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Indicators and monitoring systems for urban climate resiliency

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Abstract
Cities in the USA and around the world have begun to take an active role in responding to climate change. A central requirement for effective urban climate strategies is the capacity to understand and measure how the climate is changing, the physical, environmental, and social impacts of the changes, and whether adaptation and resiliency policies and programs put in place in response are working. The objective of this paper is to review and assess how urban climate change and resiliency efforts can be measured and to define what might serve as meaningful indicator and monitoring protocols. The New York City Panel on Climate Change (NPCC) is used as a case study along with a reviews of the emerging literature of urban climate change indicators to analyze the requirements and processes needed for a successful urban climate resiliency indicator and monitoring (I and M) system. In the paper, the basic requirements of a proposed Urban Climate Resilience Indicators and Monitoring System are presented. A specific illustration of an I and M system for tracking the urban heat island highlights challenges as well as potential solutions embedded within such systems. Discussions how these protocols can be translated to other locales and settings, as well as the relationship to the US National Climate Assessment indicator process, are presented.

Keywords New York City Panel on Climate Change · Urban Climate Resilience Indicators and Monitoring System · Climate assessment

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1 Introduction

A key challenge for US cities as they begin to respond to climate change impacts is how to measure, monitor, and evaluate critical climate change indicators. A tracking system for urban climate indicators is an important tool for decision-makers to help them plan climate change responses and timelines and to communicate with the general public about growing risks and the need for such decisions. By monitoring trends, for example, in coastal flooding, decision-makers and scientists can be cognizant of approaching “tipping points” in regard to system-level thresholds and act as decision triggers for strengthening adaptation measures (Solecki et al. 2015a, b). Creation of an effective indicators and monitoring (I and M) system involves not only defining key climate variables and impacts but also the tracking of adaptation and resiliency measures. Effective indicators are based on sound science, communicate readily with the general public, are promulgated at regular intervals, and provide useful information for decision-making (de Sherbinin et al., 2013). This paper proposes an *Urban Climate Resilience Indicators and Monitoring System* that includes a set of climate change-related indicators and an associated monitoring system protocols that could be implemented by large- and medium-sized cities in the USA.

Peer-to-peer learning is important in advancing responses to climate change across multiple cities. Through the New York City Panel on Climate Change (NPCC), New York City can share lessons learned that are relevant to other cities, recognizing that each city’s context differs. Urban climate change indicators and monitoring emerged as an essential tool for adaptation decision-making with the first New York City Panel on Climate Change (NPCC 2010) and continued as a central focus in the 2015 and 2019 reports (NPCC 2019; NPCC 2015; Jacob et al. 2010a, b). The NPCC 2015 and 2019 reports defined climate change indicators as *empirically based quantities that can be tracked over time to provide relevant information for stakeholder decisions on climate resiliency and on the efficacy of resiliency measures to reduce vulnerability and risk*. They extended the NPCC 2010 approach by elucidating how climate change and urban systems are linked, exploring potential data sources from existing monitoring systems with a view to operationalizing them, and proposing a set of indicators to aid climate change decision-making in New York City (Solecki et al., 2015a, b; Blake et al. 2019).

An ambition of cities is to design and implement a climate resiliency indictors and monitoring system that provides actionable data and opportunities for new analysis. This will, by necessity, be an incremental and additive process, building to a large extent on current environmental monitoring systems. Further, such systems should reflect ongoing technical and research advances, infrastructural changes, and governance shifts within and across cities so as to provide timely information for climate resiliency decision-making over the coming decades. The most broad expectations of an Urban Climate Resilience Indicators and Monitoring System is that it includes capacity to provide data and information directly relevant for a wide group of potential users through a process that is sustainable and transparent. The requirements needed to achieve these conditions are described in the paper. In this regard, the paper addresses and considers (1) conditions to enable indicators and monitoring systems already in place in cities to be applicable to climate change risk management, (2) opportunities and barriers in establishing a climate change indicators and monitoring system in cities, and (3) how can a system of this type be translated to cities throughout the USA.

The proposed Urban Climate Resilience Indicators and Monitoring System is structured to achieve several overarching goals. First, it must integrate with national- (i.e., the US Global Change Research Program (USGCRP) indicator system and associated National Climate

Assessment indicator process[1]), state-, and local-level indicator systems and monitoring capacities. Second and more specifically, it should be designed to be responsive to the requirements of climate change action in urbanized settings and demands of city-level climate risk managers and urban system operations specialists. Urban climate indicators will be required to encompass the tightly coupled structure of urban systems and the complex context of contemporary social, economic, and political conditions found in cities. Third, it should explicitly focus on the indicator and monitoring needs of the local disaster risk reduction and climate change adaptation communities, and potential linkages between the two. Secondary objectives of such a system in New York City are to track the evolution of global and metropolitan climate change, document climate change vulnerability and interdependent impacts in the region, and enable the evaluation of programs and policies designed to enhance resilience. Co-benefits include the use of the indicators for research and the linkage of climate change action in the New York metropolitan region to the fulfillment of the United Nations' Sustainable Development Goals.

Overall, this effort was designed to be part of the Kenney and others lead *Climatic Change* special issue on climate indicators and monitoring (Kenny et al. 2018) and to have specific reference to cities and urbanized areas (Kazak 2018; Sanchez et al. 2018; Tyler et al. 2014, 2016; USDN 2016; de Groot-Reichwein et al., 2018). The paper also reflects the growing interest in the development and implementation of city-focused I and M systems. This interest has emerged from two primary sectors: (1) climate change networks focused on cities including C40, ICLEI, and RC100 (Rockefeller Foundation Resilient Cities 100 program, UCCRN (Urban Climate Change Research Network), and USDN (Urban Sustainability Directors Network) and (2) individual cities with robust climate change strategies (Blake et al. 2019). Many of these initiatives such as the STAR communities' program or ICLEI's Resilient Cities initiative initially[2] were focused on broader issues such as urban sustainability and have included increased attention to climate change indicators.

The primary focus on city-focused indicator analyses and studies has been on climate change risk metrics (i.e., conditions of changing or dynamic weather and climate) and climate mitigation metrics (i.e., rates and ratios of carbon emission reduction). With the development and implementation of indexes on infrastructure and social vulnerability (e.g., SoVI®), climate impacts and vulnerability became measured and cataloged more regularly. Most recently, equity and adaptation indicators have been considered even though they have proved to be the most difficult to define and implement because of the complex character of metrics (i.e., comparative and subjectivity) and monitoring requirements (e.g., short-term, acute exposure that difficult to predict and in turn measure).

2 Requirements

Primary requirements of an urban indicator and monitoring systems are that it must link with existing I and M systems, the conditions and constraints of the urban context, and evolving disaster risk reduction and climate change adaptation strategies. Each of these issues is examined below.

[1] See www.globalchange.gov/indicators for more information.
[2] See weblinks: http://www.starcommunities.org/get-started/leading-indicators/ and http://resilientcities2015.iclei.org/fileadmin/RC2015/files/A1_WCCD_Panel_FinalSessionDescription.pdf.

2.1 Linking with existing systems

Cities throughout the USA (along with their county, state, and federal partners including the USGS, EPA, NOAA, and DHS) already track many indicators in monitoring programs that focus on the environment and human health (USGAO, 2004). The extent and scope of environmental quality monitoring grew dramatically in the 1970s with the advent of comprehensive federal legislation focused on hazards, pollution, and hazardous and toxic material management and control. Within a typical US city, municipal, county, state, and federal agencies likely collect environmental data and information on dozens of conditions including basic metrics such as temperature and rainfall, tide cycles, flooding and water flow, water storage, soil moisture, relative humidity, air quality, water quality, and combined sewer overflows, among many others. These data are gathered via a wide diversity of collection strategies and mandates while coordination is often lacking (USGAO, 2004).

A critical need to define how cities can expand these programs to assess ongoing and accelerating climate risks and evolving resiliency strategies. While distributed ownership of elements of the system is important, it is also crucial that I and M systems build towards larger resiliency goals that cannot be accomplished through individual agency efforts alone.

Translating traditional environmental quality indicators to effective climate resiliency indicators is a several-step process. A first step is an evaluation of how well these indicators address climate resiliency requirements (e.g., Moench et al., 2011; Tyler et al., 2014, 2016) and are policy relevant, analytically sound, and measureable (see Appendix 1) (NPCC, 2010; Jacob et al., 2010a, b; Kenney et al., 2014). Urban physical and social vulnerability is a key concern (Romero Lankao and Qin, 2011; Swart et al., 2012). Previous I and M systems in cities also have addressed urban sustainability (Shen et al., 2011) and assessed air and water quality (EIU 2012; Muller et al., 2013).

A successful urban climate resiliency I and M system needs to link with the evolving state-, national-, and global-level climate change indicator protocols. For example, the US Global Change Research Program (USGCRP) initiated an indicator system development process starting in 2010 (Janetos et al., 2012). Through this process, a set of pilot climate change and impact indicators was defined that form the basis for a sustained national climate change indicators system to support the National Climate Assessment (NCA) (Kenney et al., 2016; USGCRP, 2016). The USGCRP along with the NCA process and federal agencies have continued to develop the indicator system and created an indicator platform for users and engagement.

Elements of this approach have been incorporated into an ongoing effort to develop a climate change indicator and monitoring system for the City of New York through the work of the NPCC. NPCC and its partners in the city government identified three categories of indicator metrics. Those are related to (1) changes in the physical climate; (2) risk, exposure, sensitivity, and vulnerability; and (3) tracking the efficacy of adaptation measures (Jacob et al., 2010a, b; Solecki et al., 2015a, b). The city is now in the process of defining specific indicators and their composition and structure to reflect those used at other spatial scales to provide line-of-sight comparison and comparative metrics (see Table 1).

2.2 The urban context

A successful Urban Climate Resiliency Indicators and Monitoring System should be attuned to the environmental data and information conditions and constraints present in contemporary US

Table 1 Pilot indicators from the US National Climate Assessment and applications to the global, national, and city level (USGCRP, 2016; adapted by Center for Climate Systems Research, 2016)

National climate assessment indicator	Global	National	City
1. Annual Greenhouse Gas Index	✓	✓	✓
2. Arctic sea ice extent	✓		
3. Atmospheric carbon dioxide	✓		
4. Forest cover	✓	✓	✓
5. Frost-free season		✓	✓
6. Global surface temperatures	✓		
7. Grassland, shrubland, and pasture cover	✓	✓	
8. Heating and cooling degree days		✓	✓
9. Ocean chlorophyll concentrations	✓	✓	
10. Sea surface temperatures	✓		✓
11. Start of spring		✓	✓
12. Terrestrial carbon storage	✓	✓	
13. US surface temperatures		✓	✓
14. Vibrio infections		✓	✓

cities. Six dimensions can be defined through a review of relevant literature and experience: flexibility, continuity of data, complexity, equity, operational resiliency, and multiple spatial and temporal scales. While many of these factors are applicable to non-urban settings, they become especially important when applied to urban contexts.

2.2.1 Flexibility

An urban climate resiliency I and M system needs to enable understanding of how climate is changing, what impacts are occurring, and when adaptation interventions are needed (Solecki and Rosenzweig, 2014). The systems must be able to respond to a variety of climate risk conditions, not only tracking long-term trends and shifts but also the circumstances that emerge during acute events, such as the impact of a large-scale intense precipitation event. Heat waves and coastal storms often cause the most damaging impacts on urban systems, including on health and well-being (Solecki et al., 2015a, b). The system also has to be adjustable as new climate risks, response strategies, and new sensing systems or data collection platforms (e.g., social media in the 2000s) emerge over time.

2.2.2 Continuity of data

A basic requirement of any indicators system is to facilitate understanding of trends over time. It is thus crucially important to compare existing trend data to longer-term projections, consistently over time. This condition is critical for the specification of climate change signals. Data continuity faces increasing challenges in the USA as some environmental monitoring infrastructure developed towards the end of the twentieth century is now being scaled back (Witze, 2013; Brown et al. 2012).

2.2.3 Complexity

Urban sites and cities are highly complex and comprise multiple integrated and overlapping systems (Solecki et al., 2012). These “hybridized” natural and engineered (Gandy, 2002) conditions pose challenges for monitoring systems and the identification of clear cause-and-effect mechanisms. The tight coupling of urban systems can simultaneously mask trends and result in poor understanding of interconnections (Perrow, 1999). Urban environmental conditions include properties atypical of more natural settings in peri-urban, suburban, or rural locations (e.g., distorted heat capture and energy balance, degraded hydrology, and complex flood patterns).

2.2.4 Equity

An urban climate resiliency indicator and monitoring system needs to be geared to respond to environmental equity conditions especially of interest in cities. Many residents in US cities face conditions of inequitable distribution of environmental hazard exposure and experience differential vulnerability (Cutter et al., 2014). The indicators and monitoring system should add to understanding of how disadvantaged and marginal populations face climate risks in cities and what role resiliency and adaptation strategies might or might not play in removing this burden. The issue of environmental justice and equity advanced significantly in the past several years. Within New York City, the third report of the NPCC (2019) includes a chapter on how to incorporate environmental justice concerns of disadvantaged communities into the city's climate action process (Foster et al. 2019), and in early 2020, the Mayor created the city's first ever Environmental Justice Advisory Board with the charge to help embed environmental justice into all the city's activities (NYC, Office of the Mayor 2020).

2.2.5 Operational resiliency

Once operational, the system itself must be sustainable and resilient. It must function continuously through funding crises and if key personnel leave the agency, bureau, or university that oversees or operates the monitoring system. This is particularly relevant as funding levels for monitoring systems tend to fluctuate over time. For instance, in the 1990s, some cities began funding for sustainability-related indicators however over time focus on such measures waned as other interests and funding demands captured the attention of policy makers and the public (Lovett et al. 2007). The sensor system and monitoring infrastructure also will be required to withstand damage and even vandalism sometimes seen in urban settings (Muller et al., 2013). In general, the question of how cities can develop and sustain funding for climate indicators needs to be documented and more fully researched. One factor that might promote long-term maintenance of these systems in some cities is the extent that managers can utilize existing data monitoring and sensing requirements (such as those data for water quality and air quality US federal standards) (Blake et al. 2019). In the context of the New York City, the issue of operational resiliency also reflects how an indicator system can be tightly woven with a city's decision-making processes. As example, PlaNYC (the NYC sustainability long-term planning process and termed OneNYC) was enhanced by ensuring that all indicators were tracked by city agencies mandated to improve performance in specific areas.

2.2.6 Spatial and temporal scales

The indicator and monitoring system must be able to provide data that are meaningful and actionable for urban stakeholders and decision-makers. This might require spatially narrow neighborhood or block-level data and also wider, infrastructure-shed scale data that extend far beyond city boundaries. Furthermore, cities by definition are dependent on long-distance resource supply chains that also are subject to climate risks and that will require adaptation. The vulnerability and resiliency of these long supply chains also need to be monitored to characterize climate risks comprehensively in cities. Temporally, the indicator system should provide data at a variety of time scales from multiple readings a minute to once a month or season or year, depending on the climate risk, vulnerability, and resiliency strategy in question.

2.3 Disaster risk reduction and climate change adaptation

An Urban Climate Resiliency Indicators and Monitoring System can be a productive mechanism to foster increased interaction between a city's disaster risk reduction and response (DRR) and climate change adaption (CCA) efforts. These efforts are often silo-ed into separate operational teams with ad hoc interactions (Solecki et al., 2011). Explicit linkages can be forged with a dedicated team comprising representatives from each agency to design and co-own the part of the indicator and monitoring system that relates to extreme climate events. Additionally, climate change resilience experts can be entrained within emergency management agencies and vice versa to contribute to the development and use of the Urban Climate Resiliency Indicators and Monitoring System. This can be an effective way to overcome organizational and operational silo conditions.

Good relationships, partnerships, and understanding built around joint work on an indicator and monitoring system can lead to more effective responses from the disaster risk reduction community when climate disasters strike and to more grounded climate change adaptation and resilience measures in the longer term. Working together on the indicators and monitoring system is an effective way for the DRR and the CCA groups to develop shared vocabularies and thus mutual understanding. Protocols for choosing indicators, metrics, and monitoring strategies should be standardized across the urban disaster risk reduction and climate change adaptation domains and linked with federal and state management efforts.

With respect to technology, many cities in the USA are now implementing high-tech command centers for operational management of a wide variety of real-time stresses, such as traffic jams and blackouts. Some of these stresses are climate-related such as heavy downpours with ensuing flooding and extreme heat conditions (as discussed in the case example below). Immediate use of real-time data as climate change indicators is a challenge because such data tend to be highly variable on short time scales and often lack quality control. The data from such centers should be linked up from their initiation with urban climate change resiliency indicator and monitoring systems, so that time series of climate hazards, impacts, and responses can be accumulated, quality controlled, and analyzed. Representatives from climate change adaptation teams could be assigned to the operations centers so that linkages and learning can be achieved and maximized.

3 Development process

The development of an Urban Climate Change and Resiliency Indicator and Monitoring System should involve explicit roles for government agencies and academic experts in a clearly defined co-production process through which multiple partners in a transparent process can generate the system. Together, these groups form a policy-maker-practitioner-scientist partnership that implements a series of steps to scope the goals and objectives of the system, vet and assess potential indicators, structure the overall system, plan its operation and maintenance, and ensure evaluation and decision-relevant analysis.

3.1 Stakeholder-scientist partnerships

The roles of government and university researchers in developing I and M systems have to be well defined. While university researchers are often not equipped, nor funded, to sustain monitoring efforts over long periods, they play a vital role in developing climate resiliency indicators and analyzing indicator data in regard to key thresholds and decision-making. Government agencies are equipped to implement and maintain monitoring systems but will require explicit funding to enable an effective integration of climate resiliency indicators into their existing portfolio.

An important challenge is to ensure that underrepresented stakeholders are brought into the I and M process. Too often, co-production processes are limited to "the voices in the room" and are not sustained over time leading to the exclusions of groups. Inclusion and transparency can help participatory stakeholder processes to be more robust, relevant, and legitimate (Rosenzweig et al., 2015). For example, as early as 2009, the Baltimore Sustainability Office has engaged disenfranchised communities in the development of their all-hazards sustainability plan (Baltimore Office of Sustainability, 2009) leading to more successful planning efforts. More recently, stakeholders and scientists in New York City generated a set of questions that focus on current and future understanding of climate risks, key stresses, and opportunities and challenges for climate adaptation which provide a useful illustration (see Appendix 2).

3.2 Specifying climate resilience indicators

After the policy-maker-practitioner-scientist partnership is established, a next critical activity is the development of climate resilience indicators. The New York City on Panel Climate Change has presented seven key steps to achieve this (Solecki et al., 2015a, b). These steps include:

1. Hold multiple stakeholder meetings to determine needs for information, questions to be answered, and focus decision spaces.
2. Conduct data searches.
3. Develop preliminary indicator set.
4. Host stakeholder meetings to present pilot indicators, solicit reviews and comments, and explore scope for implementation.
5. Revise initial set of indicators based on stakeholder inputs.
6. Implement indicator system with scientist and practitioner partners.
7. Evaluate indicators, analyze trends, and continue stakeholder interactions through time.

3.3 Potential indicators

Illustrative indicators that emerged from this approach are shown in Table 2 (derived from Solecki et al., 2015a, b), categorized by climate, impacts, vulnerability, and resiliency indicators. Most are at citywide scale, but some of at neighborhood scales. Citywide coverage of social factors aids decision-making by enabling comparisons and thus identification of climate change "hotspots." This in turn helps a city government to prioritize intervention across neighborhoods.

Social vulnerability metrics are important climate change indicators, since exposure to hazards does not explain outcomes alone. For example, Fig. 1 shows levels of poverty across hurricane evacuation zones in New York City. Sensitivity and adaptive capacity are critical as well. People will not experience a climate event in the same way across a city's neighborhoods. The combining climate risk information and social factors is critical, especially for public health indicators (Kinney et al., 2015).

3.4 Use of existing environmental indicators and monitoring for climate risk management

Municipal-scale environmental monitoring has been taking place in US cities for centuries. The importance of environmental monitoring is clearly evident in the case of New York City. Its drinking water supply sources are located up to 125 miles from city boundaries, and approximately 1.6 million people commute in the region's urban core (i.e., Manhattan) every day. When, for instance, hurricanes disrupt the region's commuter transportation system, significant damages and losses ensue. Energy is another crucial urban infrastructure system—more than 80% of New York's electricity comes from a regional energy grid outside its borders. Heat waves and storms often bring power outages on a regional scale.

The resiliency of New York City and its capacity to adapt to climate shifts are dependent on monitoring of conditions across the entire metropolitan region and will involve dozens of public agencies and private entities including key energy and natural resource industries, as well as companies involved with storage and distribution of materials. Site-based observing stations and satellite remote sensing are two approaches used in tracking climate (Solecki et al., 2015a, b). The former measure specific locations, while the latter give information on broader scales. Tasks involved in developing a useful set of climate indicators include sampling methods and remote sensing analyses. Physical climate indicators will likely encompass atmospheric, terrestrial, hydrological, and marine domains.

A key attribute of remote sensing data is that it covers broad scales at repeating times (de Sherbinin et al., 2014; Weber et al. 2015). Weber et al. (2015), for example, highlight the opportunities to successfully integrate observation based data with satellite data on surface heating to define areas of heat vulnerability in Philadelphia. The National Oceanic and Atmospheric Administration (NOAA) and the US Geological Survey (USGS) are providers of remote sensing data. Existing indicators and monitoring initiatives can be integrated in a new I and M system and applied to climate change analysis (see Appendix 3.) The pilot Climate Resiliency Indicators and Monitoring System for New York that utilizes existing data sources is under development by a collaboration of NPCC3 scientists and stakeholders on the City's Climate Change Adaptation Task Force (CCATF). The focus is on indicators related to the major climate hazards that pose the greatest risks to each of the CCATF Sector Work Groups and includes indicators that highlight the interdependencies among these groups.

4 Urban heat island test bed

Tracking and illustrating metrics of extreme heat risk in New York provides a useful test bed to present the complications of developing an urban climate indicator and monitoring system. Cities are warmer than their hinterlands because impervious surfaces and buildings affect

Table 2 Potential urban indicators of climate change, impacts, vulnerability, and resiliency

a. Potential urban climate change indicators
• Number of heat advisories per year
• Surface and air temperature during peak hot weather periods (i.e., July–August in New York)
• Number of extreme precipitation events (95th percentile values) per year
• Number of coastal flooding advisories for major or moderate flooding
• Trend in mean sea level
• Trend in peak storm surge for 100-year and 500-year storms
• Number of days per year with sustained winds or gusts exceeding certain thresholds

b. Potential climate impact indicators
• Heat-related morbidity and excess mortality from extreme heat events per year (e.g., heat-induced strokes)
• Other climate hazard–related morbidity and mortality per year (e.g., drowning due to storms)
• Number of days per year with observed air quality index > 100
• Cooling (and heating) degree days per year
• Duration of blackouts/brownouts per year associated with weather-related events
• Number of weather-related transit and subway outages per year
• Number of weather-related telecommunications outages and customer hours without telecommunications per year
• Area of land inundated by coastal flooding per year
• Costs of additional water treatment owing to extreme rainfall events per year
• Total economic losses from climate-related events per year

c. Potential climate social vulnerability indicators
• Disparity in heat-related morbidity and mortality across neighborhoods with respect to equity conditions (e.g., income, race/ethnicity, non-English speaking population, housing stock)
• Disparity in other climate-related morbidity and mortality across neighborhoods with respect to equity conditions.
• Disparity in households without air conditioning across neighborhoods with respect to equity conditions.
• Percentage population with a disability (one or more of six types: hearing, vision, cognitive, ambulatory, self-care, independent living)
• Social vulnerability indices[a], tailored as needed to specific climate hazards, for example:
• Heat Vulnerability Index in census block groups experiencing relatively higher heat stress
• Social Vulnerability Index scores related to access to green space
• Social Isolation Index in census block groups in flood evacuation zones

d. Potential resiliency indicators
• Change in vegetation cover
• Number of trees planted per year
• Square footage of white/green roofs
• Surface temperature change in areas that have adopted white/green roofs relative to non-white/green roof locations
• Estimated percent of households with residential air conditioning
• Number of citizen groups engaged in climate resiliency programs per year
• Square footage of residential, commercial, industrial space not flood-proofed or elevated in areas within the 100-year floodplain
• Number of residential units in 100-year floodplain implementing Core Flood Resiliency Measures[b]
• Percentage of flood-affected areas with improved storm drainage
• Acres of restored coastal wetlands
• Miles of coastal defenses erected (dune replenishment/hard defenses)
• Population growth/decline in the 100-year floodplain
• Percentage of NYC transportation assets adapted for climate change resiliency
• Financial expenditure on resiliency activities per year, as a percent of total expenditure

[a] The Heat Vulnerability Index (HVI) and Social Vulnerability Index (SVI) are composite measures based on multiple indicators that summarize population vulnerability by geography to extreme heat based on published epidemiological studies and, in the case of the HVI, prediction of increased mortality during extreme heat events (the SVI is described in Reid et al. 2009; the HVI in Madrigano pers. com., 2014). Social isolation has been a risk factor for heat-related mortality and can increase vulnerability to a variety of climate hazards. A commonly used index for assessing social connections and isolation among seniors is described in Lubben (1998).

[b] Core Flood Resiliency Measures, proposed in the Special Initiative for Rebuilding and Resiliency (City of New York, 2013), include elevation or other flood protection of critical building equipment and utilities: fire protection, electricity, heating, ventilation, air conditioning, plumbing, telecommunications, elevators, and emergency generators and associated fuel tanks and pumps.

radiation and heat processes (Oke, 1982). For a city government, the UHI poses science questions in regard to its intensity and extent and how climate change may affect them, and policy questions in regard to which interventions are more effective in reducing it. Indicators and monitoring are needed to address both types of questions. For example, in New York City, a study in 2009 found that surface air temperatures in the city were a few degrees warmer than the immediate surrounding suburbs, and up to 8 °F warmer than rural areas in a 100-km radius around the city (Rosenzweig et al., 2009). Increasing reflectivity, e.g., by painting rooftops white, and augmenting evapotranspiration, e.g., through tree-planting, can reduce these temperatures (Rosenzweig et al. 2006; Gaffin et al., 2012a, b). Roofs in urban areas can cover up to 20% of land area (Rosenzweig et al., 2009). This figure is about 19% in New York City (Solecki et al., 2006). Interventions to modify the urban heat island include green roofs and tree = planting; installation of bioswales (vegetated ground surfaces) can work to reduce the urban heat island and to improve flash flooding from storms (Larsen, 2015). To reduce its urban heat island and lessen heat stress, New York City initiated its Cool Roofs program, with an ambitious goal of applying white paint to multiple roofs (Solecki et al., 2015a, b). The NYC Cool Roofs program further aims to reduce energy use and peak electricity demand, especially during heat waves (see www.nyc.gov/coolroofs). See Appendix 4 for further details.

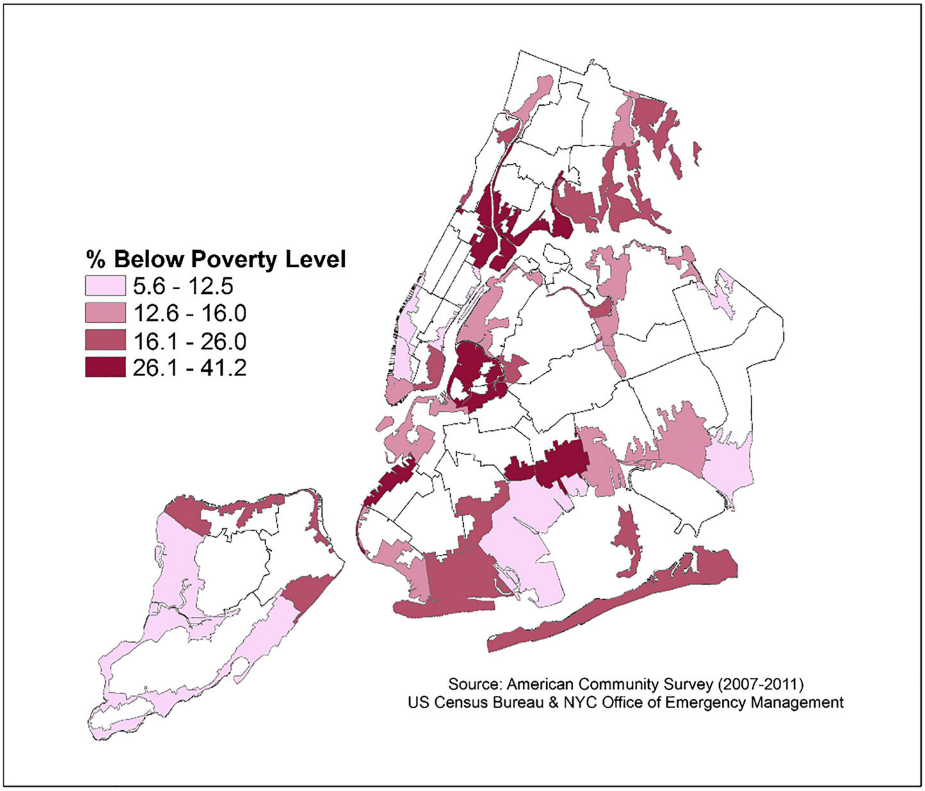

Fig. 1 Poverty rate within 2012 NYC hurricane evacuation zones. Source: Lane et al., 2013

4.1 Indicators and monitoring for Cool Roofs in New York

In order to track the efficacy and progress of the Cool Roofs program, the New York City Mayor's Office of Resiliency (MOR) and Department of Buildings (DOB) supported the implementation of a set of monitors and analysis of the data collected (Gaffin et al., 2012a, b; Solecki et al., 2015a, b). The primary goal is to measure the degree of achievement towards New York City's policy goal of reducing the UHI. This fits into the fourth category of indicators, adaptation measures, in the NYC Climate Resiliency I and M system. The users of the pilot Cool Roofs I and M system are the City's Urban Heat Island Task Force (led by the MOR) and the communities in which the Cool Roofs program was carried out.

Indicators for the NYC Cool Roofs program are number of buildings; electricity usage and costs; area painted; reductions in greenhouse gas emissions; green workforce[3] trainees; and green workforce trainees who go on to secure jobs and/or further education following their involvement in the program. Scientists are involved in the monitoring of the project, collecting data on surface temperatures, albedo, and thermal emissivity. This is done both for coated and uncoated roofs to test the effects of the white paint. Black and white roof temperatures demonstrate that the white paint causes a significant reduction in peak temperatures (Fig. 2) (Gaffin et al., 2012a, b). A record peak surface temperature was recorded on a black roof (170 °F) during a heat wave indicating a massive citywide electricity load given an acute need for air conditioning. Similar dark asphalt surfaces are likely to behave in similar ways throughout many metropolitan regions, and the indicators and monitoring demonstrated here show how urban climate resiliency measures can be targeted to mitigate the urban heat island effect.

Implicit in this discussion is the notion that a robust and widely accepted climate change indicator and monitoring would promote more meaningful adaptation decision in communities and that they could advance more concerted and effective adaptation responses. Within the Cool Roofs program, examination of the spatial patterns of indicator data could help determine particularly hot neighborhoods and extreme heat loads on a seasonal, monthly, weekly, or diurnal basis. At the same time, "before and after" monitoring of adaptation inventions, such as green or white roof strategies, would illustrate the benefits of specific types of actions. A full assessment of the value and significance of fully functional indicator and monitoring systems is beyond the scope of this paper and represents a valuable area for additional research.

5 Scaling-up strategies and conclusions

From the outset, building effective urban climate resiliency indicator and monitoring systems at local, regional, and national scales will be incremental and additive. The systems will, by necessity, reflect ongoing technical and research advances and structural changes within and across cities so as to provide timely and state-of-the-science information over the coming decades. Increased coordination between agencies and organizations that currently collect climate-related data in metropolitan regions is essential. Stronger efforts at the federal level have been developed through the work of the USGCRP and National Climate Assessment to promulgate I and M systems to help to build climate resiliency at national scales (Kenney et al., 2016); however more work at the regional, state, and local levels needs to be done. The New York City Urban Climate

[3] The NYC Green Workforce is made up of people from underserved communities who have completed a training program on clean energy.

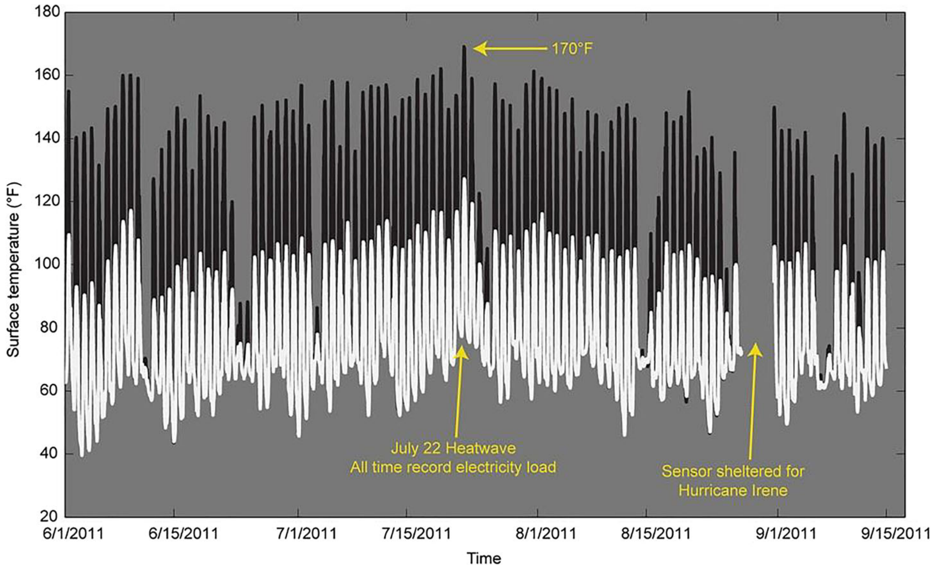

Fig. 2 Surface temperatures for a freshly painted white roof compared to those of a control black roof at the Museum of Modern Art, Queens, NY. Source: Gaffin et al., 2012a

Resiliency Indicator and Monitoring System could contribute to a nationwide dialog on how to build I and M systems at the sub-national level. Unfortunately, a large obstacle facing cities and states in developing urban indicators and monitoring capacity is that many of them do not have the resources to mount independent, scientifically rigorous systems.

Several strategies exist to overcome this challenge. One is to link with researchers in local universities and colleges through ongoing stakeholder-scientist collaborative, co-production partnerships, such as the NPCC. These partnerships, including City Climate Change Panels, have been effective mechanisms to promote indicators and monitoring systems in a variety of different-sized cities (see Urban Climate Change Research Network uccrn.org; Rosenzweig et al., 2018). Another strategy is to utilize the federal agency regional districts, such as FEMA and EPA and federal science programs (see Mount et al., 2016 for examples associated with drought management and western water supply). Furthermore, the ten NOAA RISAs, nine Department of the Interior Regional Climate Science Centers, and ten HUD regional offices could be encouraged to develop a major program on indicators and monitoring for urban climate resilience across the USA in coordination with the US National Climate Assessment. Another untapped opportunity for urban climate resiliency indicators and monitoring efforts in financially strapped US cities is to utilize citizen science. Local and regional universities, non-governmental organizations, or community-based organizations can lead programs that engage citizens to report on weather events, their impacts, and the effectiveness of resilience strategies.

To achieve a national capability in cities to develop a Climate Resiliency Indicators and Monitoring System as part of the larger NCIS effort described in other papers in this Special Issue, cities should build on existing efforts but go beyond them to create a system that answers the needs of the nation’s urban areas. A broad group of policy-maker and practitioner partners is needed for engagement with city agencies, state-level groups, and federal partners, such as engineers, urban planners and designers, and community activists. Together these integrated groups can develop robust and relevant programs to decide and implement climate indicators and monitoring systems, including the important task of analyzing trends and potential thresholds (Solecki et al., 2015a, b). Securing on-going funding sources for these efforts is essential. The creation of local, regional, and national working groups on specific City Climate Resiliency Indicators and Monitoring Systems would be particularly meaningful.

A community-driven approach to Urban Climate Resiliency Indicators and Monitoring System development must provide opportunities for the co-production of knowledge by all interested citizens. Through this process, urban dwellers and their neighborhood organizations play active roles in the city's decision-making on climate change preparedness, thereby helping to ensure that climate resiliency actions are both inclusive and fair.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

Appendix 1. Selection criteria for NPCC climate change indicators (source: Jacob et al., 2010a, b)

Policy relevant. Policy-relevant indicators are representative of the overall climate conditions faced by a city, and they measure stakeholder-relevant climate change hazards and a society's responses. These indicators are simple and easy to interpret, show trends over time, and are responsive to changes in climate and related human activities. They represent a baseline, threshold, or reference value against which to compare progress. For scalability, policy-relevant indicators provide a basis for intra- and inter-city comparison and have a scope that applies to broader regional climate issues.

Analytically sound. For an indicator to be analytically sound, it must be theoretically well founded in both technical and scientific terms. Such indicators are based on local, national, or international standards that demonstrate a consensus about their validity. In addition, analytically sound indicators can be readily linked to economic models, scenario projections, and information systems.

Measurable. A chief criterion for indicators is measurability. These indicators are based on data that are readily available or at a reasonable cost-benefit ratio. Indicators should be adequately documented, be of known quality, and be updated at regular intervals in accordance with reliable procedures. The record for an indicator should be of sufficient length in time to allow for a quantitative statistical evaluation of the uncertainties associated with the data.

Appendix 2. Key questions for development of urban climate indicators (Solecki et al., 2015a, b)

Climate change impacts, vulnerability, and resiliency

- What important climate impacts are occurring or are predicted to occur in the future?

- What are fundamental vulnerabilities and resiliencies to climate variability and change?
- What systems and groups are most at risk to climate impacts?
- What are the targeted policy questions for which indicators should be designed?
- What information is needed to improve resiliency to rapid change or extreme events related to climate?
- What adaptation measures are in place, and how may they change over longer time frames?

Climate change indicators and monitoring

- Is climate in the metropolitan region changing now?
- How is the climate projected to change in the future?
- What are the critical climate variables, indices, and extreme events to monitor?
- What is the baseline reference for the data (i.e., start date and end date)?
- For a given indicator, should it be calculated annually, seasonally, monthly, or weekly?
- What is the appropriate averaging period (e.g., 1-day or 4-day precipitation)?
- What is the appropriate spatial averaging (e.g., neighborhood, city, metropolitan region)?
- How should thresholds be chosen: statistically (e.g., 95th percentile) or relative to a critical value based on infrastructure vulnerability?
- What evidence is needed to determine if/when certain thresholds are being reached?

Appendix 3. Data sources for key New York metropolitan indicators (source: Solecki et al., 2015a, b)

Weather and climate

Ongoing weather and climate monitoring is conducted by multiple federal agencies, academic institutions, and private companies (Solecki et al., 2015a, b) (Fig. 3). Long-term observation sites include NOAA's Historic Climatology Network (HCN), with 712 sites in the 31-county metropolitan region. At these sites, instruments collect continuous data on basic meteorological variables such as surface temperature, precipitation, wind speed, and solar radiation, among many others. Data from these sites are subject to a common suite of quality assurance reviews and integrated into a database of daily data.

In addition to the HCN, NOAA also maintains one United States Climate Reference Network (USCRN) site (Millbrook, NY) in the 31-county region. USCRN sites are managed with the express purpose of detecting climate change signals, and they are located in pristine settings to exclude the impacts of development on local climate and isolate a climate change signal (Diamond et al., 2013).

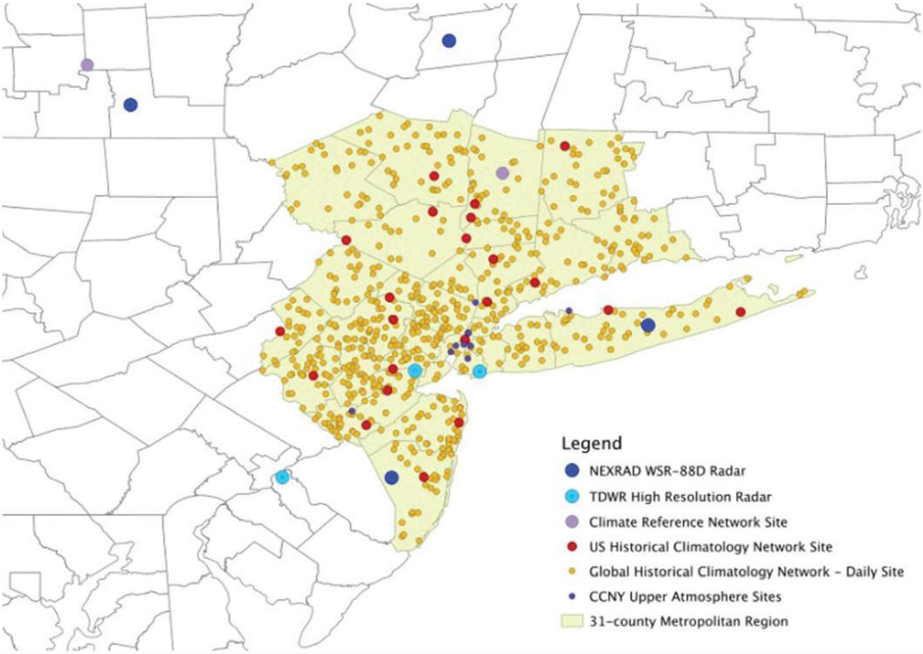

Fig. 3 Sites important in supporting climate change monitoring in the New York metropolitan region. These include NOAA's Historic Climatology Network (HCN) and Climate Change Reference Network (USRCN), the City College of New York Upper Atmosphere Monitoring Sites, and Weather Radar Sites operated by the National Weather Service and the Federal Aviation Administration (Solecki et al., 2015a, b)

In addition to the NOAA surface observation sites, local universities (e.g., the Optical Remote Sensing Laboratory of the City University of New York) maintain the NYCMetNet that consists of several upper-air measurement sites, which provide data on wind speed profiles, aerosol concentrations, air quality, and atmospheric water content (National Academy of Sciences NRC, 2012). The observations from these ground-based remote sensing instruments allow for the urban boundary layer (the layer in the atmosphere above a city where spatially integrated heat and moisture are exchanged with the overlying air) to be monitored and studied. Real-time displays from these observations are presented on the NYCMetNet web portal (http://nycmetnet.ccny.cuny.edu/) along with a large set of regional surface observations from public and private agencies in the metropolitan region. This data record can show long-term trends as well as abrupt, acute shifts—each has relevance for understanding climate shifts and areas for appropriate resiliency and adaptation strategies.

A more robust Urban Climate Resiliency Indicators and Monitoring System would be developed by cross-platform data integration necessary to harmonize and adapt the weather and climate data from the NOAA and NYCMetNet sources to support climate change-related monitoring. University scientists can play a key role in such data integration. For example, Consolidated Edison, a major electricity provider in the New York City metropolitan region, expressed via stakeholder-scientist interaction meetings the need for understanding recent trends in extreme maximum temperature, heat waves, and humidity in the face of climate change in order for their electric utilities to prepare for future conditions (Solecki et al., 2015a, b). As a result, local climate researchers are tracking this information and developing applied science for use by urban stakeholders (Coffel et al., 2016).

Coastal zones and sea level rise

Sea level rise and associated flooding will produce some of the most significant climate change impacts on New York City, as well as other coastal cities (Solecki et al., 2015a, b). NOAA maintains tide gauge stations at two locations in the city (e.g., Battery Tunnel and Kings Point/Willets Point). These are indispensable for monitoring long-term changes in local mean sea level, water heights, and surge levels. The New York Harbor Observing and Prediction System (NYHOPS), developed and managed by the Stevens Institute of Technology, maintains a network of buoy-mounted sensors, underwater probes, boat-mounted instruments, and unmanned underwater vehicles. These devices monitor water levels, currents, and water quality in the New York Harbor, the New Jersey Coast, and western Long Island Sound, all of which are critical for assessing the rate of sea level rise and the magnitude of storm surges. These data are used to assess impacts during extreme events and inform future response strategies, such as data showing the magnitude of the water level on the coast at the Battery Tunnel of New York City during Hurricane Sandy (Fig. 4). NYHOPS data adheres to NOAA standards and guidelines for operational oceanographic products and services and is synthesized at http://hudson.dl.stevens-tech.edu/maritimeforecast.

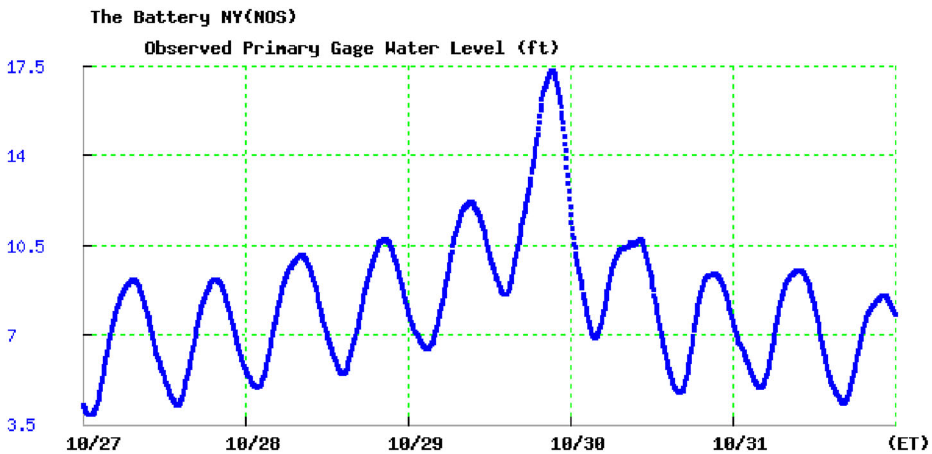

Fig. 4 NYHOPS observed primary gage water level at The Battery station October 27 to October 31, 2012, reaching 17.5 ft as Hurricane Sandy came ashore during high tide on October 29. Source: NYHOPS, 2016. http://hudson.dl.stevens-tech.edu/maritimeforecast/PRESENT/data.shtml

Water resources

Several hydrological data monitoring entities operate in the region, including New York City Department of Environmental Protection (NYC DEP), New York State Department of Environmental Conservation (NYSDEC), and the United States Geological Survey (USGS). These efforts need to be synchronized and maintained over time to support climate change-related monitoring.

The NYC DEP closely monitors the water levels and water quality of upstate drinking water reservoirs (NYCDEP, 2011). The USGS collects continuous data on streamflow, tidal flow, and groundwater at sites distributed throughout the 31-county region. The network proved to be very effective in post-event analysis of the hydrological and water quality impacts of Tropical Storm Irene and Lee during the late summer and early fall of 2011 when enhanced water turbidity required an aggressive and costly response by the NYC Department of Environmental Protection. Numerous government agencies and NGOs conduct regular water quality monitoring in the New York metropolitan region. However, the datasets they collect are not standardized across institutions. This makes comparison difficult and creates a challenge to their use in developing climate change indicators.

The recently established Hudson River Environmental Conditions Observing System (HRECOS), a network of water quality monitoring stations in the Hudson River Estuary, may serve as a model for integrating water quality monitoring data to support climate change indicators (Solecki et al., 2015a, b). Data from the network of stations along the length of the tidal Hudson River are collected using clear guidelines defined in the project's quality assurance plan, and data are thus readily intercomparable. Data collected through the project are integrated, archived, and made accessible through the project website (http://hrecos.org). A critical next step is to combine water quality data from HRECOS and other local, state, and federal efforts to support climate change-related monitoring.

Biodiversity and ecosystems

Observational data are available to assess how climate change has impacted natural ecosystems in the New York metropolitan region. The US Fish and Wildlife Service, the National Parks Service, the New York City Department of Parks and Recreation, as well as many local organizations and academic researchers conduct field surveys in different parts of the region. However, few efforts have been made to synthesize the results and analyze them to better understand how climate change may be influencing regional ecosystems. Efforts to do so should be a priority in the development of a New York City Climate Resiliency Indicators and Monitoring System.

The biodiversity indicators developed to support the global Convention on Biological Diversity (Butchart, 2010) may provide a good model for a New York City framework. Examples of these indicators include metrics for wild bird population trends, trends in the areal extent of wetlands and marine grasses, and trends in numbers of invasive species. A resource that many cities in the country can turn to is a tool called i-Tree from the US Forest Service, which provides a software to track urban forestry and benefits. States like Tennessee are using this tool to understand urban tree cover and its benefits for climate change mitigation potential in Tennessee's most populous communities (Fig. 5).

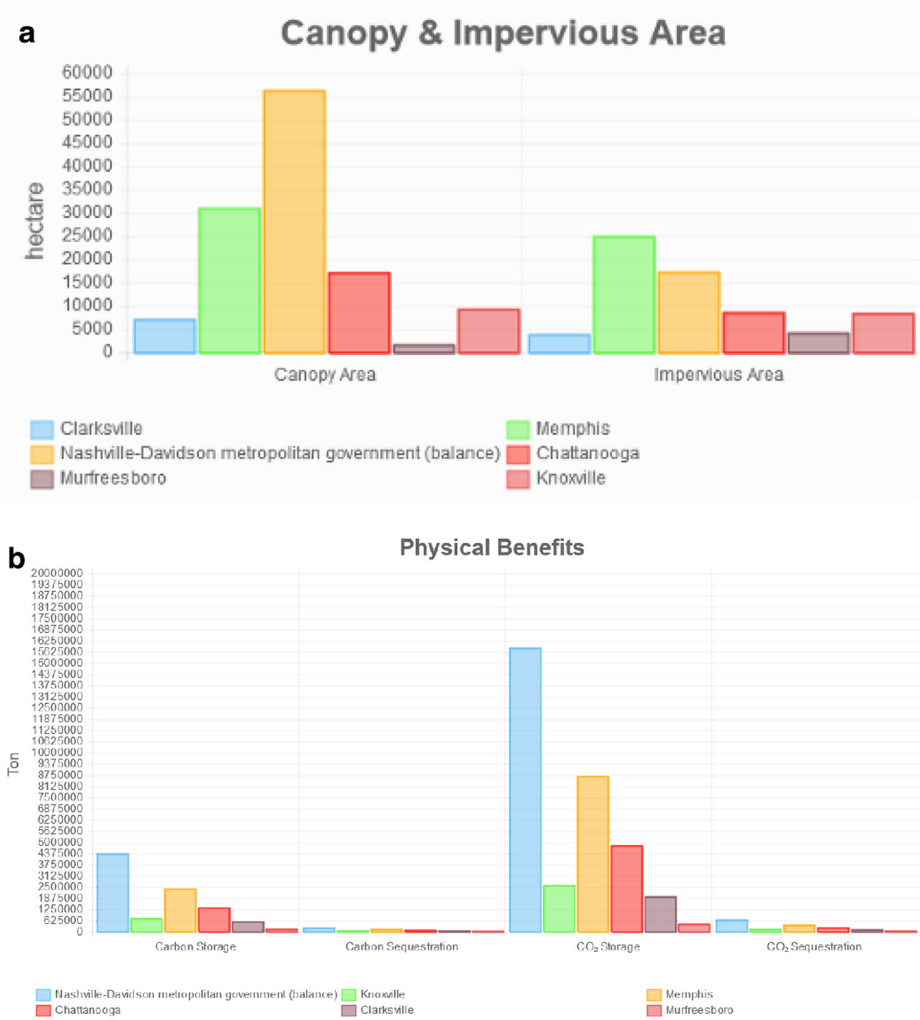

Fig. 5 Data compiled using i-Tree tools to quantify **a** canopy and impervious areas and **b** physical carbon and CO2 storage potential benefits, in six Tennessee cities: Clarksville, Nashville, Murfreesboro, Memphis, Chattanooga, and Knoxville. Accessed from: i-Tree Landscape, 2015. URL: https://landscape.itreetools.org/report/082aa821-c3ab-4971-84eb-eb00ef6d56f1/summary-of-tree-cover-and-associated-benefits/

Remote sensing data, such as aerial photography, provide an important source of fine-scale information on the ecosystems of the New York metropolitan region and how they are being affected by climate change (Morgan et al., 2010). The NYC Department of Information Technology and Telecommunications (NYC DoITT) manage aerial photographs for New York City. Aerial imagery for the remainder of the 31-county area can be obtained from the New York Statewide Digital Orthophotography Program (NYSDOP), the New Jersey Department of Environmental Protection, and the Connecticut Department of Environment. However, in order to utilize this imagery for the development of climate change urban ecosystems indicators, algorithms will need to be developed to standardize these different datasets for the New York metropolitan region.

Land cover

Regional land cover plays an important role in the interpretation of climate change monitoring data and the development of indicator metrics. Land cover data sets that cover the entire 31-county region at 30-m resolution can be obtained from the National Land Cover Database (Homer et al., 2012), developed in partnership by several federal agencies. Updates to this database are released approximately every 9 years. This data set provides important information on the vegetative or impervious land cover (i.e., deciduous forest, wetlands, and urban) and would be greatly enhanced by analysis of supporting data on land use activities (i.e., commercial and residential). This type of information is provided for counties in limited parts of the region (e.g., New Jersey Department of Environmental Protection NJDEP, 2010), but similar data sets are not available for other parts of the New York metropolitan region. Researchers working on the NYC Climate Resiliency Indicators and Monitoring System will bring these remote sensing datasets together as part of its development.

Appendix 4. Urban heat island and NYC Cool Roofs program

A key driver of the UHI is the change in the energy balance, including fluxes of heat and moisture influenced by urbanization. Rooftop surfaces and their micrometeorological fluxes interact with the atmosphere and thereby are part of the city's UHI phenomenon.

In 2009, the city launched a Cool Roofs Pilot Program in Long Island City, Queens, a designated "hot spot" to test the effectiveness of cool roof coating in reducing energy consumption and cooling costs and to support the city's goal to reduce greenhouse gas emissions, later upped to 80% by 2050 (City of New York, 2014). The pilot program was designed to measure the effects of an experimental 100,000 square foot white roof (Gaffin et al., 2012a, b). The study showed that daytime peak black temperatures were, on average, 75 °F warmer than the test white surface on rooftops; thus white roofs significantly reduced the need for air conditioning and energy consumption.

Based on the pilot program's initial success, a full program was launched citywide in 2010, in collaboration with NYC Service, the New York City Department of Buildings (DOB), and the New York City Mayor's Office of Long-Term Planning and Sustainability (OLTPS) with the goal of coating up to 10 million square feet of rooftop by 2020, lowering energy usage in buildings and mitigate up to 3500 metric tons CO_2e (City of New York, 2014). The program focused on coating nonprofit, low-income housing, and government buildings. Through 2015, over 6 million square feet of rooftops had been coated on 620 buildings.

Night-time temperatures on the white and black roofs are comparable. This is expected because rooftops of both types have low internal energy storage and comparable emissivities. Thus, at sunset, both rooftop surfaces cool off rapidly and similarly.

New York City will continue to monitor and analyze the benefits and science of cool roof coatings and is currently engaged in executing a set of follow on activities (Solecki et al., 2015a, b). These include advanced sensors for surface and air temperatures, site-specific analyses, carbon emissions, and urban meso-scale and macro-scale modeling.

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