Systems Approaches for Vulnerability Evaluation and Urban Resilience (SAVEUR)

Our vision is to converge research across natural science, social science, data science, and engineering domains to reduce vulnerability to extreme weather through improved prediction of weather patterns, air quality, flooding, and social and economic impacts at neighborhood scale.

Emerging urban data resources, distributed sensing technologies, and local-to-global-scale simulation capabilities provide tremendous opportunities for scientific convergence to reduce vulnerability to extreme weather events in cities. High-resolution assessment and prediction of vulnerability in large cities presents a complex set of scientific challenges. Development of new strategies for reducing vulnerability to extreme weather will require coupling state-of-the-science earth system models with urban system models in predictive frameworks, and relating predicted vulnerabilities to actual social, economic, and health impacts at neighborhood scale (Fig. 1).

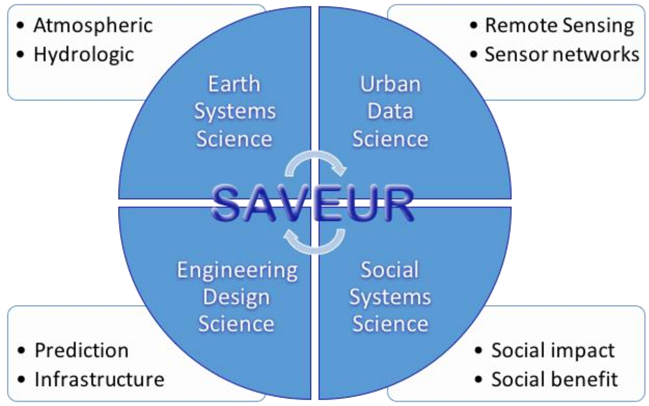

Fig. 1: SAVEUR convergence approach

We will integrate these approaches in a multi-level framework for assessment and prediction of extreme weather impacts in cities. We will use this framework to develop multi-component vulnerability maps and evaluate green infrastructure strategies to reduce ensemble city-wide vulnerability to extreme weather.

Convergence Problem Description:

Over 80% of the U.S. population lives in cities and relies on urban infrastructure networks to provide essential resources, support economic growth, and confer protection from hazards. Despite advances in distributed sensing, hazard prediction, and urban design, large cities remain vulnerable to extreme weather events – flooding, heat waves, and episodes of poor air quality (Borden et al. 2007, Luber & McGeehin 2008, Hallegatte & Corfee-Morlot 2011, Hunt & Watkiss 2011, CRED 2015, Ramaswami et al. 2016). **Convergence of natural science, social science, data science, and engineering is needed to assess current vulnerabilities and design strategies to improve resilience to extreme weather** (Wamsler 2014, Eakin et al. 2017, Shifman et al. 2017, Aerts et al. 2018, Irwin et al. 2018).

Inability to assess and predict gradients of extreme weather conditions within cities is a critical vulnerability, as it greatly hinders the design and deployment of local interventions to protect vulnerable populations (Sorenson 2000, Hunt & Watkiss 2011, Jankovic & Hebbert 2012, Voelkel et al. 2016). The poor state of urban infrastructure in U.S. cities substantially exacerbates this vulnerability. Failures of both physical and social infrastructure clearly contributed to massive weather disasters in New Orleans (Katrina), New York (Sandy), San Juan (Maria), and Houston (Harvey) – the four most costly storms in U.S. history (NHC 2018). Further, recent retrospective analysis has found that inability to forecast local event intensity hinders disaster response and exacerbates damage (Voelkel et al. 2016; Robles 2018; FEMA 2018).

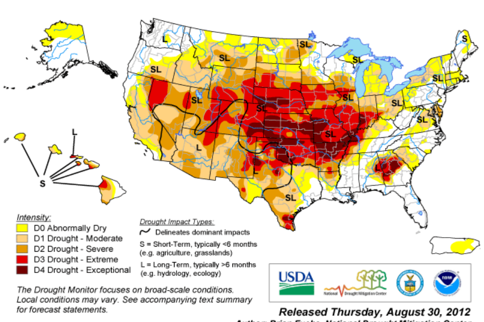

Fig. 2: 2012 U.S. heat wave and drought.

While coastal cities have received recent attention, inland cities are also subject to increasing threats from extreme weather (Zha et al. 2012, Hallegatte et al. 2013, CRED 2015). Although there has been considerable research into the risks of hurricanes and sea level rise on coastal cities, inland cities suffer more frequent, localized weather hazards (NOAA 2018a). Severe thunderstorms, heat waves, and droughts are the most frequent causes of $1B+ weather and climate disasters in the U.S. (NOAA 2018b). For example, the 2012 Midwestern heat wave and drought caused more than $30B in economic damage, 123 direct deaths, and contributed to considerable long-term morbidity and mortality across most of the central and western U.S. (Fig. 2, Rippey 2015).

In the Midwest and Great Lakes regions – collectively home to more than 60 million people and responsible for $4.5 trillion of annual economic production – high weather variability, high-intensity urban development, and undersized infrastructure yield severe and accelerating vulnerability to extreme events (Borden et al. 2007, Wilson et al. 2010, Prior et al. 2014, Winters et al. 2015, Sharma et al. 2018). For example, the megacity of Chicago – with a metropolitan population of over 10 million – suffers frequent flooding in intense, localized storms (CNT 2013, Winters et al. 2015). Under-resourced communities suffer a disproportionate burden of storm impacts, owing to the confluence of low property values and lack of infrastructure in low-lying flood-prone areas (Fig. 3, Wilson et al. 2010, CNT 2013). Extreme storms are expected to sharply increase over the next 50 years in this region (Winkler et al. 2012, Prior et al. 2014, Winters et al. 2015, Kossin et al. 2017), requiring convergent strategies to reduce vulnerabilities.

While recent attention on extreme weather vulnerability has focused on flooding, heat waves and poor air quality have a greater impact on public health (Luber & McGeehin 2008, Hahoe & Wuebbles 2008, Anderson & Bell 2011, Schnell & Prather 2017). Heat waves are notorious killers in Midwest cities (Changnon et al. 1996, Kalkstein & Greene 1997, Smoyer 1998, Palecki et al. 2001). High-density transportation and industry also impose considerable urban air pollutant loads. As with flooding, air quality impacts are disproportionately distributed (Fig. 3, IPHD 2016, RHA 2018). Midwest U.S. cities are especially vulnerable to such impacts due to their high density, older housing stocks, sensitive populations, and conducive summer weather patterns (Changnon et al. 1996, Palecki et al. 2001). Under stagnant weather conditions, heat and pollutants do not disperse, significantly exacerbating public health impacts (Luber & McGeehin 2008, Jacob & Winter 2009, Schnell & Prather 2017). While spatial patterns of impacts can be assessed *post facto* using aggregated information, a lack of neighborhood-scale forecasts hampers public health intervention efforts (Luber & McGeehin 2008, Hunt & Watkiss 2011, Voelkel et al. 2016). Projected increases in heat waves and air stagnation events will substantially increase vulnerability in cities across the U.S. (Meehl & Tebaldi 2004, Luber & McGeehin 2008, Horton& Diffenbaugh 2012, Horton et al. 2014).

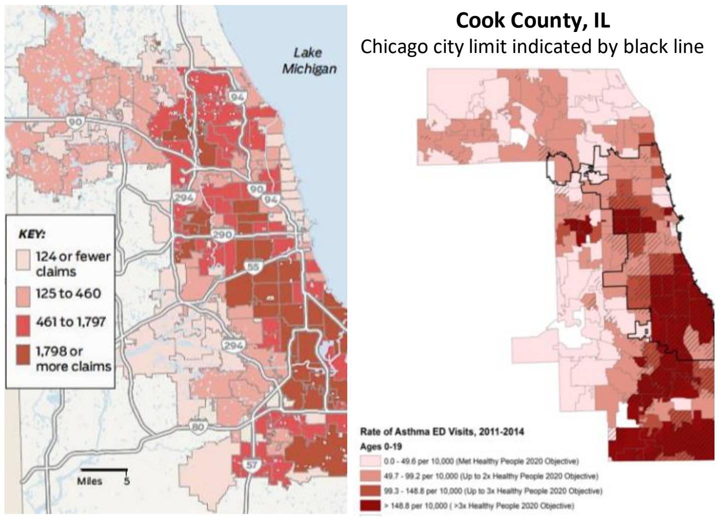

Fig. 3. Disparities in flooding and air pollution impacts in Chicago. Left: Flood insurance claims by zip code. Right: Rate of childhood asthma emergency department visits by zip code. Both impacts are greatest in areas of concentrated disadvantage on Chicago's South and West Sides.

Green infrastructure (GI), defined as "an interconnected network of natural areas and other open spaces" (Benedict & McMahon 2006), potentially provides a cost-effective and energy-efficient strategy for reducing vulnerability to weather extremes (Luber & McGeehin 2008, Bowler et al. 2010, Carson & White 2017). GI not only buffers multiple weather impacts, but also provides additional co-benefits including recreation, food, and increased biodiversity (Gill et al. 2007, Demuzere et al. 2014, Hartig & Kahn, 2016). While GI has been shown to modulate atmospheric and hydrologic conditions locally, the effectiveness of this approach as a city-scale hazard-reduction strategy is not known (Bowler et al. 2010, Demuzere et al. 2014, Hopton et al. 2015). Therefore, there is a pressing need to advance both understanding and prediction of the scales at which green infrastructure reduces vulnerability to heat, air quality, and flooding impacts.

Proposed research:

We propose a multi-level urban convergence approach engaging social, data, computational, atmospheric, and hydrologic scientists to develop a **new holistic urban systems science that seeks to understand and predict inter-relationships between environmental variability, socio-demographic patterns, and the structure of the cityscape**. Further collaboration with civil and environmental engineers will **define disaster vulnerability and impacts**, and **relate advances in scientific understanding and prediction to design of city-scale green infrastructure strategies for risk mitigation**.

Three distinct *multi-level* systems approaches are needed to achieve our Convergence vision:

1. High-frequency data using a mixture of remote and distributed sensing and distributed sensor networks to assess impacts in real time.

2. High-resolution environmental models that elucidate links between severe weather, urban infrastructure, and disaster vulnerability.

3. Socio-ecological models that assess the multiple co-occurring social and economic impacts of extreme weather, along with the relative costs and benefits of alternative solution strategies.

Convergence of these three multi-level systems approaches will inform design of resilient infrastructure for mitigating vulnerability to weather extremes. Realizing these promising opportunities will require deep data integration with convergent multi-level analysis. For this purpose, we will develop a holistic assessment and prediction framework encompassing drivers of extreme weather, interactions with urban infrastructure, and social and economic impacts. While prior urban research and operational decision-making have been segmented into single-component objectives, we will develop and test new approaches that provide comprehensive understanding of key vulnerabilities and impacts to enable resilient infrastructure design.

We propose to integrate the City of Chicago's unique data resources with advanced assessments of extreme weather conditions, distributed air and water sensing, and atmospheric and hydrologic models to inform multi-level systems analyses balancing social, environmental, and economic objectives with risks of extreme weather impacts. Integrating environmental predictions and infrastructure performance models with demographic data, community-based research, and economic damage assessments will advance understanding of the manner in which weather variability, urban infrastructure, and social organization coalesce into vulnerability. Based on assessment of factors that ameliorate local impacts, our team of natural scientists, social scientists, data scientists, and engineers will evaluate green infrastructure solutions to increase city-wide resilience and reduce ensemble vulnerability (Fig. 4). **This work will culminate in a set of high-resolution vulnerability maps for temperature, air quality, flooding, and integrated extreme weather risk under current and projected future conditions. Maps will be developed for alternative climate and land use scenarios, providing an actionable basis for design of strategies to reduce ensemble vulnerability to extreme weather**.

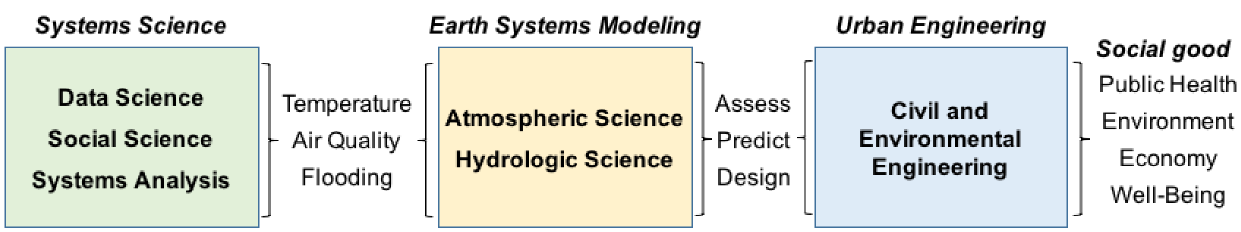

Fig. 4: Proposed convergence of multiple systems sciences with earth systems modeling and urban engineering to support assessment, prediction, and design for the public good.

Convergence Science Advances:

The proposed work will yield four interlinked science advances spanning atmospheric science, hydrologic science, social science, data science, and civil and environmental engineering. These four science advances converge to achieve the high-resolution analysis of weather, air quality, flooding, and social and economic impacts needed to design for greater resilience to extreme weather. Consequently, information from all four science advances will be used to test convergence hypotheses.

Advance 1. Extreme weather events

There is a pronounced disconnect between the scales of Earth system models (100 km) and urban neighborhoods where extreme weather impacts occur (1 km). While regional models have begun to approach neighborhood scale, key limitations in simulations of extreme precipitation, heat waves and air quality events hamper our ability to assess fine-scale vulnerabilities within cities. Using a mixture of remote measurements, *in situ* sensing networks, and high-resolution modeling, we will characterize and simulate extreme events at neighborhood scale across the city of Chicago. The integration of WSR-88d weather radar and Array of Things (AoT) sensor network data into high-resolution Large Eddy Simulation (LES) and Convection Resolving Models (CRM) will improve the resolution of extreme precipitation over Chicago to 500 m, yielding critical information for the SAVEUR team to assess flooding. Likewise, co-located AoT air quality and meteorological sensors, in conjunction with new high-resolution speciated emission data, will allow neighborhood-scale characterization of urban air-quality events. Simulation conditions will be selected by the entire SAVEUR team to best inform research objectives focused on heat and air quality (Advance 2), urban hydrology (Advance 3), and the social impacts of extreme weather (Advance 4).

Advance 2. Urban heat and air quality

Co-occurrence of extreme heat and poor air quality considerably impacts urban public health. These impacts are often unevenly distributed within cities due to demographic distributions, land use patterns, and microscale meteorological heterogeneities. However, a lack of spatial resolution in available air quality observations and models makes it challenging to untangle these complexities. Current EPA air quality monitoring networks are extremely sparse, with fewer than 10 sites across the city of Chicago (EPA, 2018). The much more extensive AoT network – with 105 nodes currently deployed, expanding to 500 over the next two years – provides greatly improved resolution of air quality, along with co-located meteorological data. We will use this information in conjunction with the advanced meteorology models from Science Advance 1 to improve the resolution of temperature and air quality products to neighborhood scales. We will assess AoT vs. EPA sensor data and examine meteorological influences on air quality at each sensor. We will develop neighborhood-scale gridded observations for comparison with operational forecasts (NOAA). Finally, we will develop air quality simulations at state-of-the-science resolution (~1 km) to enable assessment of air quality impacts across Chicago, using the CMAQ-WRF chemistry-climate model. This analysis will directly incorporate meteorological information and models from Advance 1, and inform approaches to assess and reduce socio-ecological impacts of extreme weather in Advance 4.

Advance 3. Urban flooding

Assessment and prevention of urban flooding suffers greatly from a lack of distributed data and predictions within cities. While major cities are protected by a large network of stormwater controls – including sewers, drainage channels, detention basins, and engineered waterways – this infrastructure is primarily conventional, older construction, and generally lacks *in situ* sensing and control capability. We will deploy new water sensors and computer vision software across the AoT network to obtain distributed flooding information. This will represent a completely new flood data resource for Chicago, as current flood monitoring is limited to the Chicago Area Waterways, and street flooding reports are only collected by public reporting through the through the City's 311 call line. We will use this information in conjunction with the high-resolution weather data and models described under Science Advance 1 to develop city-scale models for flooding by integrating MetroFlow and Dual-Drainage models. We will then use the combination of high-resolution data and models to evaluate flooding distributions and impacts in much greater detail than is possible today, and assess the potential for green infrastructure to reduce flooding under current conditions and future scenarios of extreme weather and land use. This work will directly incorporate results from Advance 1 and inform impact assessments and strategies for vulnerability reduction under Advance 4.

Advance 4. Urban social systems science for resilience

We will develop new approaches to assess urban vulnerability and use these methods to evaluate solutions for resilience of cities to extreme weather. Urban vulnerability has thus far been evaluated based on single impacts in isolation, and simultaneous consideration of multiple impacts has not been employed to design more effective strategies for urban resilience. Further shortcomings include a lack of direct measures of social impact, inability to assess full costs of weather impacts and control measures, and inability to directly relate neighborhood-scale interventions to local and city-wide vulnerability reductions. To remedy this, we will develop more complete social and economic measures of severe weather impacts using the unique data resources available in Chicago, such as the Chicago Data Portal, to assess city-scale impacts, and socio-ethnographic research to understand local impacts in vulnerable neighborhoods. We will then relate observed impacts to extreme weather patterns using the data and models described under Science Advances 1-3. We will use high-resolution meteorological and hydrological modeling of historical events and projected future weather conditions to evaluate social, economic, and health benefits of green infrastructure strategies to achieve multi-component reductions in vulnerability.

Convergence hypotheses:

The four convergence Science Advances, together, will be used to test the following three hypotheses:

Hypothesis 1: Improved spatial resolution of extreme weather events will greatly improve the fidelity of predictions of urban flooding, air quality, and associated social and economic impacts. This hypothesis will be tested by comparing water and air modeling predictions at current vs. improved resolution against AoT data on flooding and air quality, as well as City of Chicago public data records on flooding reports, health indicators of temperature and air quality impacts, and economic losses from flooding. Social impact data will be verified through qualitative social research in vulnerable neighborhoods.

Hypothesis 2: Urban greenspace significantly reduces air temperature, improves air quality, and reduces stormwater runoff when it comprises a majority of the local land area. These benefits occur at a scale on the order of 5x the area of the greenspace. This hypothesis will be tested by statistical analysis of air and water data from the 500 AoT nodes that will be deployed across Chicago, relative to local land cover.

Hypothesis 3: Green infrastructure will outperform conventional infrastructure in reducing vulnerability to extreme weather by providing multiple socio-ecological benefits and cost savings. Benefits will be assessed through high-resolution modeling and measurement of inter-relationships between weather patterns, green infrastructure, environmental conditions, and adverse social and economic impacts.

Testing of all three hypotheses relies on the integrated suite of Science Advances, and therefore requires a true Convergence Science approach.

Necessity of Convergence/RAISE funding:

The SAVEUR Convergence effort relies upon critical science advances spanning meteorology, atmospheric science, hydrologic science, urban engineering, data science, computational science, and social science. This effort thus spans four NSF directorates (GEO, ENG, CISE, SBE). Further, the SAVEUR science advances and hypotheses are interwoven, making it impossible to achieve them via discrete disciplinary science objectives. Improving assessment and prediction of extreme weather impacts in cities is a pressing societal challenge, as major cities in the U.S. and across the world are currently vulnerable to extreme weather, and these vulnerabilities will increase sharply over the next 10 years. The SAVEUR Convergence effort proffers a substantial, rapid set of science advances to enable prediction of extreme weather conditions, air quality, and flooding at neighborhood scale in large cities. Further, the SAVEUR team will explicitly link extreme temperature, air quality, and flooding to adverse social and economic impacts, and develop actionable strategies for reducing these impacts. We will particularly explore multi-component benefits of urban green infrastructure to reduce vulnerability. Even if component science advances could be achieved through regular programmatic funding, no regular NSF funding mechanism supports the convergence of science around social and economic impact needed to reduce urban vulnerability to extreme weather. Under normal funding mechanisms, the component disciplinary science advances would each require several years, and both science inter-linkages and research translation for the public good would remain unlikely. Through Convergence, we will both achieve and apply breakthrough science for urban vulnerability within just a few years. **RAISE funding is required to enable the SAVEUR team to coalesce diverse science advances around a common Convergence Vision for social good**.

Study Area – The Megacity of Chicago

The SAVEUR Convergence effort is enabled by the unique data resources, physical infrastructure, and operational partnerships to support urban vulnerability research in the City of Chicago. We focus on Chicago not only because of availability of unique data resources and logistical support for research, but also because the project will directly address important social, economic, and public health concerns in the city and the surrounding megaregion (Fig. 5, *America 2050*, 2014).

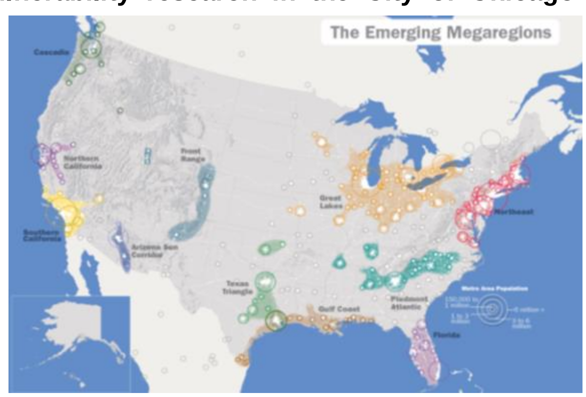

Fig. 5: Emerging urban megaregions of the U.S.

Chicago is organized into "Community Areas", which have been recognized as defined entities since the 1920s (Burgess & Newcomb 1931, Hunter 1974). Clusters of community areas are described as "Sides". Communities in Chicago's South Side and West Side suffer concentrated disadvantage, frequent flooding, and disproportionate air quality impacts (CNT 2013, 2015, Winters et al. 2015). Flooding caused over $773M in residential damage in Cook County between 2007-2011, and nearly $2B in total damage across the Chicago metro area between 2007-2014 (CNT 2013, Winters et al. 2015). Under normal weather conditions, prevailing westerly winds disperse atmospheric pollutants out of Chicago and across Lake Michigan. Nonetheless, Chicago's air quality is problematic – recent studies have placed Chicago's air quality as 22nd worst in the country and deteriorating rapidly (IDPH 2016, ALA 2018abc), spurring calls for action to improve conditions deleterious to public health (Ruppenthal 2018, ALA 2018c). Results from

Chicago are broadly translatable across the Midwest U.S. and Great Lakes – one of the most populous and economically important areas of the country. Most cities in this region have similar demographics and infrastructure. The entire region faces increasing extreme weather and mounting infrastructure costs over the next 50 years (CNT 2013, Pryor et al. 2014, Winters et al. 2015, Sharma et al. 2018).

The city benefits from a confluence of multiple levels of city, state, and federal environmental and weather data. In addition, SAVEUR will substantially leverage the new *Array of Things* (AoT) distributed sensor network that is being deployed with support from an NSF Major Research Infrastructure award (ACI-1532133). This project has developed new open-source sensor technology (*Waggle* sensor nodes) along with data transmission and archiving capability (*Beehive*, *Plenario*) to enable monitoring of environmental conditions at city scale (Beckman et al. 2016). Standard Waggle data products are listed in Table 1. 105 AoT Waggle nodes have been deployed to date (Fig. 6), and the project has now reached full commercial production, which will yield an additional 100 sensor nodes deployed within the next two months, and ultimately a total of 500 nodes across Chicago in the next two years. With support from an NSF EAGER award (EAR-1541891), we integrated water sensors into Waggle nodes and used them to monitor 6 urban nature preserves, parks, and food production facilities in the Chicago area. These Waggle research nodes incorporate additional sensors for water levels, salinity, and soil moisture, along with an imaged data product for flooding, that we developed and tested on our network of research sites.

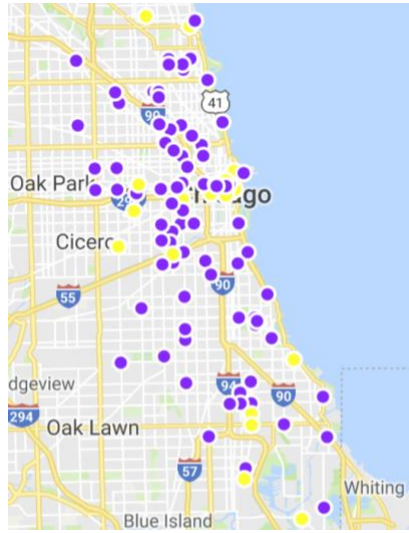

Fig. 6: Existing (purple) and planned (yellow) AoT sensor locations in the Greater Chicago area.

The proposed Convergence efforts benefits from physical and operational infrastructure in Chicago. The city has an extensive and well-coordinated network of parks, nature preserves, and other open lands, which are supported by a confederation of governmental and non-governmental groups (notably Chicago Metropolitan Planning Council, The Nature Conservancy, Chicago Park District, Forest Preserves of Cook County, and Openlands). There has recently been strong interest and investment in distributed green infrastructure for stormwater control and other urban benefits. The project team has strong partnerships with local governmental and NGO entities with responsibility for air, water, land, and data in Chicago, which includes support for site access, data sharing, and sensor deployment. These partnerships are documented with letters of collaboration from the City of Chicago Department of Innovation and Technology, Metropolitan Water Reclamation District of Greater Chicago, Lake Michigan Air Director's Consortium, and the Chicago Park District.

Table 1: Left: AoT standard atmospheric sensors. Right: AoT water and wind sensor packages.

Measurement	Range	Accuracy		Measurement	Range	Accuracy
Air Temperature (10x sensors)	-55 to +80 °C -40 to +125 °C -55 to +127 °C	±0.05 °C ±0.5 °C ±1.5 °C		**Waggle-integrated Instrumentation** Rainfall Rate	0 to 50 mm/hr	± 1%
Relative Humidity (3x sensors)	0 to 100% RH	±0.04 %RH		Wind Speed	0 to 50 m/s	± 0.5 m/s
SO_2 Concentration	0 to 20 ppm	±3%		Wind Direction	0 to 352°	± 5°
H_2S Concentration	0 to 50 ppm	±3%		Water Level	0 to 11 m	± 0.05%
O_3 Concentration	0 to 20 ppm	±3%		Water Temperature	-20 to +80 °C	± 0.1 °C
NO_2 Concentration	0 to 20 ppm	±3%		Soil Moisture	0.0 to 1.0 m^3/m^3	± 0.03 m^3/m^3
CO Concentration	0 to 1,000 ppm	±3%		Electrical Conductivity	0 to 23 dS/m	± 10%
Reducing Gases Concentration	0 to 20 ppm	±3%		Soil Temperature	-40 to +60 °C	± 0.1 °C
Oxidizing Gases Concentration	0 to 20 ppm	±3%				
Light Intensity (6x sensors) λp = 500 nm λp = 365, 640, 700, 900 nm	0 to 1000 LUX 0-124 μW/cm^2 typ	±0.68 % ±16 μW/cm^2 typ		**Locally-deployable Sensors** Water Level	0-4 cm	± 0.1 cm
Particulate matter (2x sensors) 10, 5, 2.5, 1.0, 0.5, 0.3 μm	0 – 100 μg/m^3	± 10 μg/m^3		Soil Moisture Sensor	0.0 to 1.0 m^3/m^3	± 10%
Atmospheric Pressure (2x sensors)	300 to 1100 hPa 260 to 1260 hPa	±0.02 hPa ±0.1 hPa				

Research Methods:

The convergence vision will be achieved through five interlinked research tasks (Fig. 7). Integration of weather, air quality, and stormwater models with environmental and social impact data represents a critical focus of the proposed convergence effort. To that end, weather models will be used to drive air quality and flooding assessments, and AoT data products will be used to assess and improve weather models. We will use AoT data products to detect the ground-level response to remotely sensed (radar) and sparsely sensed (air quality, flooding) conditions, which will support downscaling of models to the street level where impacts are felt. The extreme events of interest are primarily summer heatwaves, intense thunderstorms, lake-effect precipitation resulting from circulation over Lake Michigan, and winter rain-on-snow events, which are historically extremely rare, but have caused extreme flooding in the last two years (Sharma et al. 2018, NWS 2018a, Held 2018, Ruppenthal 2018b). We will particularly assess conditions that led to infrastructure failures, such as sewer overflows into Lake Michigan, and heat waves that significantly impact public health. We will combine systems analysis using distributed data resources with targeted research in local communities to assess the social, economic, and health impacts of extreme weather. Finally, we will use scenario-based predictive modeling to assess how infrastructure investments, notably distributed green infrastructure, can be used to reduce both vulnerability in highly-impacted communities and ensemble city-scale vulnerability.

Fig. 7: SAVEUR Convergence Research

Task 1. Improve characterization and simulation of extreme weather events over Chicago

Extreme storms: The primary driving variables of interest for the proposed assessment of extreme storm impacts are temperature, dew point temperature, windspeed, and rain rate at the surface. The primary data set will be NEXRAD WSR-88D weather radar (Crum & Alberty 1993), coupled with surface observations and satellite imagery. Chicago's radar is located 40 km west-southwest of the city, providing a resolution of approximately 300 m. The latest generation of NOAA weather satellites (GOES R/S) provide 1 km 13 μm imagery which can be used to derive emission temperature, which we will couple with surface observations (NOAA and AoT) to produce temperature maps.

Three approaches will be used to process precipitation data: traditional radar processing techniques, data assimilation at newly-resolved scales, and transposition of high-resolution data onto Chicago. Traditional processing will involve quality control on NEXRAD data for clutter and other artifacts, processing of polarimetric phase, retrieval of relevant data using specific attenuation, and mapping to a latitude/longitude grid. All work will be performed using the open source Python ARM Radar Toolkit developed by co-PI Collis (Helmus & Collis 2016). This technique will create a grid of rain rates at 300 m spatial resolution and 10 min temporal resolution. In order to achieve block-by-block resolution (approximately 50 m), we will perform three-dimensional data assimilation of radar and ground-level data into an LES model, using the Weather Research and Forecasting model (WRF). A third approach to providing data for precipitation extremes will be to transpose leading-edge high-resolution radar network data over the Chicago Region. We will work with the Collaboration on Adaptive Sensing of the Atmosphere (CASA) project to evaluate the use of high quality radar networks to obtain precipitation and wind data with <100 m resolution, and compare the results with our other weather assessment methods. This effort is documented in a letter of collaboration from the CASA PI, V. Chandrasekar.

Heatwave events: For diagnosis of heatwave events, we will use a data-fusion approach using AOT, station data, reanalyses and satellite data, as well as data assimilation into an LES model. Initial simulations of lake breezes (heatwave relief) over Chicago have been performed on high-performance computing systems at Argonne National Laboratory and achieved <100 m resolutions.

Analysis of air quality is detailed in Task 2, *Improve prediction of air quality distributions at neighborhood scale*, and flooding is described in Task 3, *Improve prediction of flooding distributions at neighborhood scale*. Approaches for evaluating impacts are detailed in Task 4, *Assess social and economic impacts of extreme weather across Chicago*, and simulation conditions for evaluating vulnerability to extreme weather are detailed further in Task 5, *Convergence framework to reduce vulnerability to extreme weather events*.

Task 2. Improve prediction of air quality distributions at neighborhood scale

Modeling and Simulation: There is substantial overlap between the meteorological conditions that lead to summer heat waves and those that result in poor air quality. While models capable of co-simulating high-resolution meteorology and atmospheric chemistry now exist, they are limited by the lack of high-resolution speciated emissions and observations to verify model simulations. Current operational air quality forecasts provided by the National Weather Service (NWS, 2018b) utilize the CMAQ-WRF modeling platform at 12 km resolution. However, simulations of air quality impacts are sensitive to both model and emission resolution (Thompson et al, 2014), and greater resolution of emission sources is needed to support high-resolution CMAQ-WRF simulations. Collaborators at the Lake Michigan Air Directors Consortium have developed 1.3 km resolution speciated emissions for the Great Lakes Region using the EPA's Sparse Matrix Operator Kernel (SMOKE) Modeling System, and have agreed to share this dataset as detailed in their letter of collaboration. We will use CMAQ-WRF and the 1.3 km speciated emissions data set, in conjunction with meteorological boundary conditions from the North American Reginal Reanalysis (NARR) and North American CORDEX projects, to simulate heat waves and poor air quality conditions over Chicago with neighborhood-scale resolution (~1 km).

Data analysis: To enable fusion of available air quality data products, we will first evaluate the performance of AoT air quality sensors against established air quality monitoring stations. For this purpose, we will conduct statistical time-series analysis for all monitored atmospheric conditions in the AoT nodes located at the EPA site hosted by ComEd (an AoT project partner). The AoT observing network will significantly improve current air quality monitoring density, serve to verify land use amelioration hypotheses, and help to identify GI mitigation targets. The AoT sensor network is configured to continually monitor O_3, SO_2, PM, H_2S, NO_2, and CO at 30 s intervals. Sensor performance is listed in Table 1 (above), and specifications can be found at the AoT page on GitHub (AoT 2018). The existing AoT sensor network (105 nodes) and full-scale AoT deployment (500 nodes) will provide air quality monitoring across a diverse range of land use categories, including low, medium, and high intensity urban environments, and greenspaces including urban parks, farms, nature preserves, and forest preserves.

AoT air quality observation performance will be evaluated against the operational EPA Air Quality System (AQS) observational network (EPA 2018). The AQS network utilizes ~10 monitors per measured constituent within the Chicago area, though many constituents are measured in different localations. AoT data will be assessed for bias, drift, co-variability, meteorological sensitivity, and day/night/seasonal dependencies using methods described in Fishbain et al. (2017ab). Data found to exceed performance thresholds will be used to assess the ameliorating effects of GI on heat/air-quality impacts over disparate land use categories under similar meteorological conditions, in particular during heat waves. AoT air quality observations will be aggregated using a nearest-neighbor interpolation scheme to produce a spatially-gridded high-resolution air quality constituent map. Gridded AoT data will be compared to 12 km archived operational NWS air quality forecasts, as well as our 1.3 km simulations of air quality.

Scenario-based Air Quality Simulations: Green infrastructure has been shown to ameliorate urban heat island impacts (Gill et al. 2007, Bowler et al. 2010, Demuzere et al. 2014). However, no available models support physically-based neighborhood-scale analysis of the effects of green infrastructure on both temperature and air quality. Coupling of atmospheric chemistry and meteorological model components is essential in scenario-based green infrastructure simulations due to the potential for green infrastructure design to have tradeoffs and unintended consequences, e.g., widespread implementation of green roofs may reduce the planetary boundary layer height (Sharma et al. 2016), which could potentially reduce ventilation and dispersion of air pollutants. We will utilize the CMAQ-WRF modeling platform to assess the effect of a suite of green infrastructure scenarios on extreme heat and air quality across Chicago. Green infrastructure scenarios will be co-designed with the SAVEUR convergence team and project partners, and then implemented in the CMAQ-WRF modeling platform using a) WRF's Noah LSM high-resolution land data assimilation system (HRLDAS; Chen et al. 2007) and b) commensurate changes to the biogenic emissions in the 1.3 km SMOKE dataset.

This work will directly use results of Task 1. *Improve characterization and simulation of extreme weather events over Chicago*, and inform Task 4: *Assess social and economic impacts of extreme weather*. Conditions and scenarios that will be tested are described under Task 5, *Convergence framework to reduce impact of extreme weather on urban communities*. All projections of future states will consider multiple-impact vulnerabilities, integrating information and models on extreme weather, air quality, and flooding.

Task 3. Improve prediction of flooding distributions at neighborhood scale

Data analysis: Areal flood data are essential for flood prediction, yet rarely available. We will use two approaches to gather distributed flood information from AoT. First, we will integrate water level sensors into 12 AoT Waggle sensor nodes for direct measurement of surface flooding in streets and parks. Most AoT Waggle nodes were deployed by the City of Chicago on traffic signal poles, which provide convenient platforms to measure street flooding. For this purpose, we have integrated vertically-oriented sets of water sensing switches into the Waggle platform. Each sensor detects water level over a range of 4 cm with 0.1 cm resolution. These sensors have been successfully deployed to detect flooding at the Tuley Park Fieldhouse, located in the flood-prone Chicago South Side community of Chatham (Fig. 8). We will deploy sets of these sensors at the base of traffic signal poles to monitor street and surface flooding.

Second, we will adapt computer-vision techniques used in AoT to develop "visual sensors" that measure distributions of standing water and rates of water accumulation at each Waggle node. The Waggle platform uses a single-board computer for edge processing. A Samsung quad-core CPU and GPU, more commonly used in smartphones, provides the local computing power. Prior development has shown that Waggle nodes can use both OpenCV and the deep learning (DL) framework Caffe (Jia et al. 2014) to extract data from images. In 2017, NU students extended OpenCV algorithms to detect surface water in images (Fig. 7). Using only 50 consecutive images, edge processing within Waggle nodes could segment images and calculate the portion of the field covered by water. We have successfully deployed this approach to assess surface flooding in our AoT water test sites (Fig. 8). We will refine this approach at the 12 test sites we will instrument here with water-level sensors, and then deploy it across the entire AoT network. By creating a database of "dry" reference images for each camera location and "ground-truth" water level sensor data, we can create image classifiers capable of accurately reporting water depth. We will first create a benchmark set of labelled (dry, wet, flooded) photos for initial training purposes and then refine our DL approach using the combination of Waggle images and independently measured water level data.

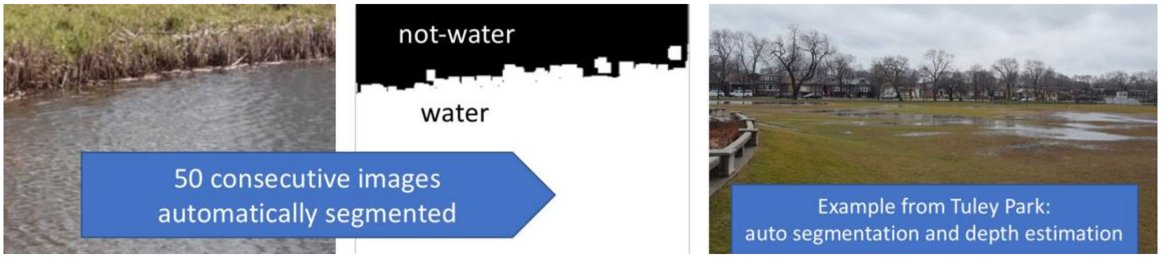

Fig. 8: Preliminary results of computer vision approach for areal estimation of flooding.

Modeling: Wastewater and stormwater are the two major water flows of concern for extreme weather in Chicago. Combined sewers collect sanitary flows and stormwater runoff from a total area of 971 km^2 (375 mi^2) (Fig. 9). Interceptor sewers primarily convey dry weather flows (DWF) to treatment plants operated by the Metropolitan Water Reclamation District of Greater Chicago (MWRD). Treated effluent is released to the Chicago Area Waterway System (CAWS). However, in case of extreme storm events, wet weather flow (WWF) in excess of the diversion capacity causes flooding into residential basements, waterways, and Lake Michigan. The massive Tunnel and Reservoir Plan (TARP) was added to provide additional storage of WWF to mitigate combined sewer overflow (CSO) and flood risks in extreme storms. Four TARP tunnel systems (Fig. 9) receive sewage from 645 overflow points by means of 252 dropshafts. Three reservoirs provide flood relief by storing the wastewater conveyed by the TARP tunnels. Stored water is treated prior to discharge into CAWS, yielding approximately 85% reduction of pollution potential (MWRD 2011). However, street and basement flooding is still a frequent problem in areas of the city not well protected by the core stormwater infrastructure system, and overflows to the lake still occur once or twice per year. This has led MWRD to pursue distributed green infrastructure solutions to reduce flooding risk.

The TARP system is fed by a complex network of urban catchments and sewers, which interact with larger intercepting sewers and flow control structures. The right panel of Fig. 9 depicts the myriad hydrologic and hydraulic processes that occur in the highly urbanized drainage system of the greater Chicago area. This metasystem results in extremely complex hydrological responses, yielding high nonlinearity and heterogeneity in stormwater flows (Cantone & Schmidt 2011). No existing hydrologic and hydraulic model is capable of accounting for all of these processes and the links between them (Luo & Garcia 2018).

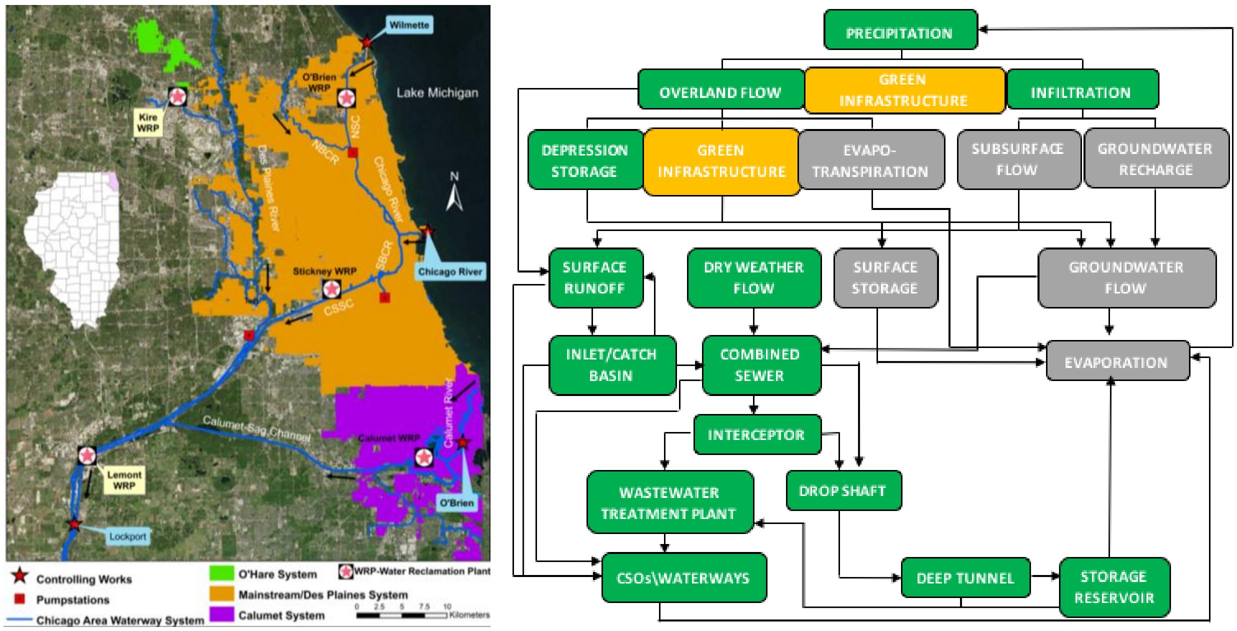

Fig. 9. Left: Chicago area stormwater control system, including TARP, water reclamation plants, and hydraulic control points. Right: Schematic of MetroFlow simulations of urban stormwater flows in Chicago (Luo and Garcia, 2018), integrating the Dual Drainage hydrologic model for green infrastructure (Yellow boxes, Nania et al., 2014).

Analysis of the interconnected street, sewer, and TARP drainage system performance is essential to design drainage system alternatives, and operate the existing, aging systems in a cost-effective manner (Adams & Papa 2000). We will expand the hydrologic and hydraulic modeling package MetroFlow to assess responses to extreme storms, including the interaction of precipitation inputs with the land surface, sewers, reservoirs, and waterways (Oberg et al. 2013, Luo et al. 2014). MetroFlow supports a suite of models to simulate the integrated urban catchment and stormwater/wastewater network in a tightly coupled manner. The current version of MetroFlow incorporates four models: the Illinois Urban Hydrologic Model (IUHM) for stormwater flow (Yen & Lee 1997, Cantone and Schmidt 2011), the Chicago of Chicago InfoWorks model of the city's combined sewer system, the City's CS-TARP model of the TARP tunnel and reservoir system (Luo et al. 2014, Luo & Garcia 2018), and the Illinois Conveyance Analysis Program (ICAP) hydraulic model of the conveyance capacity of the TARP tunnels and reservoir (Oberg et al. 2017).

To better understand the effects of land use and explore green infrastructure solutions to reduce flooding, we will add a Dual Drainage hydrologic model to the MetroFlow system (Fig. 9). The Dual Drainage model represents interactions between open land and impervious cover in the cityscape, including infiltration, runoff, and subsurface storage (Nania et al., 2014). Improved resolution of extreme precipitation plus distributed AoT data will enable us to assess patterns of flooding with greater resolution than was previously achievable. This model will enable detailed evaluation of the existing urban flow system, conventional stormwater alternatives, and green infrastructure alternatives. Simulations will be used to assess the potential of combined green-gray stormwater infrastructure to reduce urban flooding and CSOs.

This work will directly use results of Task 1: *Improve characterization and simulation of extreme weather events over Chicago*, and inform Task 4: *Assess social and economic impacts of extreme weather*. Scenarios and test cases are described in Task 5, *Convergence framework to reduce impact of extreme weather on urban communities*.

<u>Task 4. Assess social and economic impacts of extreme weather</u>

<u>City-wide impacts</u>: We will characterize the impact of extreme weather events on city residents' health, safety, and economic well-being at a high spatial and temporal resolution using the rich data from the Chicago Data Portal (Fig. 10), the Center for Neighborhood Technology (CNT, 2013) and other groups that monitor public health (e.g., CMAP 2018). To assess flooding impacts, we will aggregate City of Chicago 311 call reports at the street address level, available through the City of Chicago Data Portal, with zip-code-level flood insurance claim data collected by CNT (2013) to assess the extent, severity, impacts, and costs

of flooding between 2007 and 2011 in Chicago. Information on health impacts of high temperature and poor air quality across the city are available from Chicago public data records and the Chicago Bloomberg and COMPASS public health projects, both of which are examining the effects of air quality on negative health outcomes. The AoT network, with its newly-deployed water sensors and computer vision software, will yield distributed information on temperature, air quality, and flooding across the city. Air quality and stormwater models will use this information to provide continuous distributions across the city, linked with detailed information on spatial patterns of extreme weather.

This effort will use distributed information on temperature, air quality, and flooding across the city from Tasks 1-3 to assess critical inter-relationships between demographic distributions, extreme weather patterns, infrastructure performance (e.g., stormwater, buildings), adverse environmental conditions (flooding, high heat, poor air quality), and social, economic, and health impacts.

Fig. 10: Left: Data available through the Chicago Data Portal. Right: Spatial resolution of relevant data.

Social research in vulnerable Chicago neighborhoods: To better understand Chicago residents' perceptions, experiences, and perceived and actual impacts of flooding, extreme heat, and poor air quality, we will conduct in-depth qualitative research using standard anthropological techniques. Given the highly segregated nature of Chicago's neighborhoods and communities, a hyper-local scale will be essential to uncover disparities in outcomes and impacts, and to propose context-specific solutions. Layering socio-demographic, health, and economic data over multiple extreme weather hazards will provide a more holistic picture of impacts at the city level. We will leverage our ongoing community-based research on urban flooding and green infrastructure in the Chicago South Side neighborhoods of Chatham and Markham to assess other at-risk communities in Chicago. These areas are among the most flood-impacted communities in the greater Chicago region (CNT 2013, 2015).

Using the high-resolution vulnerability maps of extreme weather events, air quality, flooding, and socio-demographic factors developed through Tasks 1-4, we will identify communities across the city of Chicago that are particularly vulnerable to multiple extreme weather hazards. Through partnerships with local community organizations (e.g. block club associations and community groups including Center for Neighborhood Technology, Faith in Place, and The Nature Conservancy), we will recruit key informants for qualitative, in-depth interviews (approximately 10 per community) and focus group discussions (approximately 2 per community). In addition to documenting social, economic, and health consequences of flooding, extreme heat, and poor air quality, we will also assess participants' knowledge and risk perceptions of extreme events, adaptive management strategies, and attitudes toward green infrastructure, These localized qualitative data will serve to verify impacts projected from models and larger-scale data analysis. Primary data collection at the neighborhood scale provides localized analysis, and can also be aggregated to assess city-scale effects.

This work will directly utilize results of Tasks 1-3 to inform extreme weather conditions and impacts. We will incorporate this information into the SAVEUR Convergence framework (Task 5, below) to evaluate the effects of extreme weather on multiple social, economic, and health outcomes under future-state scenarios.

Task 5. Convergence framework to reduce vulnerability to extreme weather events

We will test the three Convergence hypotheses integrating the results of Tasks 2-4, and use the findings to develop a Convergence framework to inform strategies for reducing vulnerability to extreme weather. To test Convergence Hypothesis 1 (Improved spatial resolution of extreme weather events will improve the fidelity of predictions of impacts), we will first develop high-resolution vulnerability maps for temperature, air quality, flooding, and overall vulnerability to extreme weather based on current climate and land use. We will compare maps generated using currently-available weather resolution against those based on the higher-resolution information we will develop in this project, and assess the predictive power of atmospheric and hydrologic models for adverse impacts with each spatial resolution. We will compare projected vulnerability maps with impact measures, e.g., City of Chicago public data records on flooding reports, CNT flood damage assessments by zip code, health indicators of temperature and air quality impacts, and economic losses from flooding. Social outcomes will be verified through qualitative social research in vulnerable neighborhoods (Task 4). Ability to predict impacts will be evaluated in terms of both overall correlations and spatial statistics. Finally, we will parameterize a general statistical model for each impact measure at city scale, and relate these to land-use and socio-ecological measures such as distribution of greenness, impervious cover, property values, income levels, housing stocks, and infrastructure maps. We will compare our predictions of vulnerability against existing data products such as U.S. EPA's Air Quality Index maps and FEMA flood risk maps, and determine the drivers of observed differences.

To test Convergence Hypothesis 2 (Urban greenspace significantly reduces air temperature, improves air quality, and reduces stormwater runoff), we will evaluate reductions in extreme conditions observed at AoT nodes and continuous distributions obtained from atmospheric and hydrologic models against statistical measures of land cover (areal fraction and spatial distribution of greenspace, buildings, impervious cover, etc.) We will perform this analysis for a wide range of spatial averaging scales, from our maximum resolution (500 m) out to whole-city scale. This analysis will capture the spatial scale of benefits from greenspace. For example, this will indicate flood magnitude and frequency as a function of proximity to green infrastructure. We will repeat the analysis conditioned upon wind speed and direction in a Lagrangian framework, with distances transformed to yield a remapping based on travel time to upwind greenspace. This approach will allow us to assess whether spatial proximity or upwind greenspace is more important in reducing extreme weather impacts. We expect that the benefit of greenspace, i.e., direct proximity vs. upwind proximity of greenspace, will vary by type of impact: we expect that direct proximity will modulate flooding because of the local increase in stormwater infiltration and storage, whereas upwind conditions will influence temperature and air quality.

To test Convergence Hypothesis 3 (Green infrastructure will outperform conventional infrastructure in reducing vulnerability to extreme weather), we will develop predicted vulnerability maps and ensemble population vulnerability estimates for a set of future climate and land-use scenarios. We will evaluate the potential for GI to reduce vulnerability by predicting impacts for: 1) currently planned GI installations by MWRD and the City of Chicago, 2) the aspirational Chicago Green Infrastructure Vision, 3) a series of intermediate states of GI deployment, including both city-wide deployment and GI investments targeted in areas of maximum vulnerability. For each scenario, we will evaluate ensemble city-wide vulnerability based on each impact measure used to test Hypothesis 1 (described previously). In evaluating impacts, we will consider weather events that are low-frequency but high-impact (i.e., the most extreme heat waves and precipitation events on record) and high-frequency but low-impact (e.g., typical summertime heat waves and thunderstorms) to assess how different GI deployment strategies reduce long-term ensemble risks. Historical extreme events will include the July 2012 and September 2017 heat waves and the 2008 and 2013 floods. More frequent extreme events (e.g., annual maxima) will be obtained from the AoT data record.

We will use these results to evaluate opportunities to mitigate multiple extreme weather impacts through both single-purpose and multiple-effect solutions, and consider costs of alternative infrastructure solutions to reduce vulnerability. We will develop two types of indices for evaluating infrastructure alternatives. The first will be a Vulnerability Reduction Cost Index (VRCI) based on social and health costs, infrastructure construction costs, and infrastructure maintenance costs. For this analysis, we will rely on existing correlations between health and social impacts and costs developed, for example, by the US EPA for air-pollution-induced respiratory illness. We will also work with partners such as The Nature Conservancy (Chicago Urban Program and Global Cities Program) to assess the co-benefits of green infrastructure, such as increased biodiversity. However, we will only add co-benefits to the cost index in cases where there are clear methods for monetization, to ensure that the VRCI remains an actionable basis for infrastructure design to reduce vulnerability. The second infrastructure evaluation tool will be a Vulnerability Reduction Social Index (VRSI) based on social impact metrics. We will explore how existing indices such as the Social Vulnerability Index (Meerow & Newell 2017) perform for this purpose, and also investigate alternative strategies for evaluating human impact, e.g. principal component analysis of perception-based metrics such as household water insecurity experiences using high-resolution data (Jepsom et al. 2017).

The collective outcomes of Tasks 1-5 will be comprehensive understanding of the value of high-resolution data and models for prediction of extreme weather impacts, and detailed assessment of the potential for GI solutions to cost-effectively reduce ensemble vulnerability to extreme weather.

Convergence Strategy:

Our Convergence Strategy is to collaboratively pursue critical science advances in urban systems, and work with a wide range of partners to translate these advances into meaningful vulnerability reductions in our city – Chicago – and similar cities across the U.S. and around the world.

SAVEUR Convergence strongly benefits from a dedicated effort by the team to define urban vulnerabilities, science needs, and engineering solutions over the last several years. Convergence discussions were initiated at major conferences organized by team members, such as the 2016 Northwestern Climate Symposium: Water, Energy, and Climate, which specifically addressed urban climate adaptation, flooding, and green infrastructure solutions. Planning of activities linked with the AoT project fostered a tangible series of discussions on common approaches for assessment, prediction, and amelioration of extreme weather impacts. This includes detailed assessment of the data content of current AoT sensor packages, strategies for expanding the range of sensors to capture additional critical environmental parameters, and approaches for integrating environmental data with social and economic data. More recently, we have pursued targeted science objectives and societal solutions at a series of workshops. Paired workshops in Taipei and Chicago on the Sustainable Water Environment in Megacities (August and September, 2017) formulated research needs for urban water sustainability, including needs to enable assessment and design of green infrastructure solutions. The Northwestern Urban Resilience workshop (Bounce Forward: Moving Communities from Crisis to Resilience, April 19-20, 2018) explored critical challenges faced by cities and ways to integrate science and engineering advances into urban planning for resilience. The NAISE Workshop on Climate Modeling, Resilience, and Risk (April 23, 2018) supported directed discussions of how modeling tools could be advanced to improve assessment and prediction of urban vulnerability to extreme weather events. Each of these events enabled us to articulate research needs, identify opportunities, and develop partnerships that are included directly in the convergence effort proposed here.

These activities led to the **shared Convergence Vision** that is the central organizing principle of this proposal. Our common understanding of grand research challenges, shared vision for addressing these challenges, and consensus research goals to achieve this vision are critical for team cohesiveness. The deep recognition by all team members that progress can only be made on reducing vulnerability to extreme weather through close collaboration will foster true convergence of people, expertise, and methods.

To facilitate ongoing convergence, we will engage in a continuous series of activities to support close collaboration of all team members. Integrated convergence activities during the proposed work will include regular reexamination of the convergence vision and project goals, joint activity of all project-supported students and postdocs, and ongoing directed discussion involving all team members. We will hold a project kickoff workshop to align activities and engage participants around project convergence themes. This will include a review of the convergence vision and joint roadmapping of research activities with local partners (City of Chicago, MWRD, Chicago Park District, Metropolitan Planning Commission, The Nature Conservancy). This activity will not only ensure alignment of convergence research activities, but also engage partners into the formulation of impact assessments, test cases, and modeling scenarios. Subsequently, we will hold annual convergence workshops to reinforce and update the shared convergence vision, report progress to partners, and refine metrics and use cases.

Convergence activities will engage project investigators, students, and postdocs in active collaboration. We will provide unique cross-training to a cadre of students and postdocs co-advised by the entire project leadership team. Students and postdocs will be cross-trained through dedicated time working with each project investigator. The Northwestern Data Science Initiative provides specific training – coursework, short courses, and data hackathons – for students and postdocs who do not have prior experience with data analysis and programming. Cross-training will ensure that all trainees are proficient with all research methods, which will not only directly foster convergence, but also define the new urban systems science that we envision as the outcome of this convergence effort. All project investigators, students, and postdocs will hold videoconferences bi-weekly to ensure ongoing coordination. All institutions involved in this effort have excellent web-conferencing facilities to enable direct interaction in these convergence meetings.

To ensure research convergence and inter-compatibility of proposed methods, the first project activity will be a Convergence Exercise – a scaled-down case study containing all elements of proposed convergence research. This Exercise will allow us to coordinate team activity and identify key gaps and challenges that must be addressed in the full city-scale effort. The Convergence Exercise will focus on heavily-impacted areas on the South Side of Chicago, particularly the communities of Chatham and Markham. This initial exercise will compare effects of two very different greenspaces in mediating weather impacts: Indian Boundary Prairies, a large nature preserve in the suburban community of Markham, and Tuley Park, a small recreational park in the highly urbanized community of Chatham. These sites have already been instrumented with Waggle nodes, including all weather and water sensors proposed here, and we have existing partnerships with local community groups to facilitate social science assessments.

Finally, we will achieve convergence of models and data resources, which are often a sharp barrier to integrative studies. All project partners are fully committed to open-source hardware. software, and inter-operable model frameworks. AoT Waggle node hardware plans, sensor specifications, and software are all available on GitHub. Data products are available on the Plenario data archive, which is integrated with the Chicago Data Portal. We will develop and publish (on GitHub) a consistent framework for data assimilation and model integration linking urban weather, air quality, hydrology, and social and economic impacts. This will include full convergence data in addition to standard metadata, breaking the discipline-focused data/metadata framework that is a massive barrier to interdisciplinary collaboration. This will yield a full suite of data across all converged research areas, enabling true convergence of information, models, and predictions for extreme weather impacts in cities.

Intellectual merit:

Convergence Science Advances**:** Developing the science for adaptive, resilient cities will require advancements only possible through Convergence. We will foster a new urban systems science for resilience by developing a suite of multi-level systems approaches for assessment and prediction of urban vulnerability. Convergence of natural science, social science, data science, and engineering will enable assessment of current vulnerabilities and inform design strategies to improve resilience to extreme weather. This effort will require highly coordinated advancements in urban measurement and modeling to link weather, temperature, air quality, flooding, and social and economic impacts. The three key convergence advances we will achieve are: 1) Increasing the spatial resolution of extreme weather assessments to improve predictions of heat waves, air quality, and flooding in cities. 2) Integrating emerging data resources with urban simulation, prediction, and infrastructure design. 3) Relating environmental conditions, land use, and infrastructure performance to community impacts and benefits, including economic, psycho-social, and physical well-being. This convergence project will catalyze new multi-level urban assessment and prediction; yield new capability for city-scale simulations of links between weather, infrastructure, and population vulnerability; and demonstrate the first application of this new systems prediction framework for adaptive green infrastructure design.

Broader Impacts:

Convergence outcomes and impacts**:** Our proposed Convergence approach for assessing and reducing adverse impacts of extreme weather is an essential step towards urban resilience. Project results will be directly used for vulnerability assessment and infrastructure design in the Chicago area. The City of Chicago and MWRD are not only data providers and facilitators of the proposed research, but also key stakeholders who will use SAVEUR results for management and planning. The City of Chicago has made a major commitment to both open data and data analytics for purposes of better government. The City is particularly focused on identifying the potential for green infrastructure to solve air and water challenges, and have their own research on air quality impacts using AoT data, supported by a Bloomberg Resilient Cities grant. MWRD is similarly exploring green infrastructure solutions for stormwater across its service area – which includes the City of Chicago and 128 smaller municipalities. MWRD's Strategic Plan features green infrastructure solutions for stormwater, which are being implementing through community-proposed green infrastructure projects. Model simulations will indicate the potential for green infrastructure to reduce flooding, modulate heat waves, and improve air quality locally and across the Chicago megaregion. TNC and MPC will also use this information to inform near-term and long-term green infrastructure strategies. MPC, TNC, and MWRD are currently exploring stormwater trading-credit schemes that would allow land developers to invest in green infrastructure instead of conventional on-site stormwater storage. This effort will directly utilize SAVEUR Convergence data and models on the scale of localization of green infrastructure benefits for flood reduction.

SAVEUR research products and methods will be disseminated globally through our existing partnerships across the U.S., Asia, Europe, Africa, South America, and Oceana. Notable partnerships for research dissemination include cities participating in the AoT Pilot Program (Denver, Seattle, Portland, Palo Alto, Chattanooga, Detroit, Syracuse, and Chapel Hill); collaboration with The Nature Conservancy Global Cities Program on social benefits of urban green infrastructure; the Household Water Insecurity Experiences program – a global network of 32 research sites including Lagos, Accra, Beirut, Cartagena (Colombia), and Kathmandu; and the HiFreq Horizon 2020 RISE network of 20 partner institutions in the U.K., Spain, Germany, Sweden, Luxembourg, France, Australia, New Zealand, and the U.S.

Education, training, and community engagement activities: The project will support cross-training of a cohort of urban system science students and postdocs. All students and postdocs will be trained and co-advised by the entire team of project investigators to ensure proficiency in all methods used in the project. Students will receive additional training through dedicated workshops focused on open-source programming, simulation, and data analysis. These resources will be extended to the broader research and stakeholder community through AoT end-user workshops. It is anticipated that a total of 6-8 graduate students and postdocs will be directly engaged in the SAVEUR Convergence effort. A larger number of undergraduate students will be engaged through regular summer research programs at our institutions, including the Summer Research Opportunity Program at Northwestern, dedicated student support through the Northwestern-Argonne Institute of Science and Engineering, and the DOE Summer Undergraduate Laboratory Internships program. Project PIs typically engage 10-15 undergraduate students *per year* in research on sensor design and deployment, data analysis, modeling and simulation, and community assessment. Therefore it is anticipated that approximately 40 trainees (undergraduate students, graduate students, and postdocs) will be engaged in urban systems science research over the lifetime of this project.

The SAVEUR Convergence effort will also contribute to public discourse on and development of solutions for urban vulnerability to extreme weather. Project data will be publicly available through the Chicago Data Portal. Vulnerability maps will facilitate public discussion of current vulnerabilities and potential resilience strategies. We will also use these results in community education programs at parks and nature preserves in vulnerable Chicago-area communities, including Indian Boundary Prairies in Markham, Tuley Park in Chatham, and additional parks selected by Chicago Park District. We will deploy interactive displays at each site to illustrate extreme weather vulnerability and the role of greenspaces in modulating these effects. We will also hold workshops for adults and youth at local parks involving presentations on sensor technologies, model predictions, and the potential for local solutions to reduce extreme weather impacts.