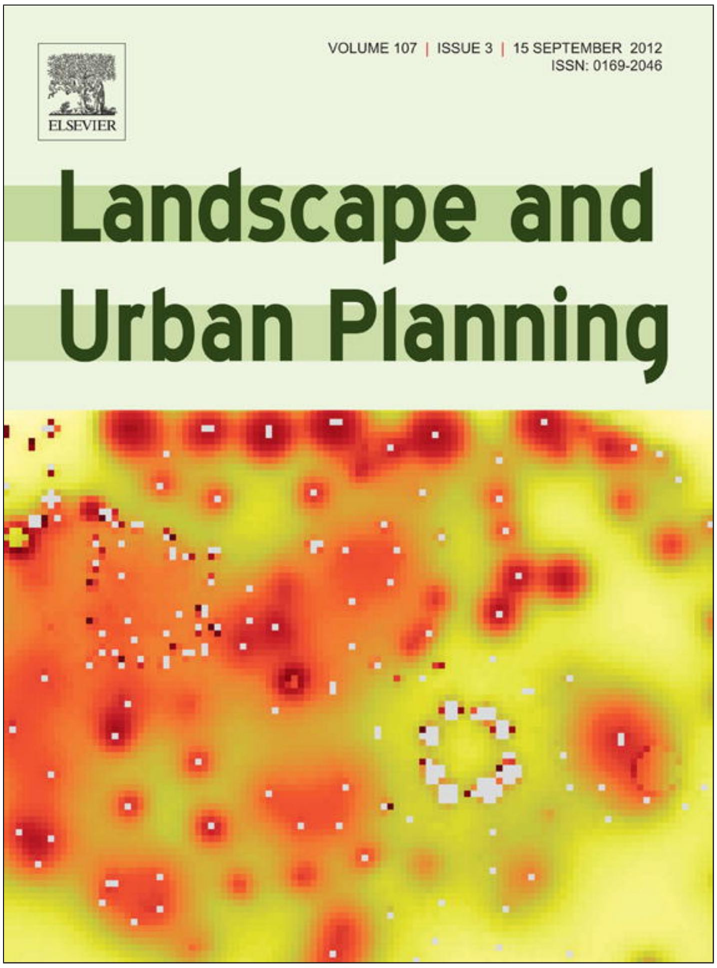
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Managing climate change in cities: Will climate action plans work?

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HIGHLIGHTS

- ▶ Large U.S. cities warmed at twice the rate of the planet between 1961 and 2010.
- ▶ The urban heat island effect is the principal driver of warming at urban scale.
- ▶ Most climate action plans fail to directly manage land-based drivers of warming.

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ABSTRACT

Since the mid-20th century, most large cities of the United States have been warming at more than twice the rate of the planet as a whole. While many municipal and state governments have developed climate action plans designed to reduce emissions of greenhouse gases, rising concentrations of greenhouse gases typically are not the strongest driver of warming in cities. Our purpose is to evaluate the likely effectiveness of municipal and state level climate action plans in slowing the pace of warming in the most populous U.S. cities over the near-to-medium term. We employ time-series temperature trend analyses to differentiate global from local-scale climate change mechanisms in large U.S. cities between 1961 and 2010. We then review all climate action plans developed at the municipal or state level in the 50 most populous metropolitan regions to identify the various emissions control and heat management strategies incorporated into these plans. The results of our assessment suggest that the climate change management policies adopted through municipal and state climate action plans may fail to adequately protect human health and welfare from rapidly rising temperatures. Based on our review, we recommend that municipal and state governments broaden climate action plans to include heat management strategies in addition to greenhouse gas emissions controls.

1. Introduction

To date, the literature on climate change science and policy has been dominated by a focus on the global scale. The periodic assessment reports developed by the Intergovernmental Panel on Climate Change (IPCC), for example, report temperature change projections for the planet as a whole, but do not consider the pace of warming at sub-continental to local scales. A wealth of recent analysis, however, finds that both the physical mechanisms driving warming trends at local to regional scales and the pace of these trends are often quite different than trends observed at the global scale. In light of these findings, there is a critical need to identify the climate management approaches that are most likely to be effective at regional to local scales, and to consider how these approaches may differ from those incorporated into international climate agreements such as the Kyoto Protocol and any successor agreements.

In this article, we explore two questions related to climate change management at regional to local scales. First, how rapidly are large metropolitan regions of the United States warming relative to the planet as a whole? Evidence of rapid warming underway as a product of global-scale greenhouse gas concentrations and local-scale land cover change in cities suggests the need for regional climate change management policies to address both the atmospheric and land surface drivers of warming. While our focus is explicitly on large cities of the United States, given the physical nature of the mechanisms involved and the wide diversity of development patterns included in our dataset, we believe our analysis to be relevant to large cities throughout the developed world.

Second, how effective are climate action plans currently in place within large metropolitan regions of the United States in combating the most powerful drivers of temperature change at the urban scale? To address this question, we review climate action plans developed by the largest U.S. cities and associated state governments to assess the extent to which both greenhouse gas emissions

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and land-based drivers of climate change are addressed through these plans. Based on the results of this document survey, we make a series of recommendations as to how such plans might be expanded to most effectively counteract ongoing warming trends.

2. Effects of land use change on regional to local-scale climate

The effects of extensive land cover change on regional to local-scale climates have been widely documented over the past few decades. The first studies to address this question focused on the rapid deforestation of rainforest biomes, such as the Amazon basin of South America. Because forest land covers are known to play an important role in the cycling of moisture between the land surface and atmosphere, scientists have long theorized that extensive deforestation could modify climate through altering rates of evapotranspiration, cloud formation, and regional precipitation. Numerous studies focused on these environments have confirmed this theory. For example, extensive deforestation underway in the Amazon and other regions of the planet is producing regional climates that are significantly drier and hotter over time (Costa & Foley, 2000; Dickinson, Henderson-Sellers, & Kennedy, 1992; Nobre, Sellers, & Shukla, 1991; Pitman, Narisma, Pielke, & Holbrook, 2004).

Urbanization, much like deforestation in a rural setting, has also been shown to directly influence regional climates. One means of gauging the effects of land cover change on climate is through a comparison of surface temperature observations with those of upper atmosphere weather balloons. Recorded well above the Earth's surface, weather balloon data is largely insensitive to the effects of land surface changes, such as urbanization, but does reflect the influence of greenhouse gases on atmospheric temperature. Employing such a technique, Kalnay and Cai (2003) compared surface and upper atmospheric weather observations over a four decade period to measure the influence of land surface change on climate across most of the continental United States. The results of their analysis found land cover changes in the form of agriculture and urbanization to account for approximately 50% of the observed warming trend since the 1950s (measured as a reduction in the diurnal temperature range), with greenhouse gas accumulation accounting for the other half.

Using the same technique, an analysis by Zhou et al. (2004) focused on southeastern China, a region characterized by rapid urbanization over the past few decades, found land cover changes to account for 68% of the observed warming trend between 1979 and 1998. A number of follow-up studies making use of recent atmospheric and land surface observations have documented a significant influence of land cover change on the regional climate record (Hale, Gallo, & Loveland, 2008; Lim, Cai, Kalnay, & Zhou, 2005).

When measured at the urban scale, the influence of land surface changes on climate is characterized as the urban heat island effect. While urban heat islands provide the most visible examples of "land-based" climate change, the underlying physical mechanisms of warming are much the same as that at the regional scale: a loss of natural land cover tends to reduce the rate of evapotranspiration and modify surface albedo. What differentiates the urban phenomenon from rural land clearance practices is the physical character of the modified land surface. The urban construction materials of cement, asphalt, and bituminous roofing have a much greater thermal capacity than pasture or cropland. These materials generally lack any capacity for evapotranspiration and instead tend to absorb, store, and emit far more thermal energy than the degraded but still hydrologically active landscape materials that displace natural land covers in the rural context. Also important is the dense morphology of urban districts and the greater direct emission of waste heat from industry, buildings, and mobile sources in urbanized areas, which typically plays a smaller but measurable role in urban heat island formation (Oke, 1987).

The character and intensity of urban heat island formation has been exhaustively documented though the field of urban climatology since the 1960s (Chandler, 1962; Oke, 1982; Taha, 1997). While the phenomenon differs in magnitude by city size (Oke, 1973), and urban morphology (Kobayashi & Takamura, 1994; Nunez & Oke, 1977), the maximum intensity of the effect has been measured between 4 and 22 °F (2 and 12 °C) (Oke, 1987), suggesting that most large cities have already experienced a magnitude of warming roughly equivalent to that projected to occur through the global greenhouse effect this century. What has not been widely studied, however, is the rate at which heat islands have intensified over the last several decades. If the planet as a whole is expected to experience an increase in globally averaged surface temperatures of 2–12 °F by 2100, what rate of warming is to be expected in urbanized regions?

Our own work has sought to address this question through the analysis of temperature trend data collected at urban and rural meteorological stations in proximity to the most populous U.S. cities. If the urban heat island effect is playing a role not only in the present day temperature differential between urban and rural areas, but the rate of increase in urban temperatures over time, then IPCC projections for climate change may underestimate the true extent of warming experienced in urban areas. To understand why IPCC projections may fail to accurately reflect future conditions in cities, it is first necessary to consider how these projections are developed. What follows is a brief overview of the methods employed to measure and forecast temperature change and the results of our analysis of temperature trends in the most populous U.S. cities.

3. Measuring temperature change in cities

Annual reporting on global or national average temperature trends is perhaps the most widely recognized evidence of climate change. As illustrated in Fig. 1, these trends provide the basis for identifying the warmest years on record and are constructed from a network of surface meteorological stations with observations dating back to the 19th century. What is not widely understood about these time series climate analyses, however, is that they do not accurately measure temperature trends in urban areas. As most of the planet's weather stations are located in proximity to urban areas, were scientists to rely on these urban stations to measure average global climate trends, the trends reported would undoubtedly be heavily influenced by the urban heat island effect, and would thus fail to accurately reflect conditions over the vast majority of the global land surface. In consideration of this potential source of urban "contamination" in the global temperature record, data from urban weather stations are statistically adjusted to conform to the temperature trends of nearby rural stations (Hansen et al., 2001).

As a result of this data adjustment, present and projected global climate trends may not accurately reflect conditions in urbanized regions. In light of the need to assess the potential magnitude of warming in cities – when accounting for both the global greenhouse effect and the urban heat island effect – a number of studies have compared historical rates of temperature change in urban and rural areas (Gallo, Easterling, & Peterson, 1996; Gallo, Owen, Easterling, & Jamason, 1999; Hale, Gallo, Owen, & Loveland, 2006; Hansen et al., 2001). Our own work has focused on this particular issue for the largest U.S. cities. Here, we make use of a subset of the

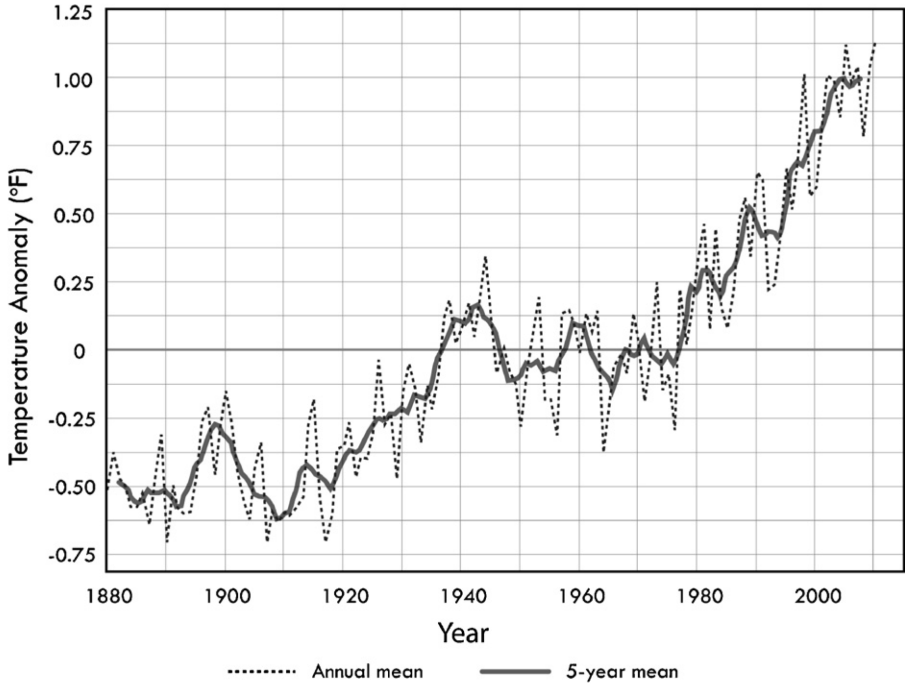

Fig. 1. Global temperature anomalies: 1880–2010.
Adapted from the Goddard Institute for Space Studies surface temperature analysis (*GISS: GISS Surface Temperature: Analysis Graphs and Plots*. http://data.giss.nasa.gov/gistemp/graphs/).

same national network of meteorological stations employed by the NASA's Goddard Institute for Space Studies in global-scale analyses, yet we do not exclude or statistically adjust data from urban weather stations.

3.1. Methods

Our analysis includes the 50 most populous U.S. metropolitan regions for which continuous climate data is available for both urban and nearby rural weather stations between 1961 and 2010. All weather stations included in our database are drawn from the Global Historical Climatology Network (GHCN), have been fully adjusted for standard inhomogeneities, such as a change in station location or instrumentation, and provide a minimum of 550 of 600 complete months of mean monthly temperature observations (derived from daily maximum and minimum temperature records). As continuous, multi-decade temperature data is only available from a limited number of first-order weather stations in large U.S. cities, and in some cases is not available at all, urban temperature trends are constructed from a single first-order meteorological station in all cities included in the study. Temperature trend data are adjusted for differences in elevation and latitude between paired urban and rural stations in each region, but urban observations are not adjusted for the effects of urbanization.

The availability of only a single fully corrected, multi-decade temperature record for each urban area included in our analysis represents an important limitation to the study. Due to the great heterogeneity of land surface conditions throughout a large urbanized region, no single meteorological station can accurately represent region-wide temperatures. To address this limitation, we derive our urban temperature trend data from 50 urban meteorological stations across the United States and only report results for multi-decadal trends found to be statistically significant.

Three additional criteria are used in the selection of rural temperature trend data for inclusion in the analysis. First, to be eligible a rural weather station must be located within a maximum 250 km (∼150 miles) of an urban station, with most falling within 150 km (∼90 miles). Second, a rural meteorological station must be located in an area characterized by a population size of less than 10,000, indicative of rural land use patterns. And, finally, we make use of night light measurements obtained through the Defense Meteorological Satellite Program Operational Linescan System (OLS) to characterize all meteorological stations meeting the first two selection criteria as rural based on the intensity of luminosity measurements. Stations located in areas classified by NASA as "bright" are excluded from the analysis, while stations located in areas classified as "dark" or "dim" may be included if all other selection criteria are met. The outcome of this selection process is the identification of three rural meteorological stations in proximity to each city that are used to establish a single, average rural temperature trend.

3.2. Results

Fig. 2 presents the results of our analysis. Reported as trends in urban and rural temperature "anomalies," the graph illustrates the average deviation from a long-term average temperature (1951–1980), which is represented by the zero value on the *y*-axis. This approach is the same as that employed in annual reporting by NASA and is useful in highlighting the magnitude of change over time.

The trends depicted in Fig. 2 attest to the significance of land use to urban-scale climate change in several respects. First, the rural temperature trend shows an increase over the five decade mean temperature of about 1.4 °F (0.8 °C). If we assume the rural weather stations included in the database are not impacted by the effects of urbanization, then the observed warming trend may be presumed to result in large part from the global greenhouse effect. And, indeed, this rate of decadal warming is similar to that measured for the planet as a whole over this period.

Second, at any point in time, urban weather stations are warmer than proximate rural stations. This finding suggests that the urban

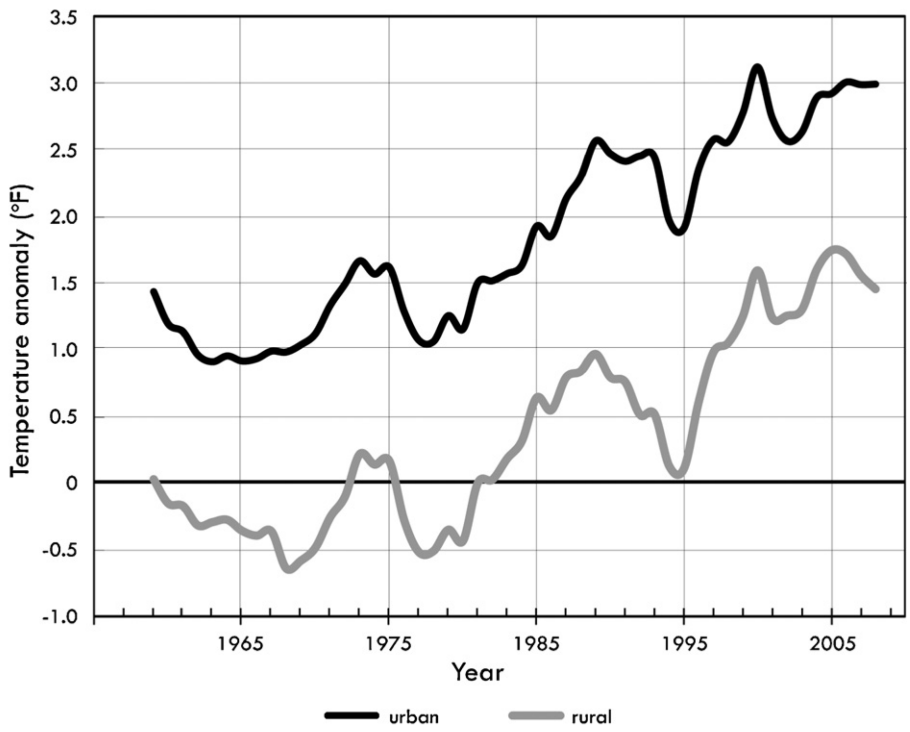

Fig. 2. Urban and rural temperature anomalies (5 year means) for 50 large U.S. cities over the period of 1961–2010. *Note*: These data are updated from an earlier analysis covering the period of 1951–2000 (Stone, 2007) and include first-order weather stations from the Global Historical Climatology Network (GHCN v2). The final two years in the dataset are excluded due to the lack of a full five years for computing the average anomaly.
These data were obtained from the NASA Goddard Institute for Space Studies (http://data.giss.nasa.gov/gistemp/).

heat island effect is acting to further amplify warming trends brought about through the global greenhouse effect, which is present in both the rural and urban trends. One means of gauging the relative contribution of global and local drivers of warming in cities is to measure the difference between the urban and rural trend lines. The distance between the zero anomaly line and the rural trend line (where positive) most directly captures the influence of rising concentrations of greenhouse gases on temperatures in both rural and nearby urban areas. The distance between the rural and urban trend lines most directly captures the influence of the urban heat island effect on urban temperatures. Importantly, the mean difference between urban and rural trends over the five decade period is greater than the magnitude of the rural anomaly itself (the distance between the zero anomaly line and rural trend line), suggesting land use is playing a more significant role in the warming trends of cities than the emissions-related effects present in both trends.

Although emissions of greenhouse gases tend to be higher in urban areas than in non-urban areas, these emissions have not been found to significantly elevate the pace of warming in cities. The reason for this is that any observed increase in the concentration of greenhouse gases in urban airsheds – sometimes referred to as a CO_2 "dome" – is found only in the lowest levels of the atmosphere. Due to atmospheric mixing at higher altitudes, most of the air column above cities consists of greenhouse gas concentrations equivalent to the global average, with any elevation in GHG concentrations lower to the surface accounting for only very minor enhancements in temperature. For example, Balling, Cerveny, and Idso (2001) found a 40–60% increase in near-surface CO_2 over background levels in Phoenix, Arizona to account for an increase in surface temperatures of about 0.2 °F (0.1 °C), a small component of the region's 9–18 °F (5–10 °C) heat island (Balling et al., 2001).

Finally, the mean decadal rate of warming across the urban stations is significantly higher than that of the rural stations. Averaged over the full period, the mean rate of warming in urban areas was found to be about 0.43 °F (0.24 °C) per decade ($p > 0.001$), compared to mean rate of warming across the rural stations of about 0.29 °F per decade (0.16 °C) ($p > 0.001$). A *t*-test of the difference in urban and rural temperature trends shows these differences to be statistically significant ($p < 0.001$). These numbers indicate that urban areas are amplifying background rates of warming, on average, by about 50%.

It is important to note that the intensity of heat islands is not growing in all cities in our sample. In 14 out of 50 cities, the intensity of heat islands was found to have remained largely constant or decreased slightly over the five decade period, serving to lower the average rate of change for the full dataset. While there are several potential explanations for this phenomenon, one important variable is the pace at which land cover is changing in proximity to these cities. To assess the extent to which rural areas are being converted to urban land covers within the 50 metropolitan areas in the study, we analyzed data from the National Land Cover Dataset (Fry, Coan, Homer, Meyer, & Wickham, 2009), which provides uniform land cover change data for a subset of years in our study period: 1992–2006.

From an analysis of NLCD data within the boundaries of each metropolitan statistical area (MSA), we found the average rate of transition from rural to urban land covers in cities with growing heat islands to be more than double the rate of such change for cities in which heat islands are not growing over time. Over the period of 1992–2006, the urban land area grew by an average of 20.3% in MSAs with growing heat islands, compared to 8.6% in the remaining MSAs. Although we lack land cover change data for the full study period, we conclude from this analysis that heat island growth is likely to be greater in cities experiencing more rapid land cover change over time.

If we limit our analysis to the 72% of cities in which heat islands are actually growing over time, average urban temperatures are found to be increasing by 0.56 °F (0.31 °C) per decade ($p < 0.001$), compared to a rural rate of increase of 0.29 °F (0.16 °C) per decade ($p < 0.002$). A t-test of the difference in urban and rural temperature trends across the 36 metropolitan regions in which heat islands are growing over the five decade study period shows these differences to be statistically significant ($p < 0.001$). Based on this analysis, we find the degree to which cities are amplifying background temperatures increases to about 100% in most large cities. In these cities, accounting for the majority of large U.S. cities, urban temperatures are rising at double the rate of the planet as a whole.

4. Heat island management through climate action plans

Considered in aggregate, evidence from both rural and urbanized regions where land use activities have resulted in significant changes to land cover suggest land use to be a significant and measurable driver of climate change, and one that operates through a physical mechanism independent of greenhouse gas emissions. In light of this evidence, the pace of warming at regional to local scales can be slowed through one of two management approaches. First, reductions in global emissions of greenhouses gases can, over the long term, slow the extent of climate-forcing brought about through the global greenhouse effect. Because the intensity of the global greenhouse effect is largely insensitive to regional changes in greenhouse gas emissions, regional to local-scale warming attributable to the global greenhouse effect can only be addressed through global management efforts.

Second, the pace of warming at regional to local scales can be slowed through a reversal of land cover change activities that serve to reduce surface albedo or produce a shift in the surface energy balance from latent to sensible turbulent fluxes. Such activities typically include the displacement of forested or other vegetative land covers by the impervious materials of the built environment. Because albedo and surface energy balance changes are sensitive to policy action at regional to local scales, metropolitan governments can exercise measurable influence over these drivers of climate change.

Despite the wealth of scientific evidence on the role of land use in climate change, national and international climate policy generally do not recognize climate forcing agents related to changes in albedo and the surface energy balance – agents we characterize as "land-based" drivers of warming – to be a central element of climate change management policy. Under the current climate change management framework, climate mitigation is formally defined as "policies to reduce greenhouse gas emissions and enhance sinks" (Metz, Davidson, Bosch, Dave, & Meyer, 2007). Based on this definition, responses to climate change unrelated to emissions are characterized as adaptation rather than mitigation and, as such, generally have not been prioritized in national and international climate change policy. As our analysis of urban and rural temperature trends suggests, however, there is a reasonable basis to conclude that a reduction of the urban heat island effect would more effectively slow ongoing warming trends in cities than emissions reductions alone. To this end, it is important that municipal governments account for both the atmospheric (i.e., emissions) and land-based (i.e., non-emissions-based) drivers of urban warming.

To date, a large number of cities worldwide have developed municipal-level climate change management programs in coordination with Local Governments for Sustainability (ICLEI), which are referred to as "climate action plans." According to ICLEI, such plans are intended to assist cities in planning for both climate change mitigation and adaptation and to address climate change impacts at the local scale. To date, several hundred cities have adopted the ICLEI framework for developing climate action plans in North America, Latin America, Europe, and Asia. In some instances, state or provincial governments have assumed responsibility for developing climate action plans for all cities within their jurisdictions.

In the interest of assessing the degree to which climate action plans are designed to address both the atmospheric and land-based drivers of warming, we reviewed all such plans available for the 50 most populous U.S. MSAs, a list of which is provided in Table 1. To be included in the survey, a municipal or state level climate action plan must have been formally adopted at the time of our survey (January 2012), and must be available through the U.S. Environmental Protection Agency's *State and Local Climate and Energy Program*, which maintains an inventory of such plans, or directly

Table 1
Largest 50 MSAs by population.

MSA	Total population[a]	Population density[b] (per sq. mi.)
Atlanta-Sandy Springs-Marietta, GA	5,269,000	621
Austin-Round Rock-San Marcos, TX	1,716,000	401
Baltimore-Towson, MD	2,710,000	873
Birmingham-Hoover, AL	1,128,000	210
Boston-Cambridge-Quincy, MA-NH	4,552,000	1009
Buffalo-Niagara Falls, NY	1,136,000	480
Charlotte-Gastonia-Rock Hill, NC-SC	1,758,000	559
Chicago-Joliet-Naperville, IL-IN-WI	9,461,000	988
Cincinnati-Middletown, OH-KY-IN	2,130,000	477
Cleveland-Elyria-Mentor, OH	2,077,000	522
Columbus, OH	1,837,000	458
Dallas-Fort Worth-Arlington, TX	6,372,000	686
Denver-Aurora-Broomfield, CO	2,543,000	303
Detroit-Warren-Livonia, MI	4,296,000	1014
Hartford-West Hartford-East Hartford, CT	1,212,000	754
Houston-Sugar Land-Baytown, TX	5,947,000	590
Indianapolis-Carmel, IN	1,756,000	452
Jacksonville, FL	1,346,000	364
Kansas City, MO-KS	2,035,000	256
Las Vegas-Paradise, NV	1,951,000	242
Los Angeles-Long Beach-Santa Ana, CA	12,829,000	2251
Louisville/Jefferson County, KY-IN	1,284,000	306
Memphis, TN-MS-AR	1,316,000	280
Miami-Fort Lauderdale-Pompano Beach, FL	5,565,000	907
Milwaukee-Waukesha-West Allis, WI	1,556,000	468
Minneapolis-St. Paul-Bloomington, MN-WI	3,280,000	515
Nashville-Davidson-Murfreesboro-Franklin, TN	1,590,000	276
New Orleans-Metairie-Kenner, LA	1,168,000	153
New York-Northern New Jersey-Long Island, NY-NJ-PA	18,897,000	2051
Oklahoma City, OK	1,253,000	224
Orlando-Kissimmee-Sanford, FL	2,134,000	532
Philadelphia-Camden-Wilmington, PA-NJ-DE-MD	5,965,000	1225
Phoenix-Mesa-Glendale, AZ	4,193,000	287
Pittsburgh, PA	2,356,000	441
Portland-Vancouver-Hillsboro, OR-WA	2,226,000	326
Providence-New Bedford-Fall River, RI-MA	1,601,000	716
Raleigh-Cary, NC	1,130,000	526
Richmond, VA	1,258,000	215
Riverside-San Bernardino-Ontario, CA	4,225,000	154
Sacramento-Arden-Arcade-Roseville, CA	2,149,000	405
Salt Lake City, UT	1,124,000	113
San Antonio-New Braunfels, TX	2,143,000	291
San Diego-Carlsbad-San Marcos, CA	3,095,000	684
San Francisco-Oakland-Fremont, CA	4,335,000	1265
San Jose-Sunnyvale-Santa Clara, CA	1,837,000	682
Seattle-Tacoma-Bellevue, WA	3,440,000	545
St. Louis, MO-IL	2,813,000	318
Tampa-St. Petersburg-Clearwater, FL	2,783,000	835
Virginia Beach-Norfolk-Newport News, VA-NC	1,672,000	429
Washington-Arlington-Alexandria, DC-VA-MD-WV	5,582,000	926

[a] MSA population in millions. U.S. Census Bureau (2010). USA MSA total population. Retrieved January 5, 2012, from http://factfinder2.census.gov.
[b] U.S. Census Bureau (2010). Retrieved January 19, 2012, from http://www.census.gov/geo/www/tiger/shp.html.

Table 2
Categorization of management strategies in climate action plans.

Management strategy	Common components	Category
Albedo enhancement	Installation of highly reflective roofing or paving materials	Albedo enhancement
Building energy efficiency	Minimum insulation values in building codes; efficient light fixtures and appliances	Energy efficiency
Green roofs	Installation of vegetative roofing materials	Vegetation enhancement
Regional forest management	Requirements for the protection of regional forest cover in proximity to urbanized areas	Vegetation enhancement
Renewable energy programs	Requirements for wind, solar, geothermal, or other renewable energy sources	Energy efficiency
Urban tree management	Municipal tree planting programs; requirements for tree protection ordinances	Vegetation enhancement
Vehicle energy efficiency	Minimum fuel efficiency standards for municipal fleets; acquisition of alternatively fueled vehicles	Energy efficiency
Vehicle travel demand management	Ride sharing programs; transit investments; provision of pedestrian and cycling facilities	Energy efficiency

from the state or municipal government agency responsible for administering the plan. We limit our survey to only climate-related planning documents to assess the extent to which municipal and state governments are pursuing land-based strategies for the stated purposes of climate change management. While it is likely that some vegetative enhancement strategies are being pursued for other purposes, such as stormwater management, our focus here is on the extent to which government officials are cognizant of the significance of these strategies for heat abatement at the urban scale. All planning documents related to climate mitigation or climate adaptation were included in our survey of climate action planning.

From an initial review of climate action plans, eight classes of management strategies related to both the atmospheric and land-based drivers of climate change were identified. A description of these strategies is provided in Table 2.

Drawing from these climate management strategies, all plans were scored based on their inclusion of one of three general categories of management approaches. These included: (1) tree planting or other vegetation enhancement strategies such as green roof installation; (2) albedo enhancement strategies incorporating cool roofing or cool paving techniques; and (3) energy efficiency programs designed to reduce greenhouse gas emissions or waste heat production from municipal buildings, vehicles, or operations. These various strategies are presented as separate columns in Table 3.

We next scored each strategy based on one of two purposes stated in the plans: (1) local-scale heat island management, or (2) emissions reductions intended to address the global greenhouse effect. Strategies included in any plan with the stated intent of reducing urban temperatures, whether characterized as a primary or secondary benefit of the strategy, are identified in Table 3 with a closed circle. Strategies included in any plan with the stated intent of reducing greenhouse gases only are identified with an open circle.

Table 3
Mitigation strategies in climate action plans.

MSA	Vegetation enhancement	Albedo enhancement	Energy efficiency
Atlanta (2008)			○
Austin (2008)	○		○
Baltimore (2008-s)	○		○
Birmingham (1997-s)	○		○
Boston (2011)	●	○	○
Buffalo (2010-s)			○
Charlotte (2008-s)	○		○
Chicago (2008)	●	●	○
Cincinnati (2008)	●	●	○
Cleveland			
Columbus			
Dallas			
Denver (2007)	○		○
Detroit (2009-s)	○		○
Hartford (2005)	●		○
Houston (2008)			○
Indianapolis			
Jacksonville (2008-s)	○		○
Kansas City (2008)			○
Los Vegas (2008-s)			○
Los Angeles (2008)	●	●	○
Louisville (2009)	●	●	○
Memphis (1999-s)			○
Miami (2008)	●	●	○
Milwaukee (2008-s)	○		○
Minneapolis (2008-s)	○		○
Nashville (1999-s)			○
New Orleans (2008-s)	○		○
New York City (2008)	●		○
Oklahoma City			
Orlando (2008-s)	○		○
Philadelphia (2007)	●	○	○
Phoenix (2009)			○
Pittsburgh (2008)	●	○	○
Portland (2009)	●		○
Providence (2002-s)	○		○
Raleigh (2007)	○		○
Richmond (2008-s)	○		○
Riverside (2008-s)			○
Sacramento (2008-s)			○
Salt Lake City (2007-s)	○		○
San Antonio			
San Diego (2005)	●	●	○
San Francisco (2004)			○
San Jose (2008-s)			○
Seattle (2007)	○		○
St. Louis (2002)			○
Tampa (2008-s)	○		○
Virginia Beach (2008-s)	○		○
Washington, DC			

● Heat island mitigation strategy.
○ Greenhouse effect mitigation strategy.
Note: The year of adoption for the most recent climate action plan in each city is listed in parentheses. Cities for which only a state level climate action plan is available are noted with an "s".

4.1. Results

Categorized in this fashion, the results of our survey suggest that only a limited number of large U.S. cities are actively taking steps designed to address urban scale, land-based drivers of climate change. As reported by previous analyses of climate action plans, a number of cities lack any such plans altogether (Betsill & Rabe, 2009; Wheeler, 2008). Associated with no strategies in Table 3, about 14% (7) of those cities surveyed have not adopted climate action plans, and thus presently are neither working to reduce municipal emissions of greenhouse gases or to manage the local-scale drivers of rising temperatures. In these cities, no planning is being undertaken at the local, state, or national levels to slow or prepare for the effects of climate change. Our results further find that an additional 21 cities have not developed their own climate action plan, and thus rely on state level plans to address regional emissions and heat-related challenges.

Out of the 50 cities included in the survey, only about a quarter (12) are pursuing strategies designed to increase vegetative cover or surface reflectivity as a means of reducing ambient temperatures. All 12 of these cities have included vegetation enhancement strategies in their climate action plans, while only 6 include strategies focused on increasing the reflectivity of roofs or surface paving for the purposes of UHI management. We find that no cities lacking a municipal level climate action plan (i.e., cities for which only a state level plan is in place) are requiring of vegetation or albedo enhancement for the purpose of urban-scale heat management. We also find the greatest concentration of cities actively working to address the urban-scale drivers of warming to be located in the northeastern U.S. (5 of 12), with no southwestern cities, where summer temperatures tend to be greatest, having adopted heat management strategies in their climate action plans.

To the contrary, all cities that have developed climate action plans or are governed by state level plans have included strategies to enhance the energy efficiency of buildings, vehicle fleets, or power generation systems. As none of these plans cites waste heat reduction as a policy objective, we conclude that energy efficiency strategies are being undertaken in all cities with climate action plans for the sole purpose of greenhouse gas reductions.

In concert, these findings suggest that relatively few of the most populous U.S. cities are explicitly focused on managing local-scale drivers of warming or on reducing the occurrence of extreme heat over the next several decades. Consistent with the orientation of global climate policy, most municipal governments are pursuing strategies designed to reduce the emissions of greenhouse gases alone, which by themselves will yield no protective benefits to cities and, even if pursued globally, are unlikely to yield protective benefits for many decades, if not centuries. In short, most large U.S. cities are taking no steps designed to counteract a leading threat of climate change to urban populations in near term: an increasing frequency of extreme heat.

The good news is that many cities are pursuing emissions-reduction strategies that carry the unintended benefit of managing local-scale drivers of warming as well. In recognition of the benefits of tree planting and reflective roofing for cooling buildings, and thus reducing energy consumption for air conditioning and associated greenhouse gas emissions, three out of five cities surveyed have included provisions in climate action plans for these strategies – strategies that also serve to reduce ambient temperatures. These policies constitute at least the beginnings of a more locally adaptive approach to climate change management.

5. Managing extreme heat through land-based mitigation

Our review of municipal and state level climate action plans suggests that, while a majority of large U.S. cities is taking action to reduce greenhouse gas emissions, only about one in four is developing programs explicitly designed to address non-emissions-related drivers of warming. As it is these local-scale, land-based drivers of climate that account for the majority of urban warming to date, there is a growing need for municipal and state governments to complement emissions control programs with heat island management strategies.

While there may be many reasons municipal and state governments have prioritized emissions control strategies over direct heat management in their climate change planning, the international policy framework developed to combat climate change at the global scale has undoubtedly influenced the management approaches adopted at the urban scale. As noted above, the formal definition of climate change mitigation identifies emissions control and enhanced carbon sequestration as the sole management tools available to address climate change, effectively overlooking the potential for modifications to the surface energy balance and albedo to slow the pace of warming trends. Importantly, however, this overly narrow definition of mitigation is in conflict with the IPCC's own definition of climate change, which states that "climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere *or in land use*" (IPCC, 2001, emphasis added). Although recognized by the IPCC to be a forcing agent of climate change, the physical character of the land surface has not yet been recognized in international policy accords as an agent of climate change mitigation.

In response to this oversight, we believe the concept of mitigation should be broadened to account for both the atmospheric and land-based drivers of climate change. Defined herein as land surface changes producing an increase in surface albedo or a shift from sensible and/or radiative energy fluxes to latent energy fluxes, "land-based mitigation" complements conventional, emissions-based mitigation through addressing the regional to local-scale drivers of climate change that are often the principal driver of ongoing warming trends at these scales (Stone, 2009).

There is evidence to suggest that an exclusive focus on emissions-oriented approaches to mitigation in international climate accords, such as the Kyoto Protocol, may be impeding municipal governments from incorporating land-based mitigation strategies into climate action plans. Organizations and initiatives with a focus on climate change management at the urban scale, such as ICLEI, the C40 Cities Climate Leadership Group, and the U.S. Conference of Mayors' Climate Protection Agreement, have tended to identify emissions control as the principal – and generally singular – approach to urban climate management. The U.S. Conference of Mayors Climate Protection Agreement, for example, now signed onto by the chief executives of more than 1000 U.S. cities, commits these cities to emissions reductions consistent with targets established under the Kyoto Protocol but entails no commitments for land-based mitigation techniques demonstrated to moderate urban heat island formation. Likewise, the climate action plan milestones established by ICLEI are focused exclusively on greenhouse gas emissions control.

With this observation in mind, an important question to raise about urban climate mitigation strategies targeted toward emissions reduction concerns the extent to which such strategies provide an effective means of local heat management. As noted above, the actual cooling benefits of urban-scale emissions reductions are assumed to be negligible due to the small contribution of these emissions to regional tropospheric concentrations of greenhouse gases. In terms of direct heat island management, the often modest scale of these initiatives, with green roof or cool roof initiatives limited to municipally-owned buildings in the majority of cities having adopted these strategies, should not be expected to significantly modify city-wide temperatures. In modeling studies finding land-based mitigation to be effective at the urban scale, such strategies are implemented on a much broader scale throughout a metropolitan region. Also important is the often narrow focus of land-based mitigation strategies in current climate action plans, with few cities simultaneously investing in multiple types of vegetation (e.g., green roofs and tree planting initiatives) and albedo enhancement. To be most effective in urban heat island management, land-based mitigation strategies must be designed with region-wide heat management as their chief purpose.

The need for cities to take steps to address the land-based drivers of urban-scale warming is highlighted by a number of recent studies on extreme heat in large cities. A recent analysis of the annual occurrence of extreme heat events in cities – days in which temperatures exceed a regional threshold beyond which hospital admissions for heat-related illness increase – finds the number of such events to have almost doubled in large U.S. cities since the 1950s, rising from an average of about 10 extreme events a year that decade to about 18 such events today (Stone, Hess, & Frumkin, 2010). As demonstrated by the more than 70,000 heat-related deaths now attributed to the European heat wave of 2003, the magnitude of the threat posed by extreme heat during such events is as great as any challenge posed by climate change (Robine, Cheung, Le Roy, Van Oyen, & Herrmann, 2007). And such events are projected to grow increasingly common over the next few decades. Through a study accounting for the impacts of rising greenhouse gas emissions and heat island effects on urban temperatures, McCarthy, Best, and Betts (2010) find that many of the world's most populous cities will see the number of extreme heat events increase by a factor of three or four by 2050, with some large cities projected to experience more than 50 extreme heat events a year.

Both experimental and modeling studies of land-based mitigation strategies have found such techniques to measurably slow warming trends when implemented extensively throughout urbanized regions. Over the last two decades, a large number of studies have found variable combinations of tree planting and vegetative cover (including green roofs), albedo enhancement, and reductions in waste heat emissions to reduce city-wide temperatures by between 2 and 13 °F (~1 and 7 °C) (Kikegawa, Genchi, Kondo, & Hanaki, 2006; Lynn et al., 2009; Rosenzweig, Solecki, & Slosberg, 2006; Taha, 1997; Zhou & Shepherd, 2010). Of the three classes of land-based mitigation, tree planting and other vegetative strategies are generally found to be the most effective, with surface reflectivity and waste heat strategies typically accounting for somewhat lower reductions in near surface air temperatures, depending upon the spatial extent of coverage and the regional landscape type (Hart & Sailor, 2009; Lynn et al., 2009; Zhou & Shepherd, 2010).

Importantly, many synergies exist between strategies designed to control greenhouse emissions and strategies designed to mitigate the urban heat island effect. In addition to the potential for emissions control programs to yield co-benefits in the form of reduced waste heat emissions, a direct cooling of the ambient air through vegetation and albedo enhancement carries benefits for building energy consumption in the summer. While such strategies may serve to increase energy consumption for heating in the winter, studies have found the net benefits of reduced cooling for greenhouse emissions to be greater for mid- to low latitude settings, a geographic region encompassing most large U.S. cities (Akbari, Konopacki, & Pomerantz, 1999). When implemented extensively throughout a metropolitan region, such approaches have been shown to reduce energy consumption by as much as 10%, suggesting a strong potential for emission reductions and surface heat abatement to be managed concurrently (Akbari, Pomerantz, & Taha, 2001).

It has been our purpose in this article to argue for a broadening of climate action plans to incorporate land-based mitigation strategies designed to moderate the urban heat island effect. In so doing, it is not our intent to diminish the direct and unequivocal significance of greenhouse gas emissions to the ongoing process of climate change. Rather, we draw upon an established body of evidence pertaining to the role of land use in climate change to propose that the problem of slowing warming trends across a range of scales is more complex than presently reflected in climate management frameworks. There is no doubt that urban emissions of greenhouse gases must be reduced substantially to make progress in combating climate change. But the extent to which ongoing warming trends in cities can be managed through emissions reductions alone, particularly over the next few decades, is limited. In consideration of this fact, climate action plans adopted by both local and state governments should complement emissions reduction strategies with programs designed to address the land-based drivers of warming.

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