Grid Resilience Team Lead*
**Diego Cerrai,** *Assistant Professor, Manager of the Eversource Energy Center*
**Malaquias Peña,** *Associate Professor*
**Giulia Sofia,** *Assistant Research Professor*
**Xinyi Shen,** *Assistant Research Professor*
**Guiling Wang,** *Professor*
**Wei Zhang,** *Assistant Professor*

### Department of Computer Science and Engineering
**Amir Herzberg,** *Comcast Endowed Professor for Security Innovation*
**Fei Miao,** *Assistant Professor*

### Department of Electrical and Computer Engineering
**Yang Cao,** *Associate Professor*

### Department of Finance
**Fred Carstensen,** *Professor, Director of the Connecticut Center for Economic Analysis*

### Department of Mechanical Engineering
**Georgios "George" Matheou,** *Assistant Professor*

### Department of Natural Resources and the Environment
**Robert Fahey,** *Assistant Professor, Associate Director of the Eversource Energy Center, Tree and Forest Management Team Lead*
**Thomas H. Meyer,** *Professor*
**Anita Morzillo,** *Assistant Professor*
**Jason Parent,** *Assistant Research Professor*
**Chandi Witharana,** *Visiting Assistant Professor*
**Thomas Worthley,** *Assistant Extension Professor, Forestry Specialist*
**Zhe Zhu,** *Assistant Professor*

### Department of Operations and Information Management
**David Wanik,** *Assistant Professor in Residence*

## Graduate Research Assistants

### Department of Civil and Environmental Engineering
Ezana Atsbeha
Zhixia Ding
Brenden Edwards
Stergios Emmanouil
Kang He
Lanxin Hu
William Hughes
Fahad Khadim
Ummaul Khaira
Mariam Khanam
Marika Koukoula
Qin Lu
Xiaolong Ma
Mahjabeen Fatema Mitu
Jason Philhower
Genevieve Rigler
William Taylor
Michael Walters
Zhe Wang
Peter Watson
Feifei Yang
Mejian Yang
Yue Yin
Tasnim Zaman
Jintao Zhang

### Department of Computer Science and Engineering
Guannan Liang
Tristan Peppin

### Department of Electrical and Computer Engineering
Mohamadreza Arab Baferani

### Department of Natural Resources and the Environment
Amanda Bunce
Jacob Cabral
Emlyn Crocker
Steve DiFalco
Nancy Marek
Kerste Milik
Kexin Song
Danielle Tanzer

### Department of Statistics
Jieying Jiao

### Department of Agricultural and Resource Economics
Donghoon Kim

### Postdocs
Md Abul Ehsan Bhuiyan
Brian Maitner

### Center Research Staff
**Cory Merow,** *Assistant Research Professor, jointly with Department of Ecology and Evolutionary Biology*
**Ha Nguyen,** *Assistant Research Professor, jointly with Department of Electrical and Computer Engineering*
**Raymond V. Petniunas,** *Associate Research Professor*
**Xinyi Shen,** *Assistant Research Professor, jointly with Department of Civil and Environmental Engineering*
**Giulia Sofia,** *Assistant Research Professor, jointly with Department of Civil and Environmental Engineering*

### Center Staff
**Ronny Heredia,** *Financial Assistant for Eversource Energy Center*
**Claudia Dijmarescu,** *Student Assistant*

### Collaborators
**Zoi Dokou,** *Assistant Professor, California State University, Sacramento*
**Baptiste Francois,** *Research Assistant Professor, University of Massachusetts, Amherst*
**Marcello Graziano,** *Associate Professor, Southern Connecticut State University*
**Peter Gunther,** *Senior Research Fellow, Connecticut Center for Economic Analysis*
**George Kallos,** *Professor, University of Athens*
**Andreas Langousis,** *Assistant Professor, University of Patras*
**Jonathan Mellor,** *Lecturer, University of Massachusetts Dartmouth*
**Efthymios Nikolopoulos,** *Assistant Professor, Florida Institute of Technology*
**Peng Zhang,** *Associate Professor, Stony Brook University*

Our Center originated from a partnership between Eversource Energy and the University of Connecticut, with the purpose of enhancing electric utility preparedness, hardening infrastructure, and embracing the grid of the future: intelligent, interactive, automated, reliable, and safe! The Center comprises experts at universities, state organizations, and the electric utility industry, collaborating within the framework of a Center of Excellence. Marshaling the expertise of these various stakeholders through an integrated analytical approach enables us to advance forecasting tools, proactively manage risk landscape, and embrace new technologies, yielding strategies and actions to manage severe weather hazards. Importantly, research at the Center features a dynamic vision: it accounts for climate evolution, as well as the changes in exposure and vulnerability to extreme weather events produced by different societal activities and demographics.

## Key initiatives

**Among the Center's key initiatives in 2020 were the launching of numerous research projects, the introduction of a new graduate certificate program in grid modernization, and the successful engagement of female and underrepresented minority undergraduate students in peer-reviewed research.**

### RESEARCH PROJECTS

In 2020, the Center initiated 22 new projects in six thematic areas:

1. Outage Prediction Modeling and Emergency Response
2. Resilience System Modeling and Economic Effects
3. Vegetation Management, Outreach, and Forest Science
4. Renewable Energy and Grid Integration Cyber and Physical Security
5. Offshore Wind Energy

### NEW GRADUATE CERTIFICATE PROGRAM

In Fall 2020, we kicked off our power grid modernization graduate certificate program with 13 industry students. Their very positive reception of the first course offered, Predictive Analytics, triggered great interest from electric utility industry engineers. Early communication with utility managers indicates the program will have 25 industry participants in 2021.

### UNDERGRADUATE STUDENT RESEARCH

In the past year, the Center engaged eight undergraduate students—five of them female and/or from underrepresented minority groups—in research ranging from designing a microgrid and mapping the groundwater footprint in Ethiopia to a wildfire ignition project in California and the prediction of storm forest disturbances and outages. Their efforts met with great success, with all the projects producing papers submitted to and published or accepted for publication by high-profile peer-reviewed journals. Currently, we are pursuing a new undergraduate research initiative for the spring, summer, and fall semesters of 2021, this time focused exclusively on underrepresented minority students.

## Our Sponsors

**Eversource**

**Electric Power Research Institute (EPRI)**

**Housatonic Valley Association**

**ISO New England**

**National Aeronautics and Space Administration (NASA)**

**National Science Foundation (NSF)**

## Strategic Partnerships

The Center is continuing its collaboration with Bay State Wind Energy and Aquarion Water Company of Connecticut in 2021 in the areas of offshore wind resource characterization and water conservation.

### BAY STATE WIND ENERGY

Bay State Wind Energy has brought together Eversource and Ørsted, builder of the first and largest offshore wind farms in the world. The new partnership combines Ørsted's preeminent offshore wind development capability with Eversource's predominant presence in the Northeast, its industry-leading financial strength, and its expertise in regional transmission development. In 2019, the Center signed a sponsor research agreement to expand its activities beyond Eversource CT. This agreement approved support for an integrated research project that aims to enhance environmental monitoring and modeling capabilities for offshore wind energy generation.

### AQUARION

Aquarion Water Company of Connecticut, a subsidiary of Eversource, is the public water supply company for approximately 198,000 customer accounts, covering more than 625,000 people in 52 cities and towns throughout Connecticut's Fairfield, New Haven, Hartford, Litchfield, Middlesex, and New London counties. It is the largest investor-owned water utility in New England and among the seven largest in the United States. In September 2019, the Center and Aquarion began their partnership with a research project that aims to make available to water providers a mechanism for encouraging homeowners to reduce turf watering voluntarily.

**The Center has also established two new strategic partnerships.**

### ELECTRIC POWER RESEARCH INSTITUTE

The Electric Power Research Institute (EPRI) is an independent, nonprofit organization for public interest that conducts research on electricity generation, delivery, and use in collaboration with the electricity sector, its stakeholders, and others focusing on electric power safety, reliability, and affordability and the nexus between electric power and the environment. In 2020, the Center established a research collaboration with EPRI to provide complete and accurate information on the vulnerability of the electric grid to weather extremes and assess trends in power outages and efforts needed to maintain reliable energy delivery. We plan to demonstrate our methodology in 2021 over the northeastern United States, where our team has many years of outage and electric infrastructure data from Eversource Energy and the United Illuminating Company. In the summer of 2021, EPRI and the Center will present our pilot study to the EPRI member advisory board for extending this effort nationwide.

### UNIVERSITY OF ALBANY ATMOSPHERIC SCIENCES RESEARCH CENTER

The Atmospheric Sciences Research Center (ASRC), of the State University of New York at Albany, was established on February 16, 1961, by the Board of Trustees of the State University of New York as a SUNY systemwide resource for developing and administering programs in basic and applied sciences related to the atmospheric environment. In 2020, ASRC and the Center submitted a planning grant proposal to the National Science Foundation for the formation of an Industry-University Cooperative Research Center (IUCRC) for Weather Innovation and Smart Energy and Resilience (WISER) that will provide state-of-the-art weather and climate information, combined with leading-edge, industry-inspired research and development, to ensure reliable and resilient energy in the 21st century.

# Center by the Numbers

## Publications and Patents

Peer-reviewed 80

Patents 2

## Expenditures

2016 $998,059

2017 $2,158,683

2018 $2,423,839

2019 $2,454,938

2020 $2,156,234

## Awarded Amounts

2016–present $19,877,956

Pending proposals $22,873,516

## Students

Undergraduates 7

Graduates 36

Postdocs 2

Alumni 47

## Tropical Storm Isaias

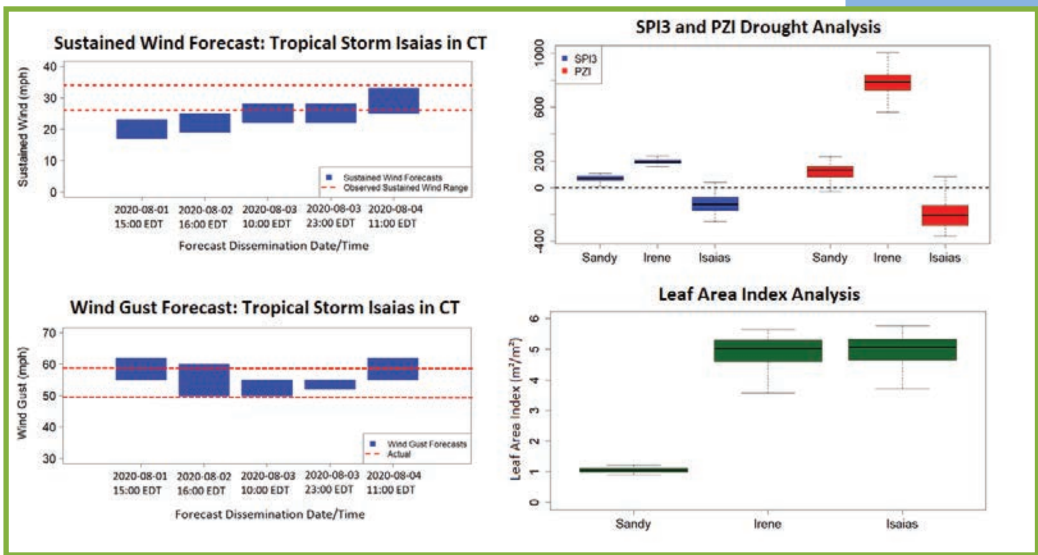
### OPM FORECASTS AND LESSONS LEARNED

Gypsy moth infestations and drought conditions in recent years have weakened trees throughout Connecticut to such an extent that forests were particularly vulnerable when the remnants of tropical storm Isaias swept through on August 4, 2020, causing extensive power outages related to tree damage.

The Eversource Energy Center issued five predictions to Eversource between August 1 and 4 for the utility company's territories across Connecticut, Massachusetts, and New Hampshire and four to AVANGRID for the United Illuminating service territory in Connecticut. Predictions were based on the UConn Outage Prediction Model (OPM), a state-of-the-art model that uses weather forecasts, land cover, vegetation and infrastructure characteristics, and historical outage records to predict the amount of damage a storm will inflict on the electric distribution system. In almost every case, the reports predicted significantly increasing storm severity across Connecticut, with the last predictions, released on the morning of August 4, indicating an extreme impact, in the range of 3,000 to 6,000 damage locations for Eversource Connecticut and 400 to 800 for United Illuminating.

Even given those increasingly ominous indicators, the storm's damage exceeded the OPM predictions across Connecticut by three- to fourfold, as strong winds blew through the state and non-meteorological factors became an unexpected part of the equation. An extreme drought affected the region in 2016, and, as of August 2020, unusually dry conditions persisted in much of the state. These conditions degraded the ability of many trees' root systems to withstand the sustained wind levels of a major weather event, particularly to the north. In addition, tree canopy defoliations resulting from gypsy moth infestations in 2016, 2017, and 2018 created vulnerabilities statewide.

Isaias also had unique characteristics that affected the OPM modeling outcome in several ways. Most particularly, the storm was disintegrating as it passed over the state, which caused higher sustained winds and microbursts in localized circulations across a widespread area. In these localized pockets, sustained winds exceeded the level experienced in both Hurricane Sandy in October 2012 and Hurricane Irene in late August 2011. At the same time, data included in the model from storms such as Sandy and Irene that were similar in magnitude to Isaias reflected significant meteorological differences between those storms and Isaias. Irene involved more precipitation than Isaias, and Sandy occurred later in the year. In midsummer, Connecticut's forests have the greatest leaf area exposed to the brunt of high winds, causing more tree and branch movement than when the leaf area is less. With drought conditions weakening the strength of root systems to an unprecedented extent, the combination of these factors caused the impact to be extreme. Moreover, the National Weather Service confirmed that a tornado, with a maximum wind speed of 95 to 105 mph, occurred in Westport, where power outages were extensive. Other small tornadoes and




**Temporal evolution of the wind and wind gust forecasts for Eversource Connecticut during the days preceding the impact of tropical storm Isaias in Connecticut (left) and comparison of two drought indices (the three-month Standardized Precipitation Index, SPI3, and the Palmer Z-Index, PZI) and the Leaf Area Index (LAI) for hurricanes Sandy and Irene and tropical storm Isaias.**

microbursts are suspected to have taken place in some locations, further indicating localized pockets of extreme winds.

Although this unusual confluence of conditions presented considerable challenges to outage prediction, Isaias has been a great catalyst for improvements to the UConn OPM. Based on the findings of preliminary research that the dryness of the soil greatly exacerbated the impacts of the storm, the OPM team is currently quantifying the effects of drought on the dynamics of weather-related power outages, as well as those of a wide range of vegetation characteristics. At the same time, the team is expanding in detail and sophistication the way in which we extract information from the meteorological characteristics of storms to enhance the description of extreme weather events for outage modeling. By incorporating these characteristics into our outage prediction model, the OPM team continues to innovate at the cutting edge of outage forecasting and environmental predictive analytics as applied to electric infrastructural systems.

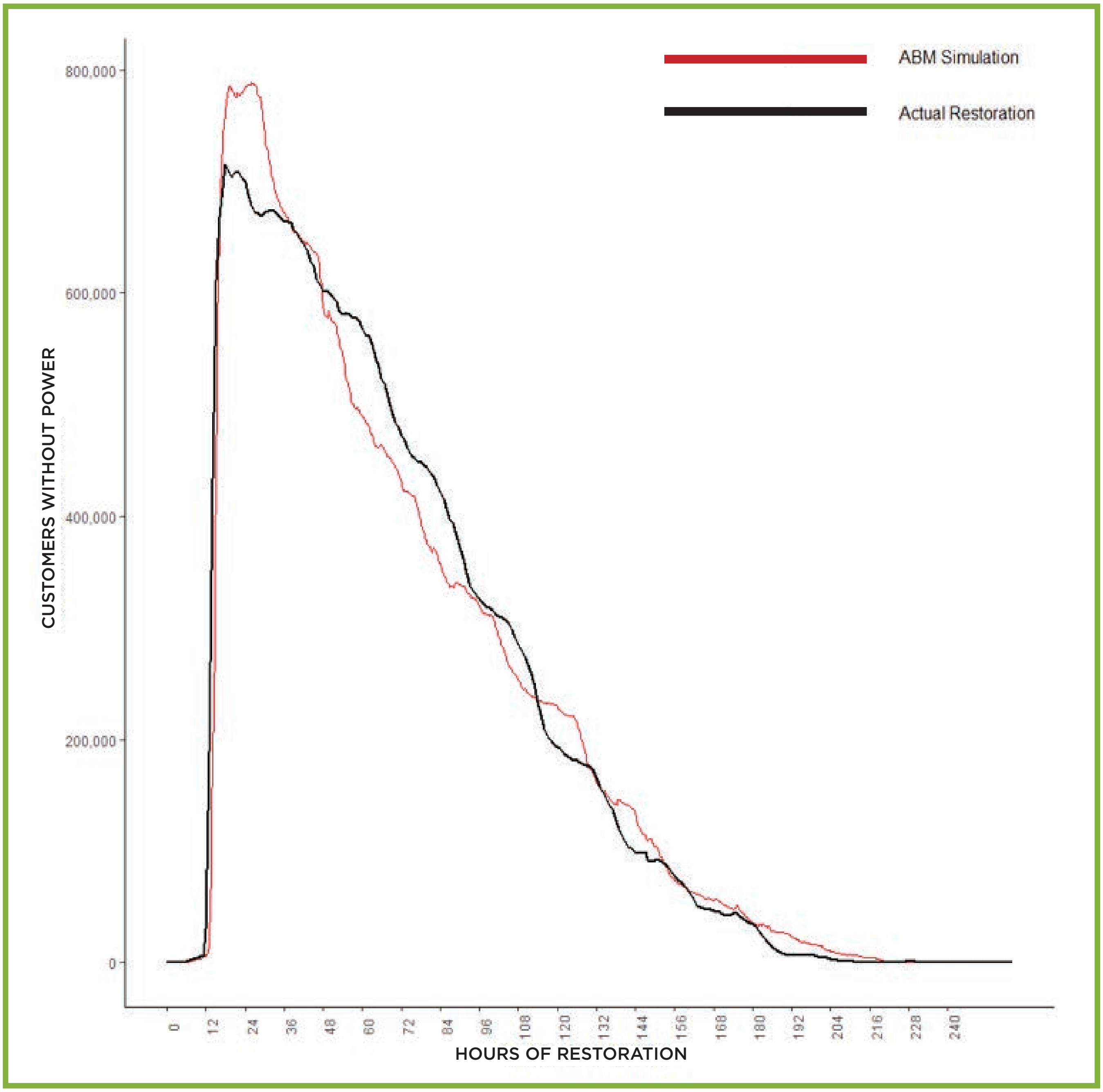
## Agent-Based Modeling to Test Restoration Decisions

Following extreme storms, power restoration by utility companies can take days or even weeks. The problem is complex, involving damage discovery and assessment, prioritization, and restoration, all happening in a post-storm emergency environment where travel can be impeded by blocked roads or difficult road conditions, crews working outside can be endangered by strong winds or freezing temperatures, and a limited number of crews is available to fix an unknown amount of damage.

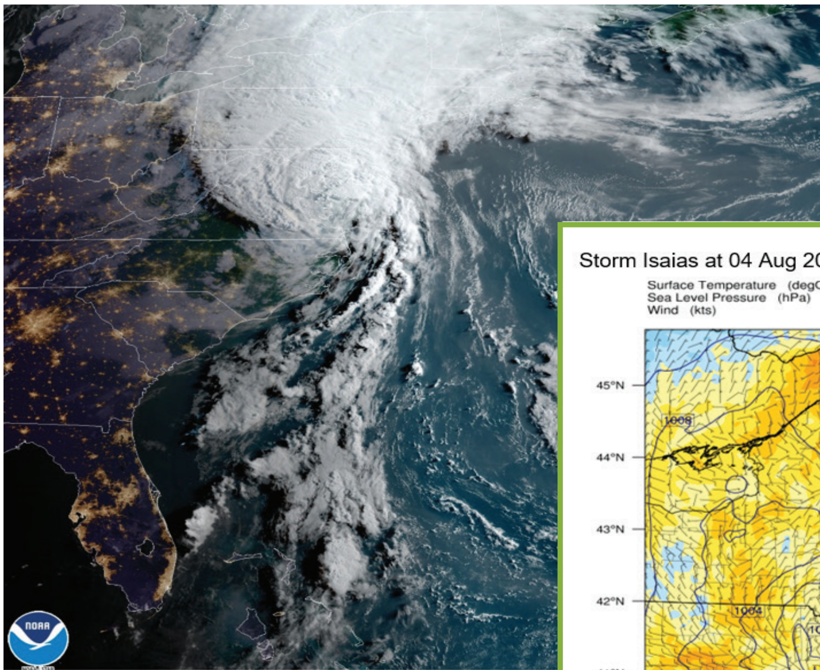
Computer simulations are an invaluable tool for testing the impact different decisions can have on restoration outcomes. At the Eversource Energy Center, we use agent-based modeling, a technique that simulates human decisions while also representing technical conditions. Our ABM provides a virtual environment where utility managers can test their restoration decisions before implementing them, or it can be used in real time to provide an estimate of the time to restoration, given available resources.

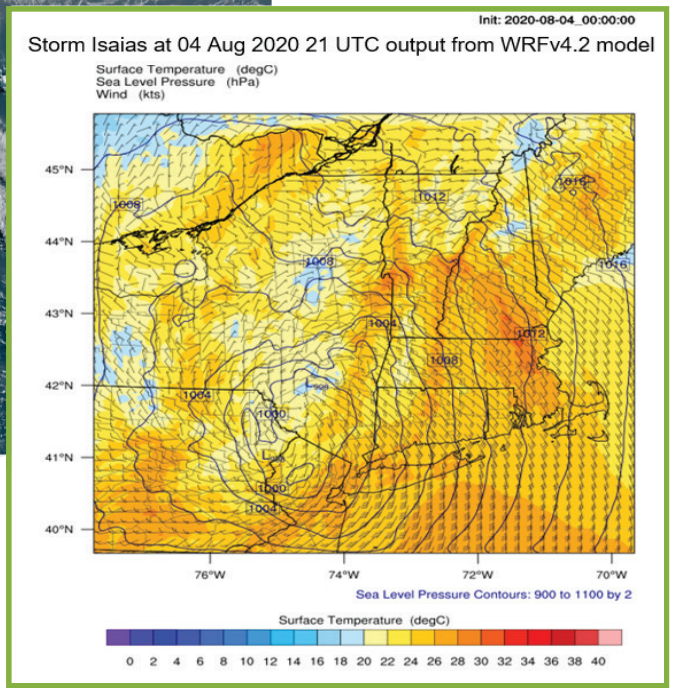
In the ABM, a set of agents (in this case, utility crews) is assigned a set of behavioral rules—regarding, for example, how to prioritize repairs, routes traveled between outages, rest periods, and so on—according to which they operate in the environment around them to effect the repairs. The user of the model then inputs and adjusts such parameters as individual outage repair times, number of crews working, outage assignment strategies, and crews working day or night. The goal is to include all the parameters relevant to restoration to study the impacts of each decision so the ABM can provide an estimate of the restoration curve, including estimated time to full restoration.

To date, the research team has used our ABM to recreate past storms, giving us a better understanding of the restoration process and helping us find the correct parameters to use in the model for storms of different magnitudes. The next step, now underway, is to identify and tune all the parameters to reproduce what actually happened with restoration during tropical storm Isaias in August 2020 and 20 additional storms. Having achieved this, we will be able to estimate the time to restoration in advance of any storm by running the ABM using forecasts of damage amounts and locations from the UConn Outage Prediction Model. This coupled system of outage prediction and restoration modeling will provide emergency managers with insights from an entire modeled storm, including weather forecasts, outage predictions, and restoration estimates, before the storm arrives. With the benefit of the complete system, they will be better prepared for extreme storms and scenarios not experienced before.




**Results of one ABM simulation (red line) compared to the actual tropical storm Isaias restoration (black line). The simulation assumes that the number of crews available for repairing outages increases from day 1 until the end of restoration. Assignments are split, with 65 percent of crews working during the day (6am to 10pm) and 35 percent at night. For the first 48 hours, 50 percent of crews are dispatched to random outages within 25 miles of their locations. The remaining crews are dispatched to the outage with the most customers affected for the first outage of the day, then are assigned to the nearest outage for the remainder of their shifts. At the beginning of the simulation, the ABM overestimates the peak number of customers without power. Continuing work on fine-tuning the parameters should result in a peak closer to the actual restoration curve.**






**Images of tropical storm Isaias, August 4, 2020: a satellite image from NOAA, the National Oceanic and Atmospheric Administration (left) and a forecast from the Weather Research and Forecasting model, WRF (right).**

## Extreme Weather Prediction for Emergency Response

The importance of predicting extreme weather events accurately is underscored by their severe effects on human lives, infrastructure, and the environment. According to the U.S. Department of Commerce, weather-induced blackouts in U.S. power distribution grids have caused over $1.5 trillion in damage since the 1980s. Impacts of weather events like Hurricane Irene (2011), Hurricane Sandy (2012), and, most recently, tropical storm Isaias (2020) highlight the need for improved disaster preparedness, response, and mitigation strategies.

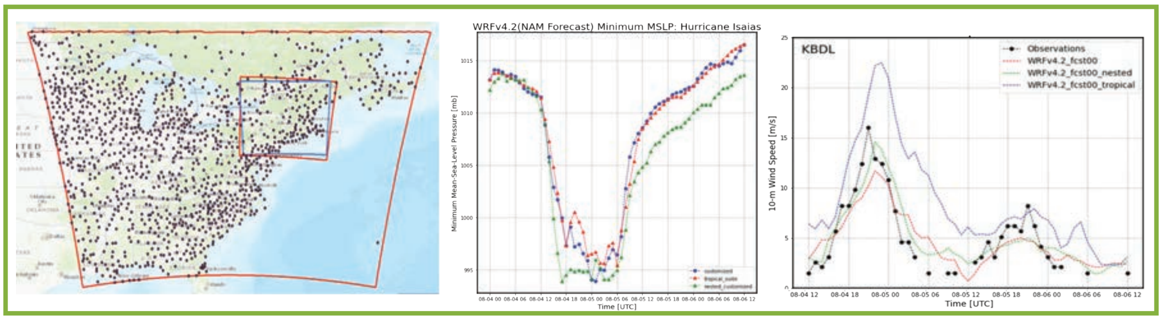
The outage prediction models (OPMs) developed by the Eversource Energy Center at the University of Connecticut use geographical data, data on attributes of the electric system, and, especially, numerical weather prediction (NWP) information to predict the impact of storms many days before they happen. The Extreme Weather Forecasting project, which began in May 2020, aims to assess the uncertainty and improve the accuracy of severe storm prediction using NWP models so we can, in turn, more accurately predict the number, location, and duration of power outages.

The Extreme Weather Forecasting project supports the needs of the Eversource Energy Center in the area of outage prediction modeling and emergency response. Its objective is to continue enhancing UConn's OPM capabilities to forecast distribution network outages from winter storms, extreme weather events, and thunderstorms.

**This new project has set out to achieve three main outcomes:**

- Revamping of in-house numerical weather prediction systems that are currently providing real-time forecasts four to five days ahead. These weather forecasts directly inform the OPM applications.
- Augmentation of our in-house predictions with real-time weather products from the National Weather Service (NWS) to quantify variability and uncertainty in storm forecasting.
- Continuation of our development of an online weather forecast verification platform so researchers and Eversource Energy managers can view successes and errors in weather forecasts in almost real time.

During the first six months of the project, we began to evaluate 24 high-impact rain and windstorms that took place in 2018–19 using




**Forecasting tropical storm Isaias: WRF model domains (left); minimum mean sea level pressure from three different model simulations (middle); and 10m wind speed for Bradley International Airport from observations and three different model simulations (right), with green lines showing the best model representation of the storm and the best forecast, respectively.**

updated versions of the Weather Research and Forecasting (WRF) model. We also evaluated the accuracy of forecasts of tropical storm Isaias, which devastated the state of Connecticut in August 2020. In the next phase of the project, these analyses will guide the selection of appropriate techniques to quantify uncertainty in storm forecasts and help us continue to improve the accuracy of our wind and precipitation predictions.

## Understanding Public Support for Vegetation Management

Trees are important to people. They provide shade, privacy, beauty, backdrops for recreation, and habitats for wildlife, and they contribute to improving air and water quality. When managing roadside vegetation, utility companies consider not just public safety and electric power reliability, but the many other reasons trees are important to people. The social science of human dimensions seeks to understand how people make decisions about natural resources like trees, and the characteristics of people that affect those decisions. As part of the Stormwise project at the Eversource Energy Center, a study in human dimensions is helping UConn researchers understand public concerns about and opportunities for roadside tree and forest management in urban, suburban, exurban, and rural communities across Connecticut.

From work in progress, we are learning how public support for different tree management strategies might vary depending on location within the Connecticut landscape. For the roadside forest, utility vegetation management involves tradeoffs between reliable electric power and tree preservation. How do people perceive these tradeoffs? To find out, we conducted a mail survey to evaluate the perceptions of residents in two areas of Connecticut. We also carried out a landscape analysis by using a geographic information system to assess information related to tree cover around each survey respondent's home.

By looking at the social survey data we collected from residents in the context of the landscape where they live, we found these residents, on the whole, had favorable attitudes toward the utility vegetation management process, and they generally understood the tradeoffs between having reliable power and protecting trees. Respondents generally also perceived that utility vegetation management improves public safety and minimizes power outages. However, they were more likely have favorable attitudes toward utility vegetation management if they had greater knowledge about trees, were more likely to believe that trees should be used for the benefit of humans, prioritized reducing power outages over preserving forest aesthetics, and considered change in roadside forests to be acceptable. The characteristics of tree cover around respondents' homes were not as strongly associated with their attitudes toward utility vegetation management.

The results of this study suggest individual attitudes toward vegetation management are likely based on the overall importance of trees to the individual rather than the characteristics of the trees around a resident's home. The existing diversity of public preferences provides opportunity to develop variability in approaches to roadside forest management.

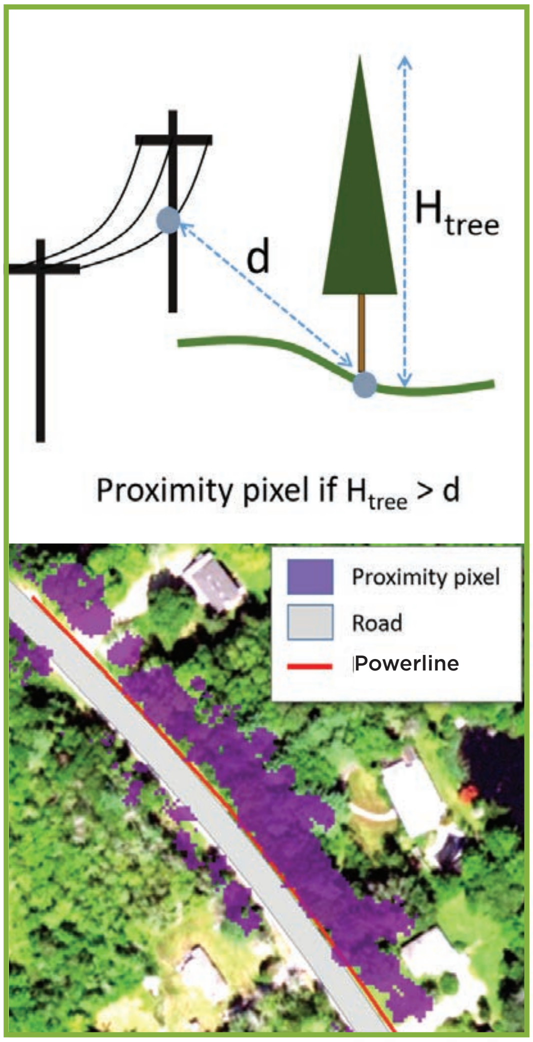
## Vegetation Risk Mapping through Remote Sensing Technology

Tree failure is a primary cause of storm-related power outages throughout the United States. In the forested Northeast, utilities report that damaged trees cause up to 90 percent of outages during storms.  Such recent storm events as Isaias, Sandy, and Irene, which struck the northeastern United States with near hurricane- and hurricane-force winds and heavy rain, resulted in widespread and prolonged outages affecting millions of people. In Connecticut alone, tropical storm Isaias caused outages for over 700,000 customers in August 2020, and Hurricane Sandy caused a similar number in 2012. In 2011, Hurricane Irene left approximately half a million customers in the dark. With storm activity expected to increase in conjunction with climate change, informed vegetation management programs for improving the resilience of the power grid have gained in importance.

Electric utilities spend billions of dollars annually on tree trimming to reduce forest risk to infrastructure. Two major factors can exacerbate this risk: the physical structure of trees and the state of their health. The physical structure of trees can affect both their exposure and their resistance to damaging winds. Those that mature in dense forest conditions tend to be poorly adapted to strong winds when they become exposed on a new forest edge. Tall trees that protrude above the forest canopy have more “sail” area than surrounding ones, and the greater leverage exerted by winds on their trunks increases the chance of uprooting or stem breakage. With respect to tree health, such stress factors as insects and disease can affect the vitality of forests significantly. Unhealthy trees are more likely to fall during storms.

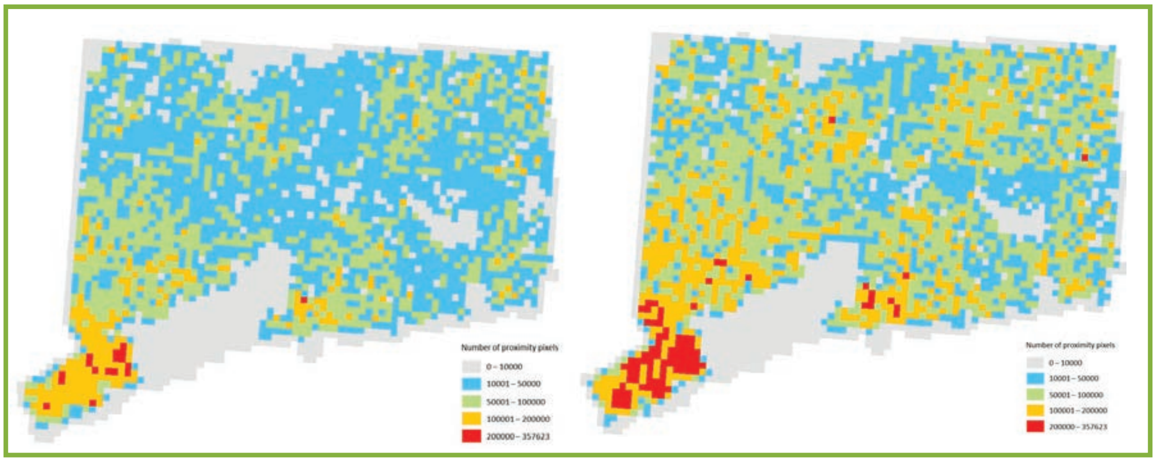
By using remote sensing technology, researchers at the Eversource Energy Center can monitor and assess both these aspects of tree and forest conditions across vast areas. Light Detection and Ranging (LiDAR) sensors can measure three-dimensional structural characteristics of tree crowns and forest canopies, while the optical imagery from satellites and aerial platforms can provide information on vegetation health. In our research, we have utilized publicly available statewide LiDAR data to develop a 3D tree canopy height model (CHM) for the entire state of Connecticut. The CHM has enabled us to identify “proximity pixels”—locations where trees are close enough to powerlines and tall enough to strike them during storms.

Our research will support efforts to improve the resilience of the electric grid to windstorm events by enabling Eversource to target more effectively the locations in greatest need of vegetation management and other resilience programs, to implement the most effective resilience strategies for given locations, and to justify mitigation strategies to regulatory agencies and the public.




**“Proximity pixels” are identified where the height of trees is greater than their distance from powerlines (top) and can be mapped along roads where powerlines are located (bottom).**

Based on these results, we have created a high-resolution proximity pixel map that covers the entire Eversource service area in Connecticut. To account for vegetation dynamics and tree growth over time, we have also extrapolated proximity model predictions, based on 2016 LiDAR data, for forecasting vegetation risk out to 2021.

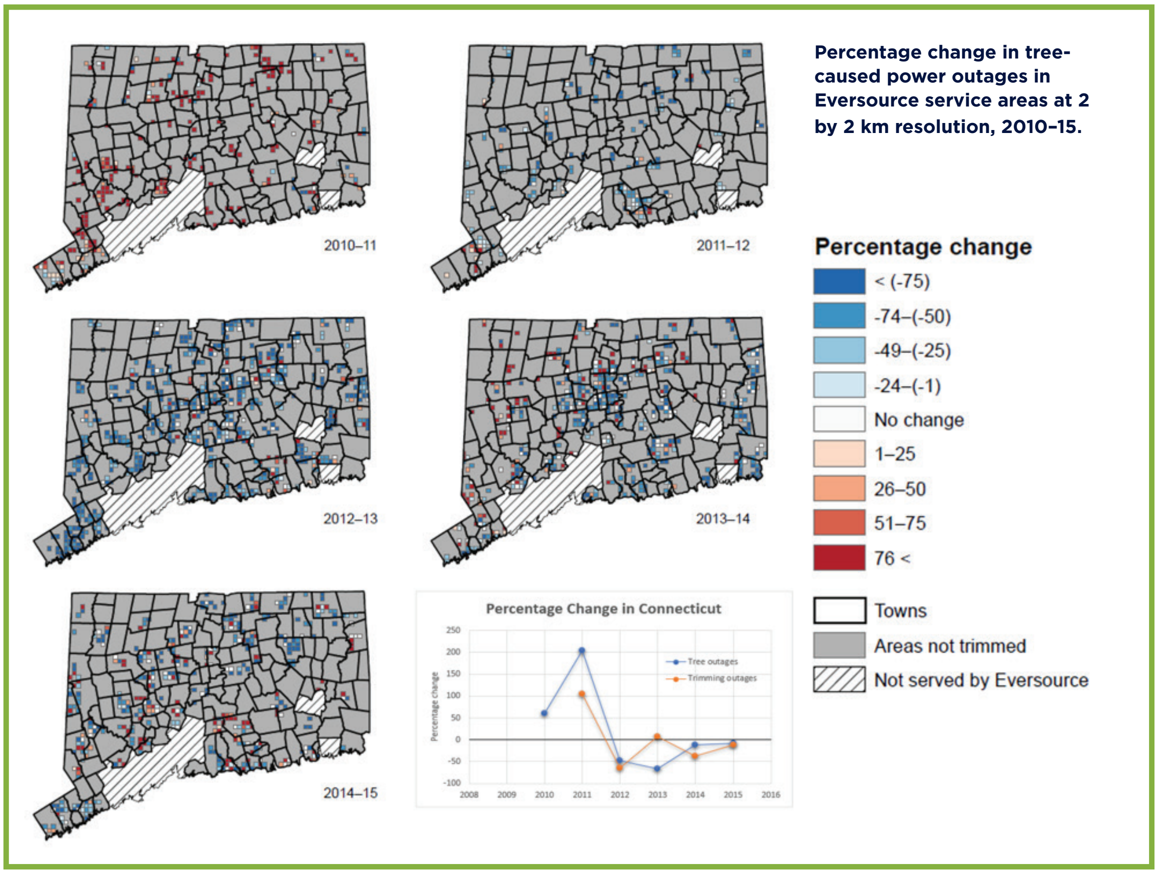



**Proximity pixel map based on 2016 LiDAR data (left) and extrapolated proximity pixel map for 2021 (right).**

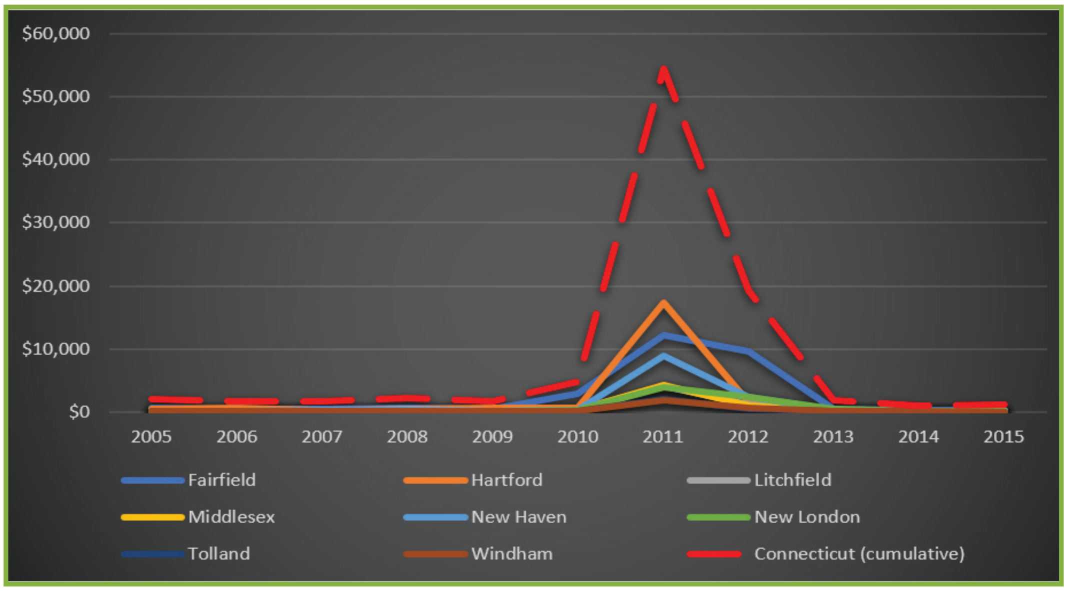
## Tree Trimming for Outage Reduction

### MEASURING THE BENEFITS

With more than half its land covered by trees, Connecticut relies on vegetation management processes (VMPs) for maintaining its powerlines and improving the reliability of its power grid. To Eversource, VMP operations are both vital and costly, especially as extreme weather events throughout the year increase in intensity with climate change. Understanding how much VMPs have helped enhance the resilience of the state's electricity and economic systems is essential to assessing the value of current operations and the potential for expanding them further; and paramount to gaining this understanding is the ability to quantify the technical and economic benefits of reducing the frequency and persistence of tree-related outages.




**Percentage change in tree-caused power outages in Eversource service areas at 2 by 2 km resolution, 2010–15.**




**Annual cost of outages five minutes or longer in Connecticut: county and state totals (in millions of fixed 2009 US$), 2005–15.**

In 2019, the UConn researchers investigating the sociotechnical and economic benefits of improved resilience focused their attention on assessing the effectiveness of VMP operations. First, they sought to ascertain how much past VMPs had reduced the occurrence and duration of outages. Working for the first time with highly refined data on outages and powerlines from 2011 to 2015, the researchers determined that conducting VMPs conferred substantial benefits throughout the entire network. They then applied these findings to inform the Regional Economics Model, Inc. (REMI), which allowed them to estimate how Connecticut's economy might react to changes in these operations.

The results of the analysis showed that, in terms of minutes without power, annual costs of outages to the state's economy from 2013 to 2018 were as high as $18 billion when extreme events, like Hurricane Sandy, hit the state. Although VMPs carried out by Eversource were expensive, the reduction in the frequency and duration of outages produced net benefits to electricity users amounting to $24 million per year. The operations also helped support thousands of jobs each year and increased the state's gross domestic product (GDP) by 0.14 percent, on average, and up to 0.28 percent when events like the 2018 nor'easter hit.

The combination of economic modeling with a technical analysis of VMPs by UConn researchers has been an absolute novelty. The approach has proved important to understanding the extent to which increasing the resilience of the power grid contributes economically to the state and to Eversource's customers.

| | AT OUTAGE MEDIAN DURATION | | AT OUTAGE AVERAGE DURATIONS | |
|---|---|---|---|---|
| | 2013-17 AVG | 2018 Nor'easter | 2013-17 AVG | 2018 Nor'easter |
| Jobs | 5,364 | 8,635 | 10,966 | 16,067 |
| GDP | 286 | 634 | 767 | 1,316 |
| Personal Income (current $) | 294 | 570 | 652 | 1,148 |
| Personal Income Taxes | 64 | 126 | 143 | 252 |
| CT Sales Tax | 13 | 28 | 34 | 59 |

Note: All monetary values are in 2005 fixed US$ unless otherwise noted.

**Annual average Connecticut benefits from TTO to Connecticut's economy at average and median outage durations (2013–19).**

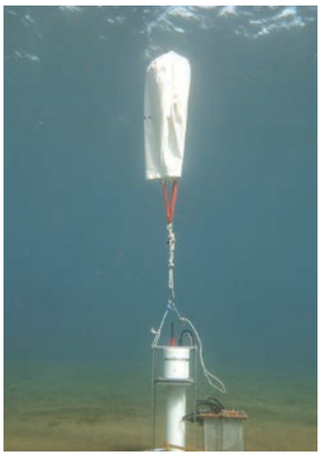
## Monitoring Wind and Waves from Satellites

To build and operate offshore wind farms, we need information. High-quality meteorological and oceanographic measurements over coastal and marine environments are crucial to decisions regarding their planning, siting, installation, operation, maintenance, and, eventually, decommissioning. Compared to onshore capabilities, however, typical monitoring of offshore wind (and wave) conditions tends to be sparse and expensive, relying on a real-time observing network consisting of wind towers, buoys, and regular reports from ships.

In recent years, however, a new generation of satellite missions has brought a dramatic increase in real-time observations over the near shore in both diversity and volume. With greater coverage, higher resolutions, and more frequent observation, we now have the potential to use these data to complement the observations gathered by the in situ observing network in offshore regions.

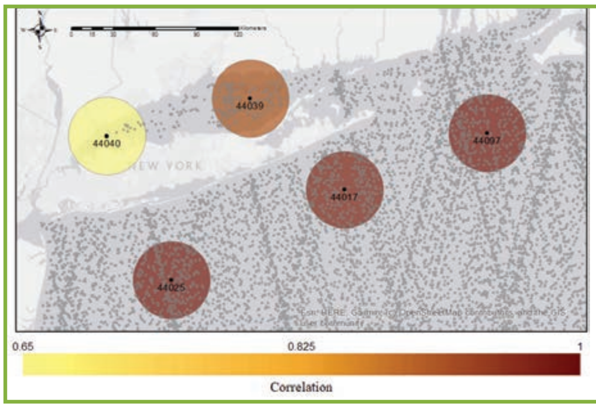
To take advantage of this opportunity, Eversource has funded a project at the Eversource Energy Center that will enhance our capacities to monitor and analyze offshore wind and waves in three domains:

**The deployment and use of new sensors, especially underwater.** Presently, the information we can gather underwater is very limited. To assess the technical viability and the environmental and biological risks of wind farm construction, we need to be able to collect data on and keep track of these conditions. Underwater data can help us evaluate and make adjustments for marine fauna and noise that could be harmful to it, facilitating both construction operations and compliance with federal regulations. To collect and analyze underwater background noise, we will be deploying in the offshore region of Massachusetts a passive acoustic sensor (PAL) built as part of this project.



**The passive acoustic sensor (PAL) to be deployed on the sea floor off Massachusetts.**

**The enabling of real-time collection and display of meteorological and oceanographic observing networks.** Traditional wind resource maps are needed for prospecting and planning for offshore wind farms, and research activities are needed to gather, assemble, perform quality control on, and organize historical wind and wave data from various sources. These include the National Renewable Energy Laboratory (NREL), which completed a national map of the mean annual wind resources in coastal waters and works with industry stakeholders for wind characterization at the local level; several observing and modeling studies funded by the Department of Energy and the National Aeronautics and Space Administration (NASA), which have provided a closer depiction of the wind resources in the New England Region for limited periods; and the National Buoy Data Center and several universities, including UConn, and research institutions that maintain a buoy network off the coast of Connecticut, Rhode Island, and Massachusetts.




**A comparison of buoy observations with satellite altimetry data, from a published study by UConn students. The color of the circle denotes the correlation.**

**The analysis and prediction of wind power ramps.** Wind power forecasting has proved an effective tool from both technical and economic perspectives for facilitating the integration of wind power into the electric grid. Ramping—the rate of change of wind power—is of concern to power grid operators, but skills in detecting and predicting power ramps are low. We are conducting a time series analysis of power and wind from the Block Island wind farm as a reference to implement and evaluate ramp prediction methods and compare observations to models to determine—and eventually improve—the skill of prediction.

## High-Resolution Wind Forecasting

According to a 2017 report by the National Renewable Energy Laboratory (NREL), many offshore wind sites that promise considerable economic potential by 2027 are located off the northeastern United States and the eastern shore of Virginia. A lack of high-quality atmospheric measurements over coastal and oceanic environments presents a challenge, however, for the siting, operation, and maintenance of offshore wind energy farms.

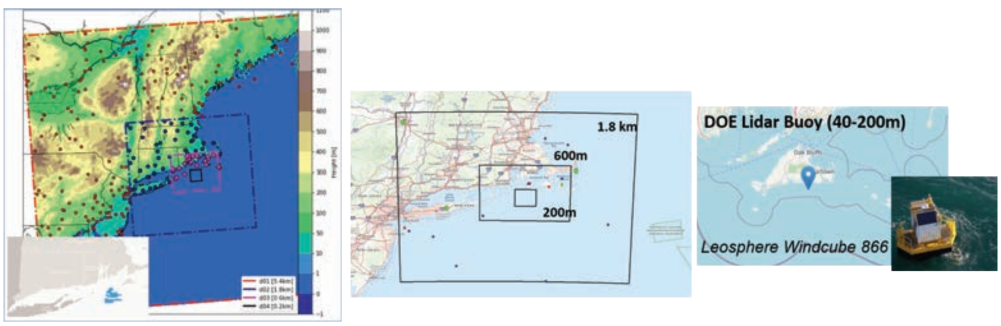
In particular, highly accurate information is needed at the level of the turbine rotor blades, generally 50–200 meters above mean sea level (MSL), where the wind often behaves differently than it does within 10 meters of the surface. To fill the gap left by inadequate measurements, numerical weather prediction (NWP) models are used to forecast atmospheric conditions over offshore areas of interest at fine spatial and temporal scales.

The Eversource Energy Center's High-Resolution Wind Prediction project aims to enhance current capabilities by developing a system that simulates localized winds at high spatial resolution for Eversource's offshore wind facility in the Northeast Atlantic cluster. In progress since January 2020, the project has three main objectives: to develop high-resolution wind prediction capabilities for the Eversource facility, to assess the accuracy of this system, and to provide recommendations to optimize the configuration of the model and improve its skill in forecasting wind conditions.

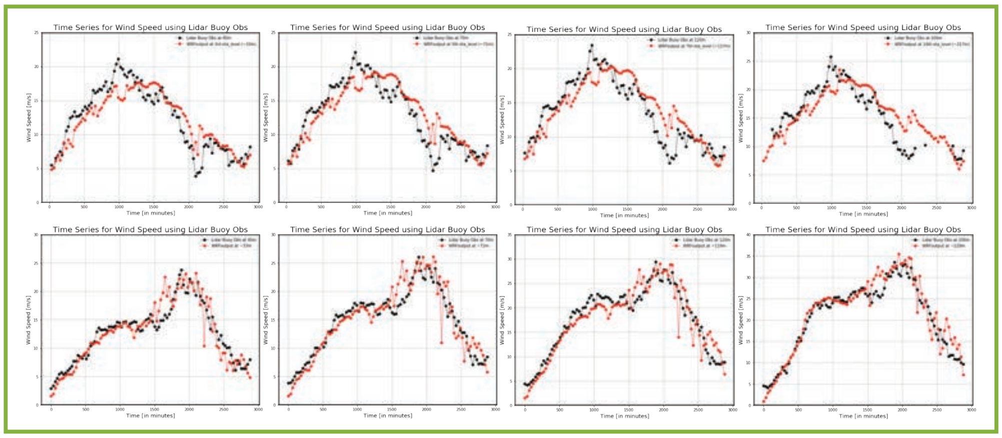
During the first year of the project, we tested multiple NWP model configurations. The underlying physics, dynamics, and numerical approximations, plus the computational cost, present great challenges to the ability of NWP models to describe atmospheric conditions accurately at such fine resolution. Furthermore, the lack of routine offshore atmospheric measurement for comparison purposes hinders the ability to evaluate and assess the model's performance.

In January 2020, as we began our project, an important new resource became available with the deployment by the U.S. Department of Energy (DOE) of a LiDAR (Light Detection and Ranging) buoy off of Martha's Vineyard that provides measurements of wind at various heights up to 200 meters above the sea surface. The data from the buoy are extremely valuable for the model evaluation we are undertaking.

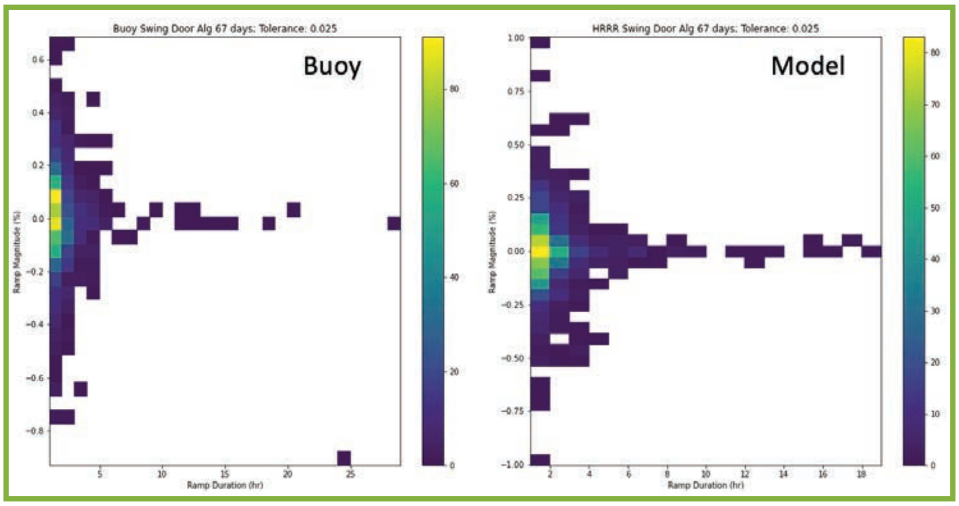
To date, we have analyzed ten cases of various wind conditions and have used onshore and offshore atmospheric observations to evaluate the performance of the model. The offshore evaluation using LiDAR buoy data shows the model is capable of accurately representing wind speed offshore. In the next phase of the project, we will continue to analyze new simulations of additional atmospheric conditions and will provide recommendations for optimal wind prediction in the offshore environment.




Model domains centered on the location of the proposed South Fork Wind Farm (left); location of available offshore observations within the NWP model domains, with a red star showing the location of DOE's LiDAR buoy (middle); and a closeup of the LiDAR buoy and its location (right).




Two of the ten wind speed cases simulated by the model for 2020. The upper row shows the wind speed evaluation for March 6–8, and the lower row shows April 12–14. Model data from the 600m domain are indicated by the red lines and observations from the LiDAR buoy at 40m, 70m, 120m, and 200m above sea level by the black lines.




**Bivariate histograms of wind ramps in observed (buoy) data and model data.**

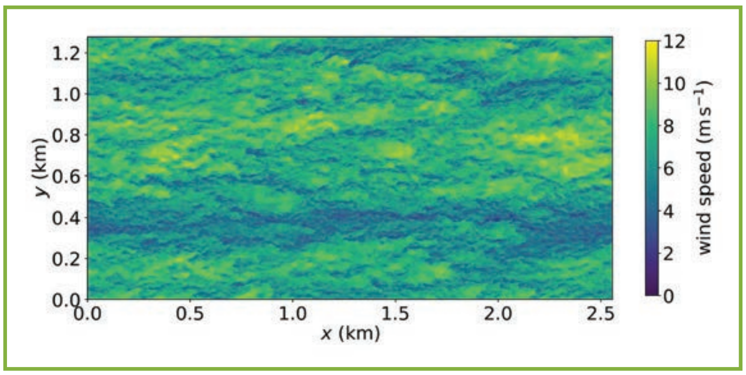
## Simulating Turbine-Level Wind Profile and Turbulence

Offshore wind is an abundant energy resource with significant environmental and economic benefits, but as a natural resource, it is variable. At the Eversource Energy Center, the Marine Boundary Layer Modeling project aims to improve the design and operation of wind farms by better characterizing meteorological conditions at the wind-farm scale.

Researchers at the Center are currently developing a high-fidelity, high-resolution computational model that is capable of simulating the atmospheric motions around individual wind turbines. Extending UConn's Large-Eddy Simulation (LES) model to include these motions will enable it to capture the interaction of individual turbines with the turbulent atmosphere. This newly developed capability will allow us to investigate the dependence of overall power output on environmental conditions and the characteristics of the wind farm, such as the type of wind turbines and their relative positioning.

The key advantage of the LES modeling is its accurate representation of atmospheric turbulence near the ground or the ocean surface. The interaction of the atmosphere with the surface, including wind shear and the effects of temperature differences between the atmosphere and the ocean, results in a rich spectrum of atmospheric motions, which depend on local meteorological conditions and directly affect wind power extraction and equipment maintenance operations. The fluctuations in wind speed and direction caused by such turbulence lead to variations in the available wind power and generate alternating forces on the turbines. High-wind-speed bands forming near the surface, for example, cause repetitive forces that can shorten the lifespan of the turbines. By helping us understand better the distinct characteristics of near-surface atmospheric turbulence, LES modeling can lead to improvements in design and maintenance operations that will lengthen the turbine lifespan.

A limitation of the LES modeling is the relatively small area—about 10 to 20 kilometers—that is simulated. To address this, researchers from the Center's Weather Research and Forecasting project are running simulations on their larger-area WRF model to provide input about meteorological conditions to the LES model. The Marine Boundary Layer Modeling project showcases the multi-scale modeling capabilities at the Eversource Energy Center by using this combination of models to simulate and predict meteorological conditions and atmospheric turbulence, from the regional scale to the wind-turbine scale.




**A snapshot of the wind field at 80m height, simulated by UConn's Large-Eddy Simulation (LES) model.**

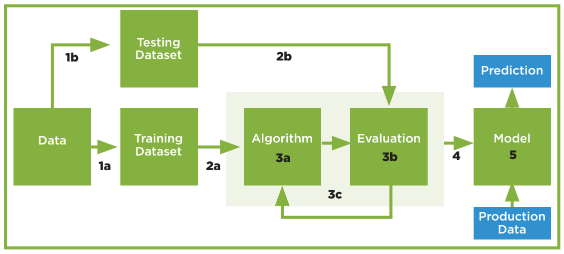
## Preparing for the Grid of the Future

### UCONN'S NEW GRID MODERNIZATION CERTIFICATE PROGRAM

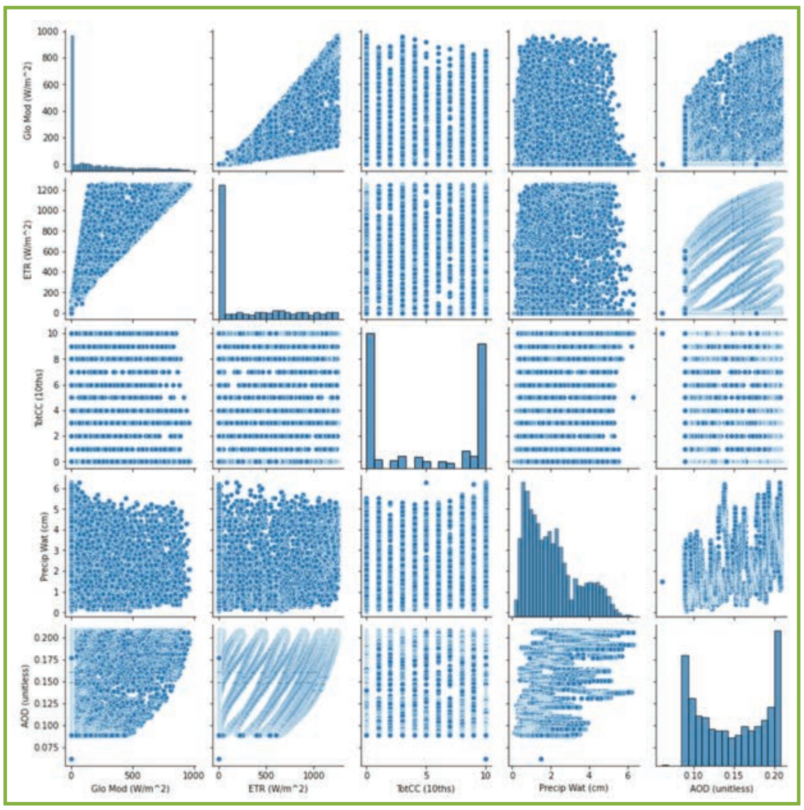
In terms of infrastructure change and public impact, grid modernization of the electric power system represents one of the largest investments and most consequential projects for utilities in the United States. The modernization effort envisions a more resilient, secure, sustainable, and reliable grid that will allow for an array of emerging services while remaining affordable to customers. It involves installing a physical framework on an existing system, optimizing the network, and processing new, large flows of monitoring data.

The proposal of a Power Grid Modernization Graduate Certificate by the Eversource Energy Center at the University of Connecticut grew from the specific need of the utility industry to prepare for its transition to the grid of the future by providing training each year to cohorts of early-career engineers on the technical aspects of grid modernization. Based on this need, the EEC designed a certificate program that increases human expertise on predictive analytics, microgrids, communication systems, and distribution management systems to enable higher-level control functions and schemes to manage the increasing levels of distribution energy resources (DER) penetration. These four courses in the study plan cover the fundamentals required to address industry's new challenges: integrating renewable energy sources into the grid; predicting future electricity demands, capacity, smart grid designs, and operations; and confronting issues surrounding physical and cyber security.

The certificate program kicked off in Fall 2020 with the predictive analytics course, provided entirely online. A dozen enrollees from utility companies took this three-credit, graduate-level course to gain expertise on methods for processing datasets related to grid modernization, weather, and renewable energy. The course featured a hands-on approach to machine learning, ranging from standard regression methods to deep-learning methods and covering a wide spectrum of applications. The training also included a team final project, which students developed throughout the semester on topics of their choice. In total, eleven projects on various topics pertaining to grid instability, renewable energy, anomaly detection, and power outage were developed and successfully carried out with the help of the two Eversource Energy Center instructors and a graduate teaching assistant.

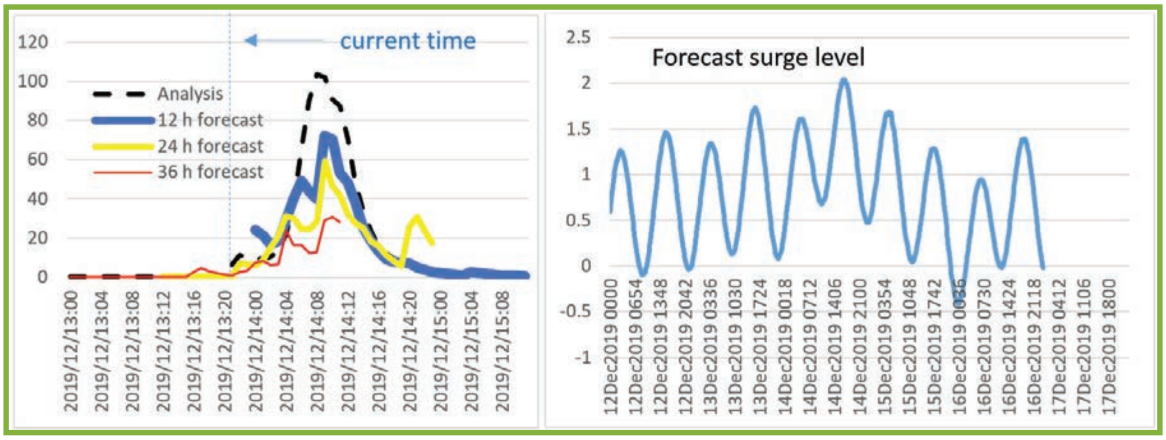



**IEEE 123 bus test grid. The diagram shows the distribution of power flows through the grid to consumers. "Eavesdropping" on the power grid can provide data on power loads to the different nodes, which a would-be cyber intruder can then analyze to determine how and when to manipulate the power loads through the botnet.**




**Pairwise relationships in a dataset used by one team to predict solar irradiance in an unspecified PV location. Solar irradiance (Glo Mod) is the predictant, whereas Extra-Terrestrial Radiance (ETR), Total Cloud Cover (TotCC), Precipitable Water (Precip Wat), and Atmospheric Optical Depth (AOD) are predictors of solar irradiance in this problem.**

## Inundation Prediction to Protect Substations

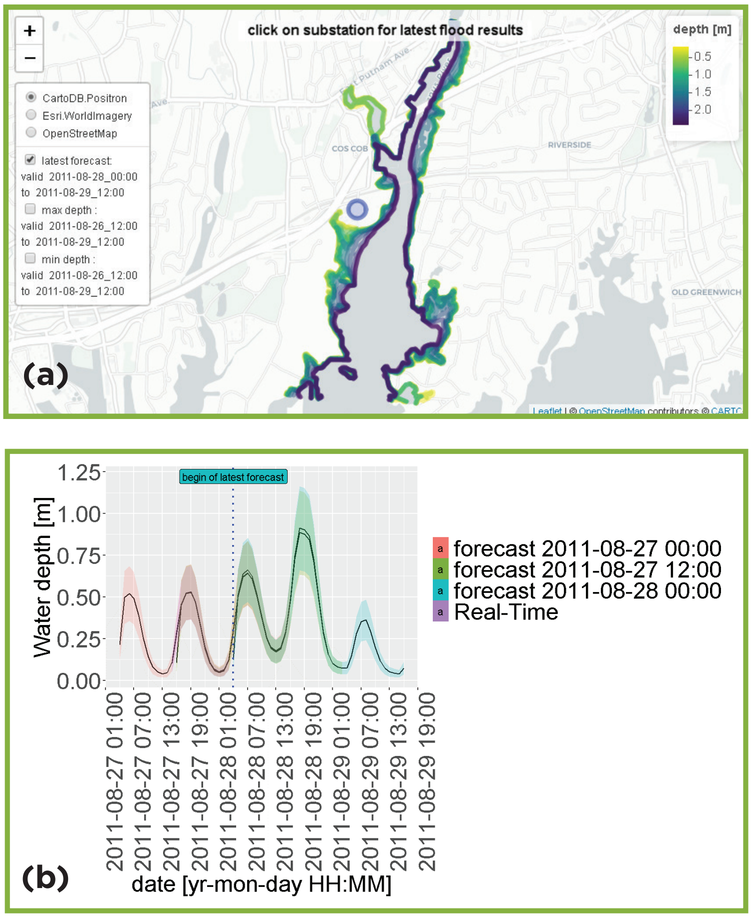



River flow and storm surge forecast, showing river flow (left) and coastal water level (right) compromised by surge and tide at one coastal substation.

The goal of the Eversource Energy Center's flood vulnerability project is to provide real-time forecasts of inundations at Eversource substations in Connecticut up to 36 hours in advance of incoming storms by integrating existing weather forecast data and hydrological and hydraulic models. The most recent phase of the project has fulfilled the previous plan of implementing a real-time forecast system based on the modeling framework, developed in the first two phases, that is used to estimate long-term risk based on past extreme weather events or long-term weather records.

To predict flood inundation, we need to use as inputs forecasts of upstream river flow and coastal storm surge water levels. The forecasts of river flow are generated by our distributed hydrological model and the storm surge water levels by spatially interpolating forecasts of storm surge by the National Oceanic and Atmospheric Administration (NOAA). Our system uses these inputs to run a hydraulic model at ultrafine resolution (1m) to generate the final predicted flood maps, including flood extent and depth. The system issues real-time forecasts at midnight and noon every day and updates the results on a webpage maintained by the Eversource Energy Center.

This is the first system that forecasts ultrafine-resolution inundation maps in real time for critical substations in the state of Connecticut. The capability it provides will help Eversource take measures to protect these substations before flooding happens.




Inundation forecast for Hurricane Irene, as visualized on the website of the CREST-SVAS and HEC-RAS forecast systems. The figures indicate inundation extent (a) and the time series of water depth at one substation (b).

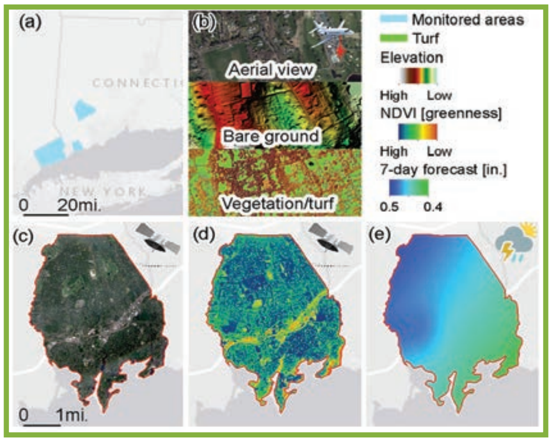
## Water Conservation through Decision Support

The average American family uses 320 gallons of water a day. About 30 percent is devoted to outdoor uses, and more than half of that goes to watering lawns and gardens. Nationwide, landscape irrigation is estimated to account for nearly one-third of all residential water use, totaling almost 9 billion gallons a day, with an associated burden on energy producers.

The high demand from excessive watering of turf during the summer months has made Connecticut and other regions vulnerable to water shortages, requiring providers to impose mandatory restrictions on the practice. To help meet this challenge, a UConn team is developing a decision support system for irrigation management that will make it easier for customers to participate in incentive programs for managing water and energy demand. Our specific focus is on variable rate irrigation, using a series of databases that include information on remote sensing imagery, observed and predicted weather, and local turf characteristics to determine where and when watering is—or is not—needed.

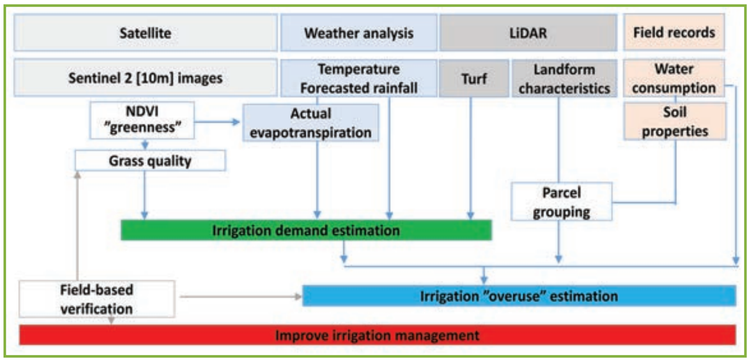
The Eversource Energy Center's Decision Support System for Variable Rate Irrigation (DSS-VRI) provides a way for the turf to tell people when it needs water. Through the automated, near-real-time integration of observations from satellite and weather forecasts, the system generates data and information in formats that are convenient for customers, water managers, and others to use. Combined with water consumption data, the results can provide a basis for predicting weekly turf water requirements over large areas to identify customers whose high water use makes them good candidates for conservation.

For some customers who use a lot of water to irrigate turf, reducing a single day of their usage levels can have a significant impact on system demand. The DSS-VRI would reduce the total volume of water used during the summer

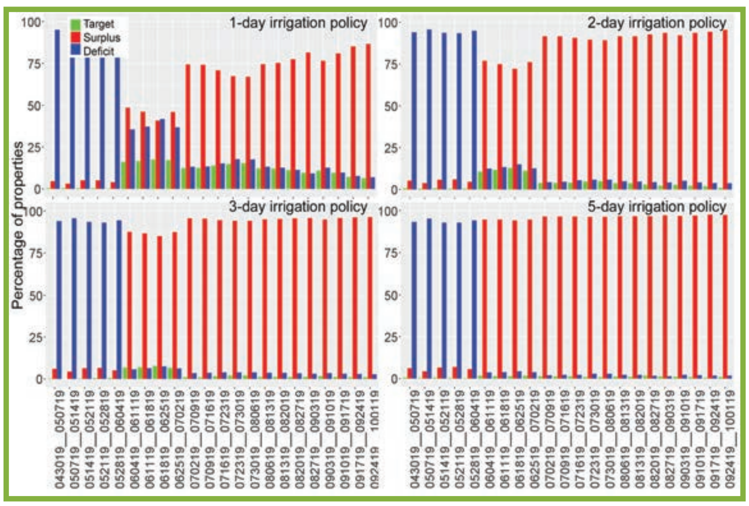



**Turf water requirements depend on the state of the grass (canopy properties) and the weather (potential evapotranspiration). The UConn researchers developed relationships between turf water use and canopy properties for six cities in Connecticut (a). They used LiDAR data to map the turf extent for each city at very high detail (b). Using Sentinel 2 images (c), they also developed relationships between canopy cover and vegetation indices (d). These relationships, together with weather data, enabled the estimation from the satellite data of actual evapotranspiration, and then the prediction of weekly turf water requirements over large areas based on weather forecasts (e).**

**NOTE:** The examples in panels (c) to (e) refer to the city of Darien, Connecticut. Panels (c) and (d) are based on a cloud-free composite Sentinel 2 image from the weeks of June 20, 2019, to July 9, 2019, while (e) shows a weather forecast based on forecasts issued by the National Oceanic and Atmospheric Administration (NOAA) on July 9, 2019.

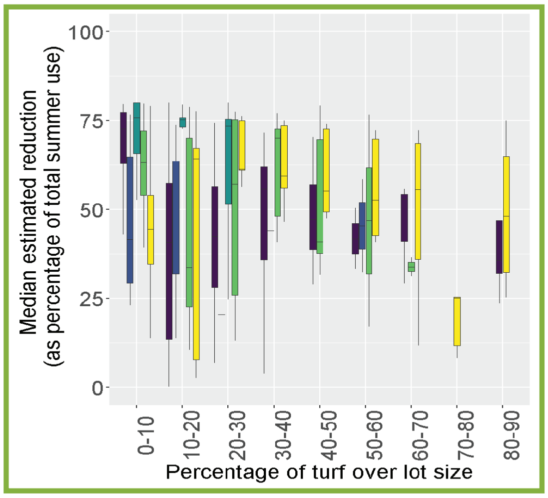



**The DSS-VRI in schematic form. The diagram shows the interplay among different datasets and processes in the model.**




**Percentages of customer properties whose water consumption estimates are close to actual turf needs, plus or minus 20 percent ("Target"), whose usage is excessive ("Surplus"), and whose usage is insufficient for the turf needs "Deficit" for irrigation schedules of one, two, three, or five days per week. Data are shown per week, from April 30, 2019, to October 1, 2019 (labels on x-axis show starting and ending days of the week in mmddyy).**

by about 8 percent for the six Connecticut cities included in the study. Households, on average, could reduce their summer water use by 20 to 40 percent, or nearly 10,000 gallons annually, providing a significant savings of both water and energy for Connecticut and any other regions that adopt the system.




**Water-saving prediction as a result of the DSS-VRI. The graph indicates the median estimated reduction in summer outdoor water use per class of customer by turf extent. Savings vary by class of customer and turf extent within each property. Overall, the proposed method would reduce the total summer water volume of the six cities by about 8 percent.**

- Commercial
- Industrial
- Public authority/ Government
- Residential (multi)
- Residential (single)

## Renewable Energy Microgrid Design for Rural Ethiopia

In the rural regions of Ethiopia, where agriculture is the main driver of the economy, long periods of drought can have severe food security and economic consequences. A collaboration of undergraduate and graduate students from various engineering disciplines and social sciences at the University of Connecticut sought to address this problem by designing a microgrid for rural Ethiopia, employing renewable energy sources (solar and hydropower) and taking into consideration the social needs of local farming communities that reside in the country's smallest administrative units, or *kebele.*

The project focused specifically on the Kudmi *kebele*, where irrigation water originates at a nearby artificial reservoir on the Koga River and is carried by an irrigation canal system to local farming sites. By estimating Kudmi's electricity demand and irrigation water needs, the research team was able to simulate a groundwater pumping schedule to supplement reservoir irrigation for a variety of crops cultivated by local farmers, such as wheat, maize, potatoes, cabbage, tomatoes, peppers, and avocados. The HOMER (Hybrid Optimization of Multiple Energy Resources) software was then used to simulate the distributed energy resources and create a realistic energy demand plan for four different usage scenarios.

Meanwhile, in a parallel interdisciplinary investigation, the sociology team conducted fieldwork interviews to assess the social needs of local communities, as well as the potential impact of the microgrid on them. Conversations with district energy and water experts, agricultural administration officials, and local farmers provided information about the most frequently used appliances and cooking schedules for the average household. They found that many local people hold positive attitudes toward the microgrid implementation and welcome the social benefits it would provide, such as better lighting, access to information, and job opportunities.

Overall, the study examined the sustainability of the microgrid as an energy source that supports farming activities by providing power for irrigation groundwater pumping, with the excess generated energy made available for community needs, such as heating, lighting, and cooking. In addition to enhancing food and health security, the system has the potential to improve the general quality of life in rural Ethiopia. Upon installation of such a microgrid, future studies may focus on the social dynamics and resulting new habits of local people, in order to optimize its performance and tailor its service to specific community needs.

*A paper on the project been accepted for publication in the July 2021 issue of the peer-reviewed journal,* ***Sustainability.***

## Patents

Anagnostou, E. N., D. Wanik, B. Hartman, and J. He: Systems and Methods for Outage Prediction, U.S. Application No. 16/317,354.

Shen, X., E. N. Anagnostou, and Q. Yang: System and Methods to Produce High Resolution Flood Maps in Near Real Time. Provisional U.S. Patent.

## Bibliography

### 2021


Emmanouil, S., E. I. Nikolopoulos, B. François, C. Brown, and E. N. Anagnostou. 2021. "Evaluating Existing Water Supply Reservoirs as Small-Scale Pumped Hydroelectric Storage Options: A Case Study in Connecticut." *Energy* 226 (July 1). https://doi.org/10.1016/j.energy.2021.120354.

Emmanouil, S., J. Philhower, S. Macdonald, F. K. Khadim, M. Yang, E. Atsbeha, H. Nagireddy, N. Roach, E. Holzer, and E. N. Anagnostou. 2021. "A Comprehensive Approach to the Design of a Renewable Energy Microgrid for Rural Ethiopia: The Technical and Social Perspectives." *Sustainability* 13 (7): 3974. https://doi.org/10.3390/su13073974.

Gallaher, A., M. Graziano, and M. Fiaschetti. Forthcoming. "Spatial Analysis of Grid Optimization in Connecticut: Quantifying the Relationship between Tree-Trimming Operations and Tree Related Power Outages." *Energy Policy.*

Hughes, W., W. Zhang, A. Bagtzoglou, D. Wanik, O. Pensado, H. Yuan, and J. Zhang. 2021. "Damage Modeling Framework for Resilience Hardening Strategy for Overhead Power Distribution Systems." *Reliability Engineering and System Safety* 207 (March), art. 107367.

Khanam, M., G. Sofia, M. Koukoula, R. Lazin, E. I. Nikolopoulos, X. Shen, and E. N. Anagnostou. 2021. "Impact of Compound Flood Event on Coastal Critical Infrastructures Considering Current and Future Climate." *Natural Hazards and Earth Systems Sciences* 21:1–19. https://doi.org/10.5194/nhess-21-1-2021.

Lazin, R., X. Shen, and E. N. Anagnostou. Forthcoming. "Predicting Flood Damaged Crop Lands Using Convolutional Neural Network (CNN)." *Environmental Research Letter.*

Li, X., P. Mitsopoulos, Y. Yin, and M. Peña. 2021. "SARAL-AltiKa Wind and Significant Wave Height for Offshore Wind Energy Applications in the New England Region." *Remote Sensing* 13 (1): 57. https://doi.org/10.3390/rs13010057.

Ma, X., W. Zhang, A. Bagtzoglou, and J. Zhu. 2021. "A Local System Modeling Method for Resilience Assessment of Overhead Power Distribution System under Strong Winds." *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering* 7 (1).

Shen, X., C. Cai, Q. Yang, E. N. Anagnostou, and H. Li. 2021. "COVID-19 Pandemic in the Flood Season." *Science of the Total Environment* 755, part 2, art. 142634, DOI:10.1016/j.scitotenv.2020.142634.

Walters, M. S., J. Yang, and M. Astitha. Forthcoming. "Winter Weather Prediction Accuracy for Impactful Snowfall Events in the NE US." *Weather and Forecasting.*

Yang, Q., X. Shen, E. Anagnostou, J. Eggleston, and A. Kettner. 2021. "An Unprecedented High-Resolution Inundation Dataset Delineated from SAR over the CONUS—from 2016 to Present." *Bulletin of the American Meteorological Society.* Published online February 18, 2021. DOI: https://doi.org/10.1175/BAMS-D-19-0319.1


### 2020


Alpay, B., D. Wanik, P. Watson, D. Cerrai, G. Liang, and E. N. Anagnostou. 2020. "Dynamic Modeling of Power Outages Caused by Thunderstorms." *Forecasting* 2 (2): 151–62. https://doi.org/10.3390/forecast2020008.

Bhuiyan, M. A. E., C. Witharana, and A. K. Liljedahl. 2020. "Use of Very High Spatial Resolution Commercial Satellite Imagery and Deep Learning to Automatically Map Ice-Wedge Polygons across Tundra Vegetation Types." *Journal of Imaging* 6 (12): 137.

Bhuiyan, M. A. E., C. Witharana, A. K. Liljedahl, B. M. Jones, R. Daanen, H. E. Epstein, K. Kent, C. G. Griffin, and A. Agnew. 2020. "Understanding the Effects of Optimal Combination of Spectral Bands on Deep Learning Model Predictions: A Case Study Based on Permafrost Tundra Landform Mapping Using High Resolution Multispectral Satellite Imagery." *Journal of Imaging* 6 (9): 97.

Cao, Yang, T. Shahsavarian, E. N. Anagnostou, and R. Kalbfleisch. 2020. "Novel Modulated Equivalent Model of Point-to-Point LCC-Based High Voltage AC/DC/AC System for Geomagnetic Storm-Induced Unbalanced Harmonic Studies." *International Journal of Electrical Power and Energy Systems* 122 (November), art. 106173.

Cerrai, D., M. Koukoula, P. Watson, and E. N. Anagnostou. 2020. "Outage Prediction Models for Snow and Ice Storms." *Sustainable Energy, Grids and Networks* 21, art. 100294. https://doi.org/10.1016/j.segan.2019.100294

Cerrai, D., X. Shen, Q. Zhang, and E. N. Anagnostou. 2020. "Brief Communication: Hurricane Dorian: Automated Near-Real-Time Mapping of the 'Unprecedented' Flooding in the Bahamas using Synthetic Aperture Radar." *Natural Hazards and Earth Systems Sciences* 20 (5): 1463–68. https://doi.org/10.5194/nhess-20-1463-2020.

Che-Castaldo, J., O. R. Jones, B. E. Kendall, J. H. Burns, D. Z. Childs, T. H. G. Ezard, H. Hernandez-Yanez, D. J. Hodgson, E. Jongejans, T. Knight, C. Merow, S. Ramula, I. Stott, Y. Vindenes, H. Yokomizo, and R. Salguero-Gómez. 2020. "Comments to 'Persistent Problems in the Construction of Matrix Population Models.'" *Ecological Modelling* 416, art. 10891. https://doi.org/10.1016/j.ecolmodel.2019.108913.

Couvreux, F., E. Bazile, Q. Rodier, B. Maronga, G. Matheou, M. J. Chinita, J. Edwards, B. J. H. van Stratum, C. C. van Heerwaarden, J. Huang, A. F. Moene, A. Cheng, V. Fuka, S. Basu, E. Bou-Zeid, G. Canut, and E. Vignon. 2020. "Intercomparison of Large-Eddy Simulations of the Antarctic Boundary Layer Challenged by Very Stable Stratification." *Boundary Layer Meteorology* 176: 369–400.

Emmanouil, S., A. Langousis, E. I. Nikolopoulos, and E. N. Anagnostou. 2020. "Quantitative Assessment of Annual Maxima, Peaks-over-Threshold (PoT) and Multifractal Parametric Approaches in Estimating Intensity-Duration-Frequency (IDF) Curves from Short Rainfall Records." *Journal of Hydrology* 589, art. 125151. https://doi.org/10.1016/j.jhydrol.2020.125151.

Hale, D. C., and A. T. Morzillo. 2020. "Landscape Characteristics and Social Factors Influencing Attitudes toward Roadside Vegetation Management." *Landscape Ecology* 39:2029–44. https://doi.org/10.1007/s10980-020-01078-6.

Hannah, L., P. R. Roehrdanz, P. A. Marquet, B. J. Enquist, G. Midgley, W. Foden, J. C. Lovett, R. T. Corlett, D. Corcoran, S. H. M. Butchart, B. Boyle, X. Feng, B. Maitner, J. Fajardo, B. J. McGill, C. Merow, N. Morueta–Holme, E. A. Newman, D. S. Park, N. Raes, and J.-C. Svenning. 2020. "30% Land Conservation and Climate Action Reduces Tropical Extinction Risk by More than 50%." *Ecography* 43 (7): 943–53.

Hu, L., E. I. Nikolopoulos, F. Marra, and E. N. Anagnostou. 2020. "Sensitivity of Flood Frequency Analysis to Data Record, Statistical Model, and Parameter Estimation Methods: An Evaluation over the Contiguous United States." *Journal of Flood Risk Management* 13 (1). https://doi.org/10.1111/jfr3.12580.

Hu, L., E. Nikolopoulos, F. Marra, E. Morin, M. Marani, and E. Anagnostou. 2020. "Evaluation of MEVD-Based Precipitation Frequency Analyses from Quasi-Global Precipitation Datasets against Dense Rain Gauge Networks." *Journal of Hydrology* 590, art. 125564. https://doi.org/10.1016/j.jhydrol.2020.125564.

Kloster, D. P., A. T. Morzillo, J. C. Volin, and T. E. Worthley. 2020. "Tree Crew Perspectives on Wood Product Recovery from Utility Vegetation Management." *Arboriculture and Urban Forestry* 46:197–209.

Lazin, R., X. Shen, M. Koukoula, and E. N. Anagnostou. 2020. "Evaluation of the Hyper-Resolution Model-Derived Water Cycle Components over the Upper Blue Nile Basin." *Journal of Hydrology* 590 (November), art. 125231. https://doi.org/10.1016/j.jhydrol.2020.125231.

Matheou, G., A. B. Davis, and J. Teixeira. 2020. "The Spiderweb Structure of Stratocumulus Clouds." *Atmosphere* 11 (7): 730.


Merow, C., and M. C. Urban. 2020. "Seasonality and Uncertainty in Global COVID-19 Growth Rates." *Proceedings of the National Academy of Sciences* 117 (44): 27456–64.

Ortiz-Rodríguez, I. A., J. Raventós, E. Mújica, E. González-Hernández, E. Vega-Peña, P. Ortega-Larrocea, A. Bonet, and C. Merow. 2020. "Spatiotemporal Effects of Hurricane Ivan on an Endemic Epiphytic Orchid: 10 Years of Follow-Up." *Plant Ecology & Diversity* 13 (1): 29–45.

Shen, X., C. Cai, and H. Li. 2020. "Socioeconomic Restrictions Slowdown COVID-19 Far More Effectively than Favorable Weather: Evidence from the Satellite." *Science of the Total Environment* 748, art. 141401. https://doi.org/10.1016/j.scitotenv.2020.141401.

Sofia, G., and E. I. Nikolopoulos. 2020. "Floods and Rivers: A Circular Causality Perspective." *Scientific Reports* 10, art. 5175. https://doi.org/10.1038/s41598-020-61533-x.

Taylor, W., M. Anagnostou, D. Cerrai, and E. Anagnostou. 2020. "Machine Learning Methods to Approximate Rainfall and Wind from Acoustic Underwater Measurements." *IEEE Transactions on Geoscience and Remote Sensing.* https://ieeexplore.ieee.org/document/9144382.

Trisos, C. H., C. Merow, and A. L. Pigot. 2020. "The Projected Timing of Abrupt Ecological Disruption from Climate Change." *Nature* 580 (7804): 496–501.

Walsh, T., D. Wanik, E. Anagnostou, and J. Mellor. 2020. "Estimated Time to Restoration of Hurricane Sandy in a Future Climate." *Sustainability* 12 (16): 6502. https://doi.org/10.3390/su12166502.

Watson, P., D. Cerrai, M. Koukoula, D. Wanik, and E. Anagnostou. 2020. "Weather-Related Power Outage Model with a Growing Domain: Structure, Performance, and Generalizability." *Journal of Engineering* 10:817–26. https://doi.org/10.1049/joe.2019.1274.

Yang, F., D. Cerrai, M. Koukoula, and E. N. Anagnostou. 2020. "Quantifying Uncertainty in Machine Learning–Based Power Outage Prediction Model Training: A Tool for Sustainable Storm Restoration." *Sustainability* 12 (4): 1525. https://www.mdpi.com/2071-1050/12/4/1525.

Yang F., P. Watson, M. Koukoula, and E. N. Anagnostou. 2020. "Enhancing Weather-Related Power Outage Prediction by Event Severity Classification." *IEEE Access* 8:60029–42. https://ieeexplore.ieee.org/document/9046816.

Witharana, C., M. A. E. Bhuiyan, and A. K. Liljedahl. 2020. "Big Imagery and High Performance Computing as Resources to Understand Changing Arctic Polygonal Tundra." *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences* 44:111–16.

Witharana, C., M. A. E. Bhuiyan, A. K. Liljedahl, M. Kanevskiy, H. E. Epstein, B. M. Jones, R. Daanen, C. G. Griffin, K. Kent, and M. K. W. Jones. 2020. "Understanding the Synergies of Deep Learning and Data Fusion of Multispectral and Panchromatic High Resolution Commercial Satellite Imagery for Automated Ice-Wedge Polygon Detection." *ISPRS Journal of Photogrammetry and Remote Sensing* 170:174–91.

Zhu, Z., J. Zhang, Z. Yang, A. H. Aljaddani, W. B. Cohen, S. Qiu, and C. Zhou. 2020. "Continuous Monitoring of Land Disturbance Based on Landsat Time Series." *Remote Sensing of Environment* 238 (March), art. 111116.

Zurell, D., J. Franklin, C. König, P. J. Bouchet, C. F. Dormann, J. Elith, G. Fandos, X. Feng, G. Guillera–Arroita, A. Guisan, J. J. Lahoz–Monfort, P. J. Leitão, D. S. Park, A. T. Peterson, G. Rapacciuolo, D. R. Schmatz, B. Schröder, J. M. Serra–Diaz, W. Thuiller, K. L. Yates, N. E. Zimmermann, and C. Merow. 2020. "A Standard Protocol for Reporting Species Distribution Models." *Ecography* 43 (9): 1261–77.

## 2019


Bhuiyan, M. A. E., E. I. Nikolopoulos, and E. N. Anagnostou. 2019. "Machine Learning–Based Blending of Satellite and Reanalysis Precipitation Datasets: A Multi-Regional Tropical Complex Terrain Evaluation." *Journal of Hydrometeorology* 20 (11). https://doi.org/10.1175/JHM-D-19-0073.1.

Bhuiyan, M. A. E., E. I. Nikolopoulos, E. N. Anagnostou, J. Polcher, C. Albergel, E. Dutra, G. Fink, A. Martinez de la Torre, and S. Munier. 2019. "Assessment of Precipitation Error Propagation in Multi-Model Global Water Resources Reanalysis." *Hydrology and Earth System Sciences* 23:1973–94. https://www.hydrol-earth-syst-sci.net/23/1973/2019/hess-23-1973-2019.pdf.

Cerrai, D., D. W. Wanik, M. A. E. Bhuiyan, X. Zhang, J. Yang, M. E. B. Frediani, and E. N. Anagnostou. 2019. "Predicting Storm Outages through New Representations of Weather and Vegetation." *IEEE Access* 7:29639–54. https://ieeexplore.ieee.org/document/8656482.

Cerrai, D., P. Watson, and E. N. Anagnostou. 2019. "Assessing the Effects of a Vegetation Management Standard on Distribution Grid Outage Rates." *Electric Power Systems Research* 175 (October): 105909. https://doi.org/10.1016/j.epsr.2019.105909.

Derin, Y., E. Anagnostou, A. Berne, M. Borga, B. Boudevillain, W. Buytaert, C.-H. Chang, H. Chen, G. Delrieu, Y. C. Hsu, W. Lavado-Casimiro, B. Manz, S. Moges, E. I. Nikolopoulos, D. Sahlu, F. Salerno, J.-P. Rodríguez-Sánchez, H. J. Vergara, and K. K. Yilmaz. 2019. "Evaluation of GPM-Era Global Satellite Precipitation Products Over Multiple Complex Terrain Regions." *Remote Sensing* 11:2936.

Derin, Y., E. Anagnostou, M. Anagnostou, and J. Kalogiros. 2019. "Evaluation of X-Band Dual-Polarization Radar-Rainfall Estimates from OLYMPEX." *Journal of Hydrometeorology* 20 (9). https://doi.org/10.1175/JHM-D-19-0097.1.

Derin, Y., E. Nikolopoulos, and E. N. Anagnostou. 2019. "Estimating Extreme Precipitation Using Multiple Satellite-Based Precipitation Products." In *Extreme Hydroclimatic Events and Multivariate Hazards in a Changing Environment: A Remote Sensing Approach,* edited by Viviana Maggioni and Christian Massari, 163–90. Amsterdam: Elsevier. https://doi.org/10.1016/B978-0-12-814899-0.00007-9.

Haileyesus, B. L., S. A. Moges, E. N. Anagnostou, E. I. Nikolopoulos, and D. H. Asfaw. 2019. "Evaluation of Global Water Resources Reanalysis Runoff Products for Local Water Resources Applications: Case Study—Upper Blue Nile Basin of Ethiopia." *Water Resources Management* 34:2157–77. https://doi.org/10.1007/s11269-019-2190-y.

Koukoula M., E. I. Nikolopoulos, J. Kushta, N. S. Bartsotas, G. Kallos, and E. N. Anagnostou. 2019. "A Numerical Sensitivity Analysis of Soil Moisture Feedback on Convective Precipitation." *Journal of Hydrometeorology* 20, no. 1 (January): 23–44. https://doi.org/10.1175/JHM-D-18-0134.1.

Li, Y., P. Zhang, W. Li, J. N. Debs, D. A. Ferrante, D. J. Kane, S. N. Woolard, R. Kalbfleisch, and K. B. Bowes. 2019. "Non-Detection Zone Analytics for Unintentional Islanding in Distribution Grid Integrated with Distributed Energy Resources." *IEEE Transactions on Sustainable Energy* 10, no. 1 (January): 214–25.

Marra, F., E. I. Nikolopoulos, E. N. Anagnostou, A. Bardossy, and E. Morin. 2019. "Precipitation Frequency Analysis from Remotely Sensed Datasets: A Focused Review." *Journal of Hydrology* 574 (July): 699–705.

McGraw, D., E. I. Nikolopoulos, F. Marra, and E. N. Anagnostou. 2019. "Precipitation Frequency Analyses Based on Radar Estimates: An Evaluation over the Contiguous United States." *Journal of Hydrology* 573:299–310.

Samalot, A., M. Astitha, J. Yang, and G. Galanis. 2019. "Combined Kalman Filter and Universal Kriging to Improve Storm Wind Speed Predictions for the Northeastern United States." *Weather Forecasting* 34:587–601. https://doi.org/10.1175/WAF-D-18-0068.1.


Shen, X., E. N. Anagnostou, and G. H. Allen. 2019. "Near Real-Time Non-Obstructed Flood Inundation Mapping Using Synthetic Aperture Radar." *Remote Sensing of Environment* 221 (February): 302–15.

Shen, X., D. Wang, K. Mao, E. N  Anagnostou, and Y. Hong. 2019. "Inundation Extent Mapping by Synthetic Aperture Radar: A Review." *Remote Sensing* 11 (7): 879.

Yang J., M. Astitha, and C. Schwartz. 2019. "Assessment of Storm Wind Speed Prediction Using Gridded Bayesian Regression Applied to Historical Events with NCAR's Real–Time Ensemble Forecast System." *Journal of Geophysical Research: Atmospheres* 124 (16): 9241–61. https://doi.org/10.1029/2018JD029590.

Zhang, X., and E. N. Anagnostou. 2019. "Evaluation of Numerical Weather Model-Based Satellite Precipitation Adjustment in Tropical Mountainous Regions." *Journal of Hydrometeorology* 20, no. 3 (February). https://doi.org/10.1175/JHM-D-18-0008.1.

## 2018

Bunce, A., J. C. Volin, D. R. Miller, J. Parent, and M. Rudnicki. 2018. "UCONN Tree Sway Biomechanics Study." *Mendeley Data,* V2. https://data.mendeley.com/datasets/65z8hkzfz7/2.

Destro, E., W. Amponsah, E. I. Nikolopoulos, L. Marchi, F. Marra, D. Zoccatelli, and M. Borga. 2018. "Coupled Prediction of Flash Flood Response and Debris Flow Occurrence: Application on an Alpine Extreme Flood Event." *Journal of Hydrology* 558:225–37.

Marra, F., E. Nikolopoulos, E. N. Anagnostou, and E. Morin. 2018. "Metastatistical Extreme Value Analysis of Hourly Rainfall from Short Records: Estimation of High Quantiles and Impact of Measurement Errors." *Advances in Water Resources* 117 (July): 27–39. https://doi.org/10.1016/j.advwatres.2018.05.001.

Nikolopoulos, E. I., E. Destro, A. E. Bhuiyan, M. Borga, and E. N. Anagnostou. 2018. "Evaluation of Predictive Models for Post-Fire Debris Flows Occurrence in the Western United States." *Natural Hazards and Earth System Sciences* 18:2331–43. https://doi.org/10.5194/nhess-18-2331-2018.

Orekan, T., P. Zhang, and C. Shih. 2018. "Analysis, Design, and Maximum Power Efficiency Tracking for Undersea Wireless Power Transfer." *IEEE Journal of Emerging and Selected Topics in Power Electronics* 6 (2): 843–54.

Wanik, D., E. N. Anagnostou, T. Layton, and B. M. Hartman. 2018. "Estimated Time of Restoration (ETR) Guidance for Electric Distribution Networks." *Journal of Homeland Security and Emergency Management* 15 (1): 1–13. https://doi.org/10.1515/jhsem-2016-0063.

Yang, J., M. Astitha, L. Delle Monache, and S. Alessandrini. 2018. "An Analog Technique to Improve Storm Wind Speed Prediction Using a Dual NWP Model Approach." *Monthly Weather Review* 146 (12): 4057–77.

Yuan, H., W. Zhang, J. Zhu, and A. C. Bagtzoglou. 2018. "Resilience Assessment of Overhead Power Distribution Systems under Strong Winds for Hardening Prioritization." *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering* 4, no. 4 (December).

## 2017

Frediani, M., T. Hopson, J. Hacker, E. N. Anagnostou, L. Monache, and F. Vandenberg. 2017. "Object-Based Analog Forecasts for Surface Wind Speed." *Monthly Weather Review* 145 (12): 5083–5102. https://doi.org/10.1175/MWR-D-17-0012.1.

He, J., D. W. Wanik, B. M. Hartman, E. N. Anagnostou, and M. Astitha. 2017. "Nonparametric Tree-Based Predictive Modeling of Storm Outages on an Electric Distribution Network." *Risk Analysis* 37, no. 3 (March): 441–58.

Li, Y., P. Zhang, L. Zhang, and B. Wang. 2017. "Active Synchronous Detection of Deception Attacks in Microgrid Control Systems." *IEEE Transactions on Smart Grid* 8, no. 1 (January): 373–75.

Maggioni, V., E. I. Nikolopoulos, E. N. Anagnostou, and M. Borga. 2017. "Modeling Satellite Precipitation Errors over Mountainous Terrain: The Influence of Gauge Density, Seasonality, and Temporal Resolution." *IEEE Transactions on Geoscience and Remote Sensing* 55 (7): 4130–40.

Mei, Y., E. N. Anagnostou, X. Shen, and E. I. Nikolopoulos. 2017 "Decomposing the Satellite Precipitation Error Propagation through the Rainfall-Runoff Processes." *Advances in Water Resources* 109:253–66.

Mei, Y., X. Shen, and E. N. Anagnostou. 2017. "A Synthesis of Space-Time Variability in Multi-Component Flood Response." *Hydrology and Earth System Sciences* 21:2277–99.

Nikolopoulos, E. I., E. Destro, V. Maggioni, F. Marra, and M. Borga. 2017. "Satellite-Rainfall Estimates for Debris Flow Prediction: An Evaluation Based on Rainfall Accumulation-Duration Thresholds." *Journal of Hydrometeorology* 18 (8): 2207–14.

Shen, X., and E. N. Anagnostou. 2017. " A Framework to Improve Hyper-Resolution Hydrologic Simulation in Snow-Affected Regions." *Journal of Hydrology* 552:1–12.

Shen, X., E. N. Anagnostou, Y. Mei, and Y. Hong. 2017. "A Global Distributed Basin Morphometric Dataset." *Scientific Data: A Nature Research Journal* 4, art. 160124 (January). https://www.nature.com/articles/sdata2016124.

Shen, X., Y. Mei, and E. N. Anagnostou. 2017. "A Comprehensive Flood Events Database in Continental United States." *Bulletin of the American Meteorological Society* 98 (7): 1493–1502.

Wanik, D., E. N. Anagnostou, M. Astitha, B. M. Hartman, M. E. B. Frediani, G. M. Lackmann, J. He, and J. Yang. 2017. "A Case Study on Power Outage Impacts from Future Hurricane Sandy Scenarios." *Journal of Applied Meteorology* 57 (1): 51–79. https://doi.org/10.1175/JAMC-D-16-0408.1.

Wanik, D., J. Parent, E. N. Anagnostou, and B. M. Hartman. 2017. "Using Vegetation Management and LiDAR-Derived Tree Height Data to Improve Outage Predictions for Electric Utilities." *Electric Power Systems Research* 146:236–45.

Yang, J., M. Astitha, E. N. Anagnostou, and B. Hartman. 2017. "Using a Bayesian Regression Approach on Dual-Model Weather Simulations to Improve Wind Speed Prediction." *Journal of Applied Meteorology and Climatology* 56:1155–74. https://doi.org/10.1175/JAMC-D-16-0206.1.

## 2016

Bartsotas, N., E. I. Nikolopoulos, E. N. Anagnostou, S. Solomos, and G. Kallos. 2016. "Moving towards Subkilometer Modeling Grid Spacings: Impacts on Atmospheric and Hydrological Simulations of Extreme Flash Flood–Inducing Storms." *Journal of Hydrometeorology* 18, no. 1 (November): 209–26.

Frediani, M. E. B., J. P. Hacker, E. N. Anagnostou, and T. Hopson. 2016. "Evaluation of PBL Parameterizations for Modeling Surface Wind Speed during Storms in the Northeast U.S." *Weather and Forecasting* 31 (5): 1511–28. http://dx.doi.org/10.1175/WAF-D-15-0139.1.

## 2015

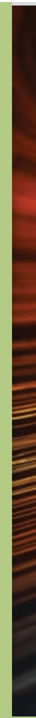
Wanik, D., E. N. Anagnostou, B. M. Hartman, M. E. Frediani, and M. Astitha. 2015. "Storm Outage Modeling for an Electric Distribution Network in Northeastern US." *Natural Hazards* 79 (2): 1359–84.

## Under Review

Emmanouil, S., A. Langousis, E. I. Nikolopoulos, and E. N. Anagnostou. "A CONUS-Wide, Long-Term and High-Resolution Precipitation Dataset Based on an Advanced Statistical Downscaling Framework." ***Water Resources Research.***

Fahey, R. T., D. Tanzer, B. Alveshere, J. Atkins, C. M. Gough, and B. S. Hardiman. "An Experimental Approach for Crown to Whole-Canopy Defoliation in Forests." ***Canadian Journal of Forest Research.***

Yang, Q., X. Shen, F. Yang, and E. Anagnostou. "Prediction of Flood Claims over the Contiguous United States (CONUS) by Building a Classification/ Regression-Hybrid Machine Learning Scheme." ***Remote Sensing of Environment.***




**Eversource Energy Center**

Innovation Partnership Building
159 Discovery Drive
Storrs, CT 06269

eversourceenergycenter@uconn.edu
**www.eversource.uconn.edu**

Annual Report 2020

EVERSOURCE
UCONN
UNIVERSITY OF CONNECTICUT

**EVERSOURCE ENERGY CENTER**

A utility-university partnership at UConn

**www.eversource.uconn.edu**