Assessing the Health Impacts of Urban Heat Island Reduction Strategies in the Cities of Baltimore, Los Angeles, and New York

Dr. Jennifer Vanos – Texas Tech University
Dr. Laurence S. Kalkstein - Applied Climatologists Inc./University of Miami
Dr. David Sailor - Portland State University
Kurt Shickman – Global Cool Cities Alliance
Dr. Scott Sheridan- Kent State University

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Executive Summary

Purpose: This study quantifies the impact that typical urban heat island mitigation strategies, such as reflective roofs and vegetation, have on weather conditions and estimated mortality during extreme heat events. Many residents within American cities are vulnerable to health and even mortality risks caused by extreme heat events. In numerous cities, the health impacts of these heat events are exacerbated by the fact that the city is significantly warmer than the surrounding rural areas during the summer. This phenomenon, known as the “urban heat island” (UHI) effect, is caused by heat absorption of paved surfaces and dark roofs, anthropogenic heat production (e.g., vehicles, industry), as well as a lack of permeable surfaces and cooling vegetation.

Research on urban environments has found that a number of strategies can reduce excess urban heat by generating perceptible ambient changes in temperature, thus making urban populations more resilient

to extreme heat events. Examples of such strategies include green roofs, shade trees, and vegetation, as well as surfaces that reflect sunlight rather than absorb it as heat (e.g., "cool roofs" and "cool pavements"). Although these UHI mitigation measures often save energy and make economic sense for building owners, policymakers are increasingly drawn to UHI mitigation to gain the health benefits of cooler cities. The findings of this paper will help urban planners and city officials looking to further quantify the health and life-saving benefits of reducing summer urban heat islands with cool surfaces and increased vegetation.

Activities Undertaken: This study estimates reductions in heat-related mortality in three cities: Baltimore, MD, Los Angeles, CA, and New York, NY. The study employs Weather Research and Forecasting (WRF) model version 3.4 in combination with meteorological data from historic multi-day heat events in each city. Using the model, the project team evaluated whether or not the 'oppressive' weather conditions (historically associated with high mortality) would have decreased due to the installation of urban heat island reduction measures. The study team identified four actual multi-day extreme heat events in each city, modeled the impact of increased surface reflectance and increased vegetative cover on meteorological conditions using three scenarios:

1. Increase urban surface reflectance by 0.10 (0.15 to 0.25);
2. Increase surface vegetation by 10% and reflectance by 0.10;
3. Increase surface reflectance by 0.20 (0.15 to 0.35).

The team then applied the modeled weather conditions to calculate excess mortality during those events. Excess mortality was calculated using empirical algorithms based on historical heat response in the given city. Some cities use these mortality algorithms as the basis of their heat advisory/warning systems.

The scope of this study is limited to the reductions in mortality resulting from altered weather conditions due to the increase in urban area covered by reflective surfaces and vegetation. Mortality reductions resulting from concomitantly improving the indoor conditions (particularly in the case of homes without air conditioning that receive a cool roof) are potentially significant but not a part of this study.

Outcomes: Changes in air temperature and humidity during the heat events (as measured by dew point temperature) in all cities were small, commonly less than a 1^{o}F decrease. The study found that reflectivity and vegetated cover were equally effective urban cooling strategies. The differences in apparent temperature and mortality reduction were similar in the first two scenarios (as listed in Table 1) employing modest increases in reflectivity, or both reflectivity and vegetation.

The temperature changes compared to actual conditions were significant enough to contribute to notable reductions of deaths (see Table 1). On average, Los Angeles demonstrated the largest decreases in temperature, and New York the least. Despite this fact, the mortality reductions in New York were significantly greater than Los Angeles for two of the three scenarios. The non-linear nature of the relationship between temperature and mortality decreases can potentially be explained by building and population density, where very small temperature changes in a very densely built and populated area can result in much less health risk.

During the period between 1948 and 2011, Baltimore, Los Angeles, and New York lost an average of 87 people each summer (June-July-August) due to heat-related mortality (Kalkstein et al., 2011). This study finds that deploying UHI mitigation strategies would save up to 32 lives in Baltimore, 22 lives in Los Angeles, and 219 lives in New York over a 10-year period. In addition, an even larger reduction would be expected in hospital admissions from heat-related illness, although an analysis of the broader health impacts was outside the scope of this study.

The changes across the urban landscape required to achieve the scenarios modeled in this study are realistically achievable for the cities in this study and many other cities with similar urban heating challenges. For example, increasing city-wide roof reflectivity by 10 percentage points is achievable by converting dark grey roofs (reflectance of 0.15) to white roofs (reflectance of 0.55) on approximately 25 percent of each city's buildings. Assuming the average roof lasts 20 years, cities could achieve this transition with end-of-life roof replacements[1] in about five years. Increasing the deployment of cool roofs and vegetation generates perceptible ambient changes in temperatures, which improve the conditions experienced by urban residents. Studies find that low-income and minority populations experience the highest levels of heat vulnerability. These populations are likely to benefit the most from investments in UHI measures.

Table 1: Average mortality reductions in each city with respect to the given mitigation strategy (scenario).

Urban Cooling Scenario	**Baltimore Mortality Reduction**	**Los Angeles Mortality Reduction**	**New York City Mortality Reduction**
1) A 10-percentage point increase in urban surface reflectivity	1%	1%	9%
2) A 10-percentage point increase in urban surface reflectivity and a 10 percent increase in vegetative cover	2%	1%	9%
3) A 20 percent increase in urban surface reflectivity	5%	21%	10%
Lives potentially saved per decade[2]	32	22	219

Introduction

The Problem of Extreme Heat

In an average year, heat kills more than 700 people in the United States, more than any other natural disaster (Centers for Disease Control and Prevention). Large urban areas are particularly susceptible to extreme heat events because their downtown areas are sometimes 5 to 6°F hotter during the day and up to 22 °F hotter at night than surrounding rural areas (Oke, 1988). This so-called urban heat island effect ("UHI") occurs for a number of reasons:

- On average, more than 50% of urban landscapes are dark, man-made surfaces that get hotter in the sunlight and hold more heat than natural landscapes such as grass or tree canopy (Akbari et al., 2009)
- Cities have less vegetation than rural areas. Vegetation keeps temperatures lower than man-made surfaces by providing evaporative cooling and shade.
- Urban areas are centers of human activity, many of which generate anthropogenic heat (e.g., air conditioning exhaust, vehicles, industrial processes)

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[1] End-of-life roof replacements mean that a cool roof is installed when the roof needs to be replaced anyway.

[2] Based on scenario 3.

In addition to causing higher daytime temperatures, these factors prevent cities and their residents from cooling off at night. Hotter nighttime temperatures are especially dangerous during extreme heat events because urban populations are often unable to recover from the daytime heat and hence become more vulnerable to heat-related health problems when heat events continue over several days (O'Niell and Ebi, 2009).

Previous research by Applied Climatologists Inc. (ACI) has determined that certain very hot, dangerous "oppressive air masses" are associated with statistically significant increases in heat-related mortality, especially from cardiac arrests, strokes, and other heat-related causes (Kalkstein et al., 2011, Luber et al., 2008). These air masses, which are most often extremely hot and humid forms of Moist Tropical (MT+, MT++) and very hot, low-humidity Dry Tropical (DT) air masses (see Table 2 for descriptions of air masses), are beyond the human threshold of tolerance in many locales, especially when they occur for consecutive days.

From 1948 to 2012, on average, 11.5%, 8.0%, and 12.4% of the warm season days[3] in Baltimore, Los Angeles, and New York, respectively, were considered "oppressive" based on air mass analysis; these frequencies vary significantly from one summer to the next. However, the number of warm season days with air masses that lead to heat warnings and health problems are increasing in frequency. For example, in the 1940s and 1950s, New York experienced these "dangerous" air masses an average of 11 days each summer (approximately 12% of the summer). During the last decade of 2003 to 2013, those dangerous air masses have occurred on over 18 summer days (approximately 20% of the summer).[4] In Baltimore, these air masses were present on 11% of summer days in the 1940s and 1950s, and now occur 13% of the time, on average. Los Angeles displays relatively low rates of oppressive days in June, July, and August (~1%), as the warmest and more oppressive weather is typically found in late summer to early fall (August, September, October). In Los Angeles, the frequency of days with "oppressive" air masses in the fall now averages 8% (up from 6% in the 1940s and 1950s). New York experiences the highest frequency of oppressive air masses of the three cities, and in the last four years, the dangerous summer days have been even more common, representing 34 days (38% of the summer days) in 2010, 15 days (17%) in 2011, and 21 days (23%) in 2012 and 2013 (Sheridan, 2013).

Strings of these oppressively hot days, comprising excessive heat events, take a disproportionate toll on low-income urban populations because they often live in neighborhoods that have older, lower quality building stock, less tree cover, and fewer buildings with air conditioning. Black Americans are 52% more likely than average to live in an area where a high risk for heat-related health problems exists. Hispanic Americans are 21% more likely to live in such conditions (Jesdale et al. 2013). Mitigating urban heat islands and the impact of extreme heat will help the large urban areas improve health equity, increase social justice, and become more sustainable.

Mitigating Urban Heat Islands

The growing risk of heat related mortality is a serious consequence of the combined impacts of more intense urban heating and projected increases in extreme hot temperatures due to climate change

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[3] "Warm season" is defined as June, July, and August for Baltimore and New York, and August, September, and October for Los Angeles.

[4] More details on historical air mass characteristics for the three cities are found on Dr. Scott Sheridan's website: http://sheridan.geog.kent.edu/ssc.html

(Vanos et al., 2014). However, urban design strategies employed to lower the air temperature near the ground surface – referred to as urban heat island mitigation strategies – are becoming increasingly important as cities grow and temperatures rise. This study evaluated two common urban heat island mitigation strategies – increasing the reflectance of the surface cover (building and ground) and increasing the overall vegetative cover.

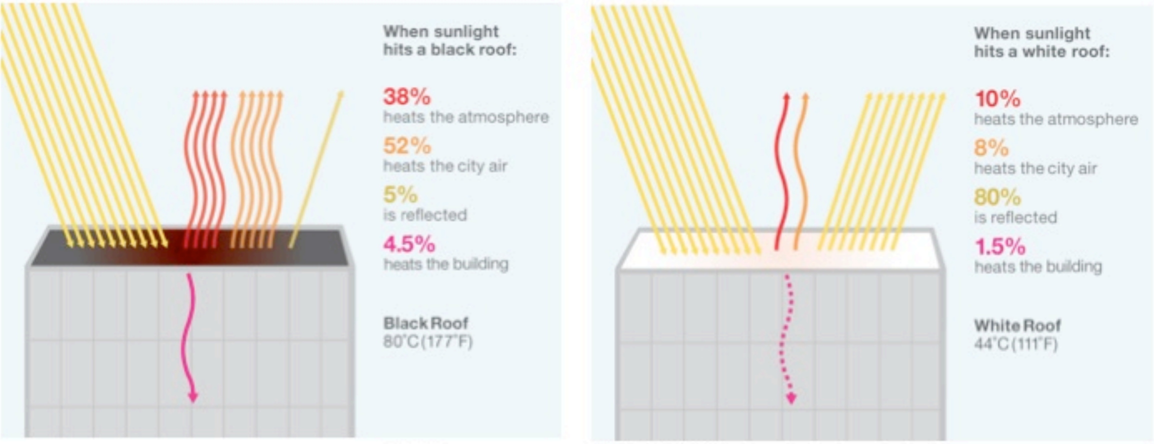
Increased Reflectance

Studies indicate that roofs and pavements make up 60% to 70% of urban surfaces in an average U.S. city; 20% to 30% are roofs and 30% to 45% are pavement (Akbari et al., 2009). Often, these surfaces are dark and absorb more than 80% of sunlight. Solar energy absorbed by roofs becomes heat that can be transferred into the building or blown off the roof to heat the surrounding community. Solar energy absorbed by pavements becomes heat that sits above the pavement or is blown around within the surrounding community.

Replacing and upgrading roofs and pavements with more reflective materials reverses this absorption and hence warming, turning urban surfaces into assets instead of burdens. Cool surfaces are measured by how much light they reflect (solar reflectance or SR) and how efficiently they radiate heat (thermal emittance or TE). Solar reflectance is the fraction of sunlight (0 to 1, or 0% to 100%) that is reflected from a surface. Solar reflectance, also referred to as albedo, typically ranges from about 0.04 (or 4%) for charcoal to 0.9 (or 90%) for fresh snow. High solar reflectance is the most important property of a cool surface.

Figure 1 demonstrates how albedo can keep a surface cool. The figure depicts two identical roofs that are receiving the same amount of sunlight. On both roofs, a portion of the sunlight will heat the building, some will heat the city air, some will heat the upper atmosphere[5], and some will be reflected into space. The white roof reflects the vast majority of the sunlight back into space, thus keeping the building, city, and planet cooler.

Figure 1. Difference in heat dispersal on a black versus white roof. Much more heat is reflected when utilizing white roofing material.



Air Temperature 37°C (99°F)

Source: Lawrence Berkeley National Laboratory

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[5] Heating the upper atmosphere may cause increases in temperature over a broad area but not to a significant degree at the urban scale.

Thermal emittance (TE) measures the efficiency (0 to 1, or 0% to 100%) with which a surface emits thermal radiation, or heat. High thermal emittance helps a surface cool by radiating heat to its surroundings quickly. Nearly all non-metallic surfaces have high thermal emittance, usually between 0.80 and 0.95. Uncoated metal has low thermal emittance, which means it will stay warm. An uncoated metal surface that reflects as much sunlight as a white surface will stay warmer in the sun because it emits less thermal radiation. The TE is the second most important property of a cool surface.

Increased Vegetated Cover

Vegetated cover can be increased in a number of ways, including vegetated roofs and shade trees. Trees and other types of vegetated cover also cool through evapotranspiration—a process by which vegetation releases (transpires) water into the atmosphere through their leaves. Evapotranspiration can cool by using heat energy from the air to evaporate water, with the caveat that water must be available; hence, a very dry, arid climate would see lower rates of evapotranspiration from vegetation. Moreover, a tree canopy also cools cities by shading the ground and structures around them. The combination of evaporative cooling and shade has been shown to decrease air temperatures within a local park by up to 11°F compared to surrounding streets (Vanos et al., 2012), with cooling extending up to 100m into the surrounding neighborhood (Slater, 2010).

Furthermore, studies indicate that tree groves can be 9 °F cooler than open, grassy areas around them (Kurn et al., 1994). The USEPA's *Reducing Urban Heat Islands: A Compendium of Strategies* reported:

> "Chicago compared summertime surface temperatures on a green roof with a neighboring building. On an August day in the early afternoon, with temperatures above 90 °F, the green roof surface temperature ranged from 91 to 119 °F, while the dark, conventional roof of the adjacent building was 169 °F. The near-surface air temperature above the green roof was also about 7 °F cooler than the conventional roof."

It is also possible to capture some of the evaporative cooling benefits with permeable or pervious pavement technologies. These pavements allow water to pass through them more easily than traditional pavements and can release some of that water back into the air.

Methodology

The study employed the WRF version 3.4 model in combination with data from historic multi-day heat events in each city. Using the model, the project team estimated whether or not the 'oppressive' weather conditions (historically associated with high mortality) would decrease significantly due to the installation of urban heat island reduction measures. The study team identified four actual multi-day heat events in each city, modeled the impact of increased surface reflectance and increased vegetative cover on meteorological conditions, and applied estimates to calculate excess mortality during those events. Excess mortality was estimated using empirical algorithms based on historical heat response in the given city. The methodology employed has been used in prior analyses for the Environmental Protection Agency of Philadelphia, New Orleans, Detroit, and New York (Kalkstein and Sheridan, 2005). The research team currently uses the heat mortality algorithms in this study as guidance to the National Weather Service to determine excessive heat warnings for the three study regions (Sheridan and Kalkstein, 1998). In addition, we have previously published results on our heat health research in New York and Los Angeles, as well as other cities around the country (Kalkstein et al., 2011). The methods employed by the team identify those oppressive air masses that have historically killed people in greater numbers during excessive heat events.

Air Mass Classification and Excess Deaths

Weather data for this study were supplied by NOAA's National Environmental Satellite, Data, and Information Service (2012). Each day in each city is classified into an air mass category using the spatial synoptic classification system (SSC; Sheridan, 2002). The SSC evaluates a broad set of meteorological conditions numerous times daily, including air and dew point temperatures, cloud cover, air pressure, and wind variations, to place each day into one of the air mass types listed in Table 2. This study focused on how the variables of air and dew point temperatures, as well as apparent temperature[6], are altered based on the UHI mitigation scenarios. The study exclusively utilizes days when the cities of interest experienced Moist Tropical Plus (MT+ or MT++) and Dry Tropical (DT) air masses because they are historically associated with increased mortality. Daily mortality data are available for the entire U.S. in digital format for the period 1975 through 2009 (Centers for Disease Control, 2012). The study focused only on the warmest seasons for each location, defined as June through August for Baltimore and New York, and August through October for Los Angeles. Total mortality counts across each city were summed for each day and then standardized to account for demographic changes in population characteristics during the period. Factors that cause growth or a decline in overall death rate for reasons unrelated to weather are accounted for in the standardization of mortality. For example, daily mortality may be significantly lower in August, when people tend to go on vacation (Ebi et al, 2004).

Table 2. Air mass types in the SSC. The DT and MT+ air masses are of greatest concern for increasing mortality when they are present in Baltimore, Los Angeles, and New York.

Air Mass	Definition
	Generally Non-Oppressive Air Masses
Dry Polar (DP)	Arrives from polar regions and is usually associated with the lowest temperatures observed in a region for a particular time of year as well as clear, dry conditions.
Dry Moderate (DM)	Consists of mild and dry air. It occurs when westerly winds warm the air as it descends the eastern side of mountain ranges.
Moist Polar (MP)	Typically cloudy, humid, and cool. MP air appears when air over the adjacent cool ocean is brought inland by an easterly wind, frequently during stormy conditions.
Moist Moderate (MM)	Considerably warmer and more humid than MP. The MM air mass typically appears in a zone south of MP air, near an adjacent stationary front (an area where warm air moves over a cooler air mass).
Moist Tropical (MT)	Warm and very humid. It is typically found in warm sectors of mid-latitude cyclones or in a return flow on the western side of a high-pressure area, such as the Bermuda High.
Transition (TR)	Defined as days in which one weather type yields to another, based on large shifts in pressure, dew point, and wind over the course of the day.
	Oppressive Hot Air Masses
Dry Tropical (DT)	Represents the hottest and driest conditions found at any location. There are two primary sources of DT: either it is transported from the desert regions, such as the Sonoran Desert, or it is produced by rapidly descending air.
Moist Tropical+ (MT+)	Hotter and more humid subset of MT. It is defined as an MT day where both morning and afternoon temperatures are above the MT averages, and thus captures the most "oppressive" subset of MT days. We have also identified an **MT++** situation, which is even more extreme; in this case, both morning and afternoon temperatures are at least 1 standard deviation above MT averages.

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[6] The apparent temperature is a combination of air temperature (T_a) and dew point temperature (T_d), resulting in an equivalent 'feels like' temperature, where AT = $-2.653+0.996 \times T_a+0.0153 \times T_d^2$ in ºC, and is derived from Steadman 1979.

After standardization, mean anomalous daily mortality—the number of deaths above what would normally be expected on that day—was calculated for each air mass type. As has been the case in most cities, the DT, MT+, and MT++ air masses are associated with the greatest increase in mortality over baseline levels, although the degree of increase varies from one city to the next (See Table 4). On such days, the oppressive weather is historically related to increased daily mortality on average by about 5.5%, 5.0%, and 7.0% above baseline, respectively (Table 4). During the most recent 3 years with data available (2010−2012), however, these oppressive air masses have been occurring on approximately 19.6%, 8.0%, 24.7% percent of summer days in the three respective cities.

Table 3: Days in the each city with dangerous air masses present during the most oppressive season.

	Baltimore		**Los Angeles**		**New York**	
	Average Summer Days	Percent	Average Fall Days	Percent	Average Summer Days	Percent
1950−1959	11.2	12.2	7.6	8.4	10.9	11.8
1960−1969	7.1	7.7	7.9	8.7	8.4	9.1
1970−1979	6.5	7.1	7.6	8.4	5.2	5.7
1980−1989	12.5	13.6	7.7	8.5	10.5	11.4
1990−1999	14.2	15.4	5.9	6.5	14.1	15.3
2000−2009	9.3	10.1	6.8	7.5	16.0	17.4
2010−2012	18.0	19.6	7.3	8.0	22.8	24.7
63-Year Average	10.5	11.5	7.3	8.0	11.4	12.4

However, not all DT, MT+, and MT++ days result in elevated mortality. To account for this variability, the project team employed a stepwise linear regression[7] that had previously been developed for each oppressive air mass in each city to estimate excess mortality. These equations account for the following, and are displayed in Table 6:

- Time of season. Historically, heat waves earlier in the summer season are more dangerous than those later in the season.
- Persistence of an oppressive air mass. Several consecutive days of an oppressive air mass are much more health-debilitating than any single-day heat event.
- Air mass character, including temperature, humidity, apparent temperature, wind speed, and cloud cover.

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[7] A stepwise linear regression is a more sophisticated technique than standard linear regression. It evaluates combinations of variables that impact mortality rather than looking at them in isolation.

Table 4. Mortality responses in different cities when DT and MT+ air masses are present.

City (% frequency DT/MT+ in hot season)	DT Mortality (% Inc)	MT+ Mortality (% Inc)
Baltimore (11.5%)	**+0.9 (4%)**	**+1.7 (7%)**
Los Angeles (8.0%)	**+8.4 (5%)**	**+8.4 (5%)**
New Orleans (2%)	None	+3.7% (9%)
New York (12.4%)	**+16.6 (7%)**	**+16.9% (7%)**
Phoenix (1%)	+2.7[b] (7%)	None
Rome (11%)	+6.2 (14%)	+5.0 (12%)
Seattle (6%)	+3.7 (8%)	+4.7[a] (10%)
Shanghai (11%)	None	+42.4 (10%)
Toronto (7%)	+4.2 (11%)	+4.0 (10%)

[a] MT+ does not occur in Seattle; moist air mass present is MT. [b] DT+ air mass for Phoenix.

Cooling Simulations Employed

Dr. David Sailor of Portland State University provided modeled meteorological data for 28 different scenarios to test the impacts of urban cooling initiatives upon air mass character and heat-related mortality. The modeled data permitted us to determine air mass type and character for a variety of cooling scenarios and changes to the urban fabric (e.g., built versus natural space). The modeled data also allowed us to evaluate how adding urban vegetation can alter the way the built and natural environment utilizes solar energy.[8] Dr. Sailor centered the study area on locations within each city where the majority of the population most vulnerable to heat-related health problems (usually the lowest-income sections of the city in terms of economics and housing stock).

A regional scale (mesoscale) atmospheric model known as the Weather Research and Forecasting (WRF version 3.4) model was used for all atmospheric modeling in this project. The WRF model is widely accepted as one of the leading atmospheric models for both operational forecasting and climate research purposes. Details of WRF can be found at www.wrf-model.org. The WRF model is typically used with grid resolutions equal to or greater than 1 km, and as such, does not explicitly resolve the detailed geometry of urban areas (e.g., individual buildings). Rather, WRF allows the user to represent urban areas through one of several urban parameterizations. In the modeling for this study, we use the single layer urban canopy model (UCM), which allows for representation of roofs, walls, and streets in three classes of urban areas: commercial/industrial, low density residential, and high-density residential. The output from the model were based on changes to the urban fabric for the given scenario in an area that closely approximates the city limits of each urban region we are evaluating.

To simulate the urban heat island mitigation strategy of increasing urban reflectivity (also known as albedo) we assumed that only roof and road surfaces would be modified. In all cases, the rooftop albedo was never increased to a value beyond 0.60 and road albedo was never increased to a value beyond 0.30. These thresholds are easily achievable with products currently available in each city. Further, they are in line with commercial codes in both New York and Los Angeles that require initial reflectance of 0.7

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[8] Solar energy is used by the environment in one of three ways: to heat the air, heat the ground, or to evaporate water. In general, areas tend to be cooler when more solar energy is used to evaporate water than to heat air or surfaces.

and an aged reflectance of 0.55, respectively.[9] The assumption for maximum pavement albedo of 0.3 is in line with the typical albedo of aged concrete. It is possible to achieve albedos closer to 0.7 if lighter, reflective coatings are employed. Reflective coating would typically be used on playgrounds, pedestrian walkways, or parking lots and generally not on roads, which is why we used the lower number.

Urban Cooling Scenarios

Three specific scenarios were investigated. In the first, referred to as **ALB1,** the overall albedo of all urban cells was increased from 0.15 to 0.25 (an increase of 0.1) by increasing road and roof albedos. Since the surface in an urban cell is not 100% built surfaces, the albedos of the road and roof surfaces were changed by greater than 0.1 in order to have an average of 0.1 albedo for the entire cell. A second scenario with increases in both vegetation *and* reflectivity were modeled in order to understand the impact of combining these commonly used UHI mitigation strategies. The scenario assumes an increase in the total urban vegetation fraction from roughly 10% to 20%, in conjunction with a 0.1 increase in albedo. The resulting second simulation is referred to as **ALB1VEG1**. Third, the study team simulated a higher albedo modification case, referred to as **ALB2,** for one or two heat events per city. In this case, the baseline albedo of all urban cells was increased from 0.15 to 0.35 (an increase of 0.2).

Heat Event Selection

We developed scenarios for four separate heat events in each city, as listed in Table 5.

Table 5: Heat events selected for the study based on the presence of 5 or more consecutive days of oppressive air masses.

	Baltimore	Los Angeles	New York
Heat Event	Jul 19–23, 1991	Aug 13–18, 1992	May 28–Jun 1, 1991
	Jul 7–11, 1993	Aug 10–14, 1994	Jul 31–Aug 4, 1995*
	Jun 17–21, 1994*	Aug 12–17, 1994*	Jul 3–Jul 7, 1999*
	Jul 4–8, 2010	Jul 22 –6, 2006	Jul 30–Aug 3, 2006

*Heat wave events where ALB2 modeling was also completed.

We generally selected early-to mid-season heat waves for the respective warm seasons, since much of our research indicates that the negative health outcomes from excessive heat events are greatest earlier in the season when the pool of susceptible individuals is largest (Kalkstein et al., 2011). Los Angeles differs from the eastern cities because of it experiences its period of excessive heat during the early fall when dry, hot Santa Ana winds become prevalent. For each of these heat waves, we modeled an ALB1 and Alb1Veg1 scenario. We also modeled an ALB2 scenario for the June 1994 heat wave in Baltimore, the August 1994 heat wave in Los Angeles, and the July 1995 and 1999 heat waves in New York. We compared these scenarios to the actual (observed) conditions that occurred during the heat wave and evaluated the following:

- Air mass type for each day: Were there changes in air mass type from MT+, MT++, and DT to more benign air mass types during any of the cooling scenarios (e.g., MT or DM)?
- Temperature and dew point temperature changes: We determined afternoon (5:00 p.m. local time) changes in these parameters for all the scenarios.

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[9] Roof albedo requirements are based on a process managed by The Cool Roof Rating Council that determines aged albedos after a 3 year aging and weathering period. In practice, some roofs will outperform the 0.55 albedo requirement because they are less than 3 years old or because they are a higher performing product. Thus we allowed for a maximum albedo of 0.6 in the study.

- Maps of temperature change: We demonstrate the changes at 4 times per day for the heat event in each city and the surrounding areas for all scenarios (Appendices A-C).
- Mortality changes: We determined estimates of mortality reduction for all heat events and scenarios using the city-specific mortality algorithms for the oppressive air mass types. The algorithms are listed in Table 6.

Table 6: City-specific mortality algorithms for the oppressive air mass types.

	DT	MT+/MT++
Baltimore	$M = -13.197 + 1.07\times DIS - 0.066\times TOS + 0.612\times Atp$	$M = -8.168 - 0.016\times TOS + 0.301\times Atp$
Los Angeles	$M = -11.0 + 2.76\times DIS - 0.017\times TOS + 0.56\times Tp$	
New York	$M = -37.4 + 8.82\times DIS - 0.11\times TOS + 1.425\times Atp$	
M is the estimate of the daily heat-induced mortality.		
Tp is the afternoon air temperature.		
DIS is the day in sequence (for example, for each consecutive day within the DT air mass, the estimated mortality increases by 2.76 in Los Angeles).		
TOS is time of season (for example, for each later day within the season, estimated mortality within the DT air mass decreases by 0.017 in Los Angeles).		
Atp is afternoon apparent temperature, similar to the National Weather Service "heat index," which combines the impacts of temperature and humidity.		

The methodology used for this report is appropriate for determining the reduction in mortality resulting from changes in outdoor weather conditions. This report does not, however, analyze or quantify the mortality reductions resulting from decreased indoor air temperatures that are associated with results from the scenarios. The reduction in indoor temperature can be significant after a reflective or green roof has been installed (due to less absorption of heat into the building material), particularly for the urban "row home" style of building that predominates in Baltimore and New York. It is likely that including indoor thermal alterations would yield significant increases in the estimates of lives saved because the most vulnerable populations tend to live in poor quality buildings without air conditioning, and hence would most benefit from the addition of a cooler roof. Further, indoor temperatures are much more sensitive to the addition of cool roofs than outdoor temperatures. The Energy Coordinating Agency of Philadelphia, which has similar residential building stock to Baltimore and New York, have found that homes with a cool roof are approximately 5 degrees Fahrenheit cooler than they were with a dark roof.[10]

Results

In the following sections, the results and tables are separated by city (Baltimore, Los Angeles, New York) for ease of locating city-specific results. We report overall reductions in air, dew point, and apparent temperatures for all cities (Tables 10, 14, and 18 respectively). On average, Los Angeles demonstrates the greatest decreases in temperature, with New York experiencing the smallest change in temperature. For example, the model output apparent temperature in Los Angeles for ALB2 was 1.8 and 1.0^{o}F lower than New York and Baltimore, respectively. However, New York's mortality response was overall the greatest of the three cities, demonstrating that even very small changes in such a densely built and populated areas results in a dramatic human health response.

A common occurrence in all cities under the ALB1VEG1 scenario was the increase in the dew point

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[10] More information on the Energy Coordinating Agency is available on their website: http://ecasavesenergy.org/

temperatures. This is due to increased vegetation that contributes to more evapotranspiration of liquid water into water vapor and into the atmosphere, thus increasing humidity. This will result in a higher apparent temperature (a combination of air temperature and humidity) than would occur with a lower dew point temperature. Similar results were noticed when developing these scenarios for Detroit, Los Angeles, Philadelphia, and New Orleans in previous analyses (Kalkstein and Sheridan, 2005).

Air masses characterize a comprehensive set of weather situations that capture the impact of weather on human health. Thus, changes in air mass type lead to greater reductions in expected mortality than changes in temperature and apparent temperature alone (see Tables 8, 12, 16). By using air mass classification, this study captures factors that are frequently overlooked in traditional climate/health analyses such as cloud cover, wind speed, and diurnal temperature range. While "oppressive" air masses (namely DT and MT+) are historically associated with a significantly higher number of deaths in the warm season, the remaining air masses (e.g., DM, MP, etc) are associated with no change from baseline or even a decrease in mortality. Hence, if a day can be moved from an oppressive air mass, such as DT, to a relatively 'benign' air mass with fair weather, such as DM, sizable reductions in the number of heat related deaths are possible. In two of the four heat events in Los Angeles and New York, this type of air mass change did occur, indicating that the changes in weather conditions attributed to the increase in albedo and/or vegetation were significant enough to elicit such an air mass change.

Four of the 12 heat events studied demonstrated air mass changes from more to less oppressive conditions, with two in Los Angeles, two in New York, and zero in Baltimore. The ratio of 50% in the first two cities is similar to what we found in our EPA-funded studies sponsored by the Heat Island Reduction Initiative (Kalkstein and Sheridan, 2005) and in a study of Washington DC (Kalkstein et al 2013).

In general, the study found that increasing reflectivity and vegetated cover in urban areas (ALB1 and ALB1VEG1) resulted in similar changes in temperature and estimated mortality reductions resulting from outdoor ambient temperature reduction. There are a wide variety of benefits (e.g., indoor comfort, stormwater management, energy cost savings) that are external to this study that should be considered by policymakers when developing an urban cooling strategy. As it relates to outside temperature, those strategic decisions will result in a similar impact on cooling and mortality.

A. Baltimore

Each of the scenarios led to some decrease in outdoor air temperature from actual conditions during all four Baltimore heat events studied (Tables 7 and 10). The majority of the decreases were not dramatic (approximately 0.4 to 0.6°F), yet even small decreases resulted in decreased potential for heat-related deaths. The greatest decreases were found in the June 1994 heat wave within the ALB2 scenario, where an average decrease in the apparent temperature of 0.8°F was estimated. The heat wave of July 4 through 8, 2010 showed slightly more cooling under the ALB1VEG1 scenario, where the average temperature decrease was 0.6°F, but with an average increase in dew point temperature by 0.2°F. Overall for the four heat events, the ALB1VEG1 scenario demonstrated greater temperature reductions than the ALB1 scenario, but the slight increases in dew point temperatures led to smaller reductions in apparent temperature. In general, there were minimal increases in dew point when vegetation was increased due to evapotranspiration; hence, lower reductions in the apparent temperatures were found in ALB1VEG1 scenarios, resulting in less of a decrease than the ALB2 scenario. The ALB2 scenario, as modeled for the June 1994 heat event, demonstrated a reduction in all three temperatures (1.1°F maximum decrease of apparent temperature on June 20, 1994).

Table 7. Temperature (T), dewpoint (Td) and apparent temperature (AT) at (5:00 p.m. local time) for the four Baltimore heat events. “Observed” represents the actual event.

Scenario:	Observed (°F)			Alb1Veg1 (°F)			Alb1 (°F)			Alb2 (°F)		
Temperature Variable:	T	Td	AT	T	Td	AT	T	Td	AT	T	Td	AT
19-Jul-91	97.0	69.1	103.6	96.5	69.2	103.2	96.8	69.1	103.5	-	-	-
20-Jul-91	96.1	70.0	103.3	95.6	70.2	103.0	95.9	70.0	103.2	-	-	-
21-Jul-91	99.0	66.0	103.8	98.5	66.1	103.3	98.8	66.0	103.6	-	-	-
22-Jul-91	93.9	68.0	99.9	93.4	68.1	99.4	93.7	68.0	99.7	-	-	-
23-Jul-91	100.0	66.9	105.4	99.6	67.0	105.0	99.9	66.9	105.2	-	-	-
Event Average	**97.2**	**68.0**	**103.2**	**96.7**	**68.1**	**102.8**	**97.0**	**68.0**	**103.0**	**-**	**-**	**-**
7-Jul-93	96.1	71.1	104.0	95.5	71.2	103.6	95.8	71.1	103.8	-	-	-
8-Jul-93	99.0	66.9	104.3	98.5	67.1	103.9	98.8	67.0	104.1	-	-	-
9-Jul-93	99.0	64.9	103.1	98.5	65.1	102.8	98.8	65.0	103.0	-	-	-
10-Jul-93	98.1	66.9	103.4	97.6	66.9	102.9	97.9	66.9	103.2	-	-	-
11-Jul-93	96.1	62.1	98.7	95.5	62.8	98.6	95.9	62.0	98.5	-	-	-
Event Average	**97.6**	**66.4**	**102.7**	**97.1**	**66.6**	**102.3**	**97.4**	**66.4**	**102.5**	**-**	**-**	**-**
17-Jun-94	86.0	73.9	96.0	85.5	74.0	95.6	85.8	74.0	95.8	85.4	73.9	95.3
18-Jun-94	93.0	70.0	100.3	92.4	70.1	99.7	92.8	70.0	100.0	92.3	70.0	99.6
19-Jun-94	88.0	79.0	101.7	87.5	79.1	101.3	87.8	79.0	101.5	87.4	78.9	101.1
20-Jun-94	88.0	71.1	95.9	87.6	70.7	95.3	87.8	70.8	95.6	87.5	70.1	94.9
21-Jun-94	93.0	75.9	104.4	92.4	76.0	103.8	92.7	75.9	104.1	92.1	76.0	103.6
Event Average	**89.6**	**74.0**	**99.7**	**89.1**	**74.0**	**99.2**	**89.4**	**73.9**	**99.4**	**88.9**	**73.8**	**98.9**
4-Jul-10	97.0	46.9	93.8	96.2	47.3	93.2	96.7	47.0	93.6	-	-	-
5-Jul-10	99.0	61.0	101.1	98.3	61.8	100.8	98.7	61.2	100.9	-	-	-
6-Jul-10	102.9	57.0	103.2	102.4	56.9	102.6	102.7	57.1	103.0	-	-	-
7-Jul-10	100.0	64.0	103.7	99.7	64.0	103.4	100.0	63.8	103.5	-	-	-
8-Jul-10	91.9	71.1	99.9	91.5	71.0	99.4	91.8	71.1	99.7	-	-	-
Event Average	**98.2**	**60.0**	**100.3**	**97.6**	**60.2**	**99.9**	**98.0**	**60.0**	**100.1**	**-**	**-**	**-**

Changes in air mass type (e.g., a DT classification dropping to a DM) did not occur based on the modeling in Baltimore, even though reductions in air temperature and apparent temperature occurred. Temperatures did not decrease enough to reach the threshold for an air mass change to occur. These thermal and dew point thresholds vary based upon time of year, and it is not easy to determine precisely when one air mass will leave a particular category and enter another because of the holistic nature of an air mass type. However, it is clear that the probability of an air mass change is higher when the alteration of thermal and dew point characteristics are more pronounced. Moreover, the fact that the air mass changes did not occur with temperatures reductions is also indicative of the heat events being quite extreme for the location and time of year.

Nevertheless, the decreased temperatures due to the albedo and vegetation increases – although minimal – did lead to a decrease in potential heat-related deaths based on the algorithms for Baltimore in Table 6. This is demonstrated in Table 9, where even without air mass changes, reductions in predicted mortality are found, although minimal in Baltimore, with less than 1 death per heat event. The impact of the weather conditions on mortality also varied from one heat event to the next. The most extreme events were in July 1993 and July 2010, resulting in an average of 48 and 36 estimated deaths for the entire heat event, while the June 1994 event was much lower at 12 deaths. Overall reductions were greatest in the ALB2 scenario for June 1994 and the ALB1VEG1 scenario for July 2010, with the least reductions in the ALB1 scenarios.

Table 8. Air mass type on each of the days during the heat events in Baltimore.

	Air Masses			
Scenario	***Obs***	***Alb1Veg1***	***Alb1***	***Alb2***
19-Jul-91	MT+	MT+	MT+	-
20-Jul-91	MT+	MT+	MT+	-
21-Jul-91	DT	DT	DT	-
22-Jul-91	MT+	MT+	MT+	-
23-Jul-91	DT	DT	DT	-
7-Jul-93	MT+	MT+	MT+	-
8-Jul-93	DT	DT	DT	-
9-Jul-93	DT	DT	DT	-
10-Jul-93	DT	DT	DT	-
11-Jul-93	DT	DT	DT	-
17-Jun-94	MT+	MT+	MT+	MT+
18-Jun-94	MT+	MT+	MT+	MT+
19-Jun-94	MT+	MT+	MT+	MT+
20-Jun-94	MT+	MT+	MT+	MT+
21-Jun-94	MT+	MT+	MT+	MT+
4-Jul-10	DT	DT	DT	**-**
5-Jul-10	DT	DT	DT	**-**
6-Jul-10	DT	DT	DT	-
7-Jul-10	DT	DT	DT	-
8-Jul-10	MT+	MT+	MT+	-

Table 9. Estimated mortality for days within the evaluated heat events in Baltimore.

	Mortality Estimates			
Scenario	***Obs***	***Alb1Veg1***	***Alb1***	***Alb2***
19-Jul-91	2.6	2.5	2.5	-
20-Jul-91	2.5	2.4	2.5	-
21-Jul-91	11.1	11.0	11.1	-
22-Jul-91	1.9	1.8	1.8	-
23-Jul-91	11.6	11.4	11.5	-
Event Total	**29.6**	**29.1**	**29.4**	**-**
7-Jul-93	2.8	2.7	2.8	-
8-Jul-93	11.1	11.0	11.1	-
9-Jul-93	11.7	11.6	11.7	-
10-Jul-93	11.7	11.6	11.7	-
11-Jul-93	10.1	10.0	10.0	-
Event Total	**47.5**	**46.9**	**47.2**	**-**
17-Jun-94	1.8	1.7	1.7	1.7
18-Jun-94	2.5	2.4	2.4	2.4
19-Jun-94	2.7	2.6	2.7	2.6
20-Jun-94	1.7	1.6	1.7	1.5
21-Jun-94	3.1	3.0	3.1	3.0
Event Total	**11.8**	**11.4**	**11.6**	**11.2**
4-Jul-10	4.6	4.4	4.5	-
5-Jul-10	8.1	8.0	8.0	-
6-Jul-10	9.8	9.6	9.7	-
7-Jul-10	11.0	10.9	10.9	-
8-Jul-10	2.1	2.0	2.1	-
Event Total	**35.5**	**34.8**	**35.2**	**-**
All Events	**124.4**	**122.2**	**123.4**	

As part of this research, the city of Baltimore and surrounding regions were mapped to determine when and where the greatest temperature reductions at 2m heights would take place under the scenarios. ALB1 scenarios for July 2010 at 1:00p.m. and 9:00a.m. are displayed in Figures 2 and 3. The maps show temperature differentials attributed to the cool technologies and the actual conditions on that day. It is noteworthy that in the afternoon of July 4th (Figure 2), the change in albedo resulted in a greater cooling (up to −1°F) within the dense city center (density of 7671 people per sq. miles), indicating that the small change in albedo had an important change on a large area of the city where many residents live. Baltimore also commonly benefits in the summer from a breeze off of the Chesapeake Bay that develops as land temperatures rise. The bay breeze occurs when the contrasting hot temperatures over land and relatively cool temperatures over the water create a flow from the Inner Harbor and the Port of Baltimore and replaces the hot air within the city center, which is is more buoyant and rises.

Table 10. Temperature changes (°F) from actual conditions under each of the scenarios in Baltimore.

🟦	0.3 to 0.5 reduction	🟥	0.3 to 0.5 increase
🟦	0.6 to 1 reduction	🟥	0.6 to 1 increase
🟦	>1 reduction	🟥	>1 increase

Scenario	Alb1Veg1 (°F)			Alb1 (°F)			Alb2 (°F)		
	Ta	Td	AT	Ta	Td	AT	Ta	Td	AT
19-Jul-91	-0.5	0.1	-0.4	-0.2	0.0	-0.2	-	-	-
20-Jul-91	-0.4	0.2	-0.3	-0.2	0.1	-0.1	-	-	-
21-Jul-91	-0.5	0.1	-0.4	-0.2	0.0	-0.2	-	-	-
22-Jul-91	-0.5	0.1	-0.5	-0.2	0.0	-0.2	-	-	-
23-Jul-91	-0.4	0.1	-0.4	-0.2	0.0	-0.2	-	-	-
Average	**-0.5**	**0.1**	**-0.4**	**-0.2**	**0.0**	**-0.2**	-	-	-
7-Jul-93	-0.6	0.2	-0.5	-0.2	0.0	-0.2	-	-	-
8-Jul-93	-0.4	0.1	-0.3	-0.2	0.0	-0.2	-	-	-
9-Jul-93	-0.5	0.1	-0.4	-0.2	0.0	-0.2	-	-	-
10-Jul-93	-0.5	0.0	-0.5	-0.2	0.0	-0.2	-	-	-
11-Jul-93	-0.5	0.7	-0.2	-0.2	0.0	-0.2	-	-	-
Average	**-0.5**	**0.2**	**-0.4**	**-0.2**	**0.0**	**-0.2**	-	-	-
17-Jun-94	-0.5	0.1	-0.4	-0.2	0.1	-0.2	-0.6	0.0	-0.6
18-Jun-94	-0.6	0.1	-0.5	-0.3	0.0	-0.3	-0.7	0.0	-0.7
19-Jun-94	-0.5	0.1	-0.4	-0.2	0.0	-0.2	-0.6	0.0	-0.6
20-Jun-94	-0.4	-0.3	-0.6	-0.2	-0.2	-0.3	-0.4	-1.0	-1.1
21-Jun-94	-0.7	0.1	-0.6	-0.3	0.0	-0.3	-0.9	0.1	-0.8
Average	**-0.5**	**0.0**	**-0.5**	**-0.2**	**0.0**	**-0.3**	**-0.7**	**-0.2**	**-0.8**
4-Jul-10	-0.8	0.3	-0.7	-0.3	0.1	-0.3	-	-	-
5-Jul-10	-0.7	0.8	-0.3	-0.3	0.2	-0.2	-	-	-
6-Jul-10	-0.5	-0.1	-0.6	-0.2	0.1	-0.1	-	-	-
7-Jul-10	-0.3	0.0	-0.4	-0.1	-0.3	-0.2	-	-	-
8-Jul-10	-0.5	0.0	-0.5	-0.2	0.0	-0.1	-	-	-
Average	**-0.6**	**0.2**	**-0.5**	**-0.2**	**0.0**	**-0.2**	**-**	**-**	**-**

The narrow bands of red suggest pockets of slight warming compared to observed. Cooling off the locations within the city lessens the land-sea differential and hence the bay breeze effect slightly on the coast. Therefore, there is a narrow band of coast that did not benefit from the sea breeze because of the reduced thermal differential between the land and the water.

Sea breezes often develop during the middle of the day when differentials between warm land and cool water temperatures are greatest. The effect diminishes as those differences in land and sea temperature shrink, typically in the evening. This midday phenomenon impacted the modeled afternoon temperature changes (1:00p.m.) on numerous days throughout the heat events in Baltimore, with further examples portrayed in Appendix A.

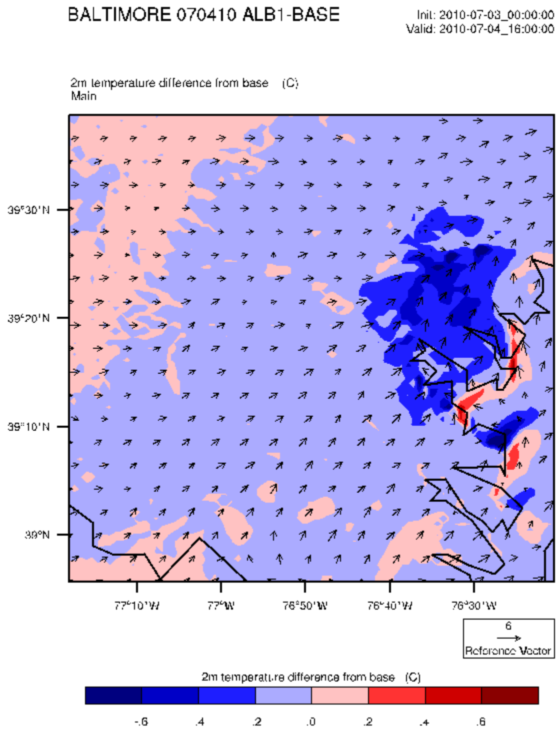


Figure 2. Temperature reductions (ALB1 – Observed) at 2m using the ALB1 scenario on July 4, 2010 1:00 p.m in Baltimore. Maps for the entire day are found in Appendix A.

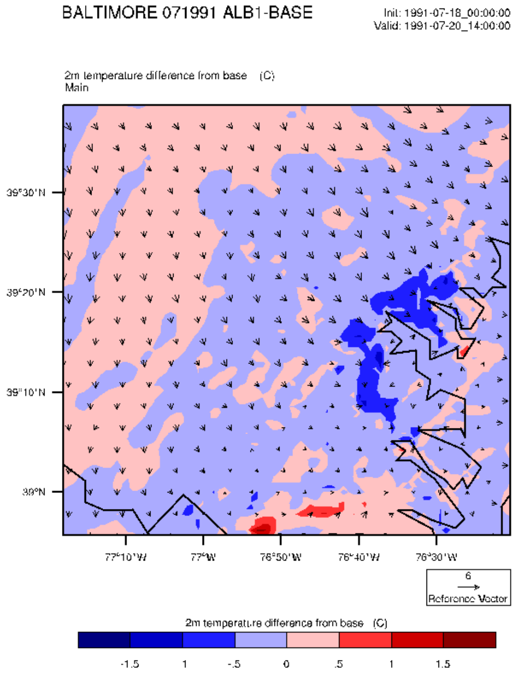


Figure 3. Temperature reductions (ALB1 – Observed) at 2m using the ALB1 scenario on July 19, 1991 at 9 a.m in Baltimore.

B. Los Angeles

Within the four heat events evaluated in Los Angeles, air temperature and apparent temperature reductions occurred in all scenarios (Tables 11 and 14). The decreases from observed conditions were more dramatic than those in the Baltimore events (approximately −0.6 to −0.8°F in magnitude). The greatest temperature and mortality decreases were found in the August 12−17th 1994 event under the ALB2 scenario. The apparent temperature was 1.6°F lower, a full degree cooler than the ALB1 and ALB1VEG1 scenarios.

The dew point increased slightly under the ALB1VEG1 scenario, resulting in a modest decrease of the apparent temperature than the ALB1 scenario. August 15, 1994 displays the most noticeable decrease within the entire August 1994 heat event, with average temperature decreases of 1.1, 0.9, and 2.1 °F for ALB1, ALB1VEG1, and ALB2 scenarios, respectively. Overall for the four Los Angeles heat events, the ALB1VEG1 scenario showed greater air temperature reductions than the ALB1 scenario, yet the apparent temperature reductions were similar due to increased humidity. The ALB2 modification decreased temperature, dew point, and apparent temperature by the greatest extent, but was only modeled for one heat event. The August 1994 heat event was also the most responsive to the UHI mitigation strategies modeled, which is indicative of the largest drops in estimated mortality and air mass change.

Two air mass modifications occurred: the August 1994 heat wave on the 5th day of the heat wave, when a DT switched to an MT air mass using the ALB2 intervention, and the 5th day of the July 2006 heat wave, where a MT++ air mass was lowered in intensity to an MT+ using the ALB1 intervention. Although in the remaining heat events reductions in the temperatures occurred throughout, the reductions were not sufficient to shift into a benign air mass (e.g., a DT classification dropping to a DM). This is indicative of the heat events being quite extreme for the given location and time of year.

Changes in air masses led to some substantial reductions in mortality for the August 1994 heat event (Table 13), and even those days without air mass alterations experienced slightly lower estimated heat related mortality due to decreased temperatures. The largest mortality reductions occur in the two heat events that experienced a switch in air mass. In August 1994, we estimate that 20 lives may have been saved using the ALB2 intervention. The scenarios without an air mass change demonstrated small declines of approximately 1 death each. Moreover, equal reductions were found in the August 1992 heat wave, also for the ALB1 and ALB1VEG1 scenarios, while within the August 10−14th 1994 heat event, minimal reductions occurred. Finally, even though the July 2006 heat wave experienced a switch in the air mass from the extreme MT++ to slightly less, but still intense, air mass of MT+, there were not marked reductions in the mortality as the predictive algorithm for the MT++/+ air masses are similar. In other words, the residents in the city of Los Angeles historically respond similarly to the weather under these two oppressive air masses.

Table 11: Temperature (T), dew point (Td) and apparent temperature (AT) at (53:00 p.m. local time) for the four Los Angeles heat events. "Observed" represents the actual event.

Scenario:	Observed (°F)			Alb1Veg1 (°F)			Alb1 (°F)			Alb2 (°F)		
Temperature Variable:	**T**	**Td**	**AT**	**T**	**Td**	**AT**	**T**	**Td**	**AT**	**T**	**Td**	**AT**
13-Aug-92	99.9	57.9	100.5	99.3	58.2	100.0	99.4	58.0	100.1	-	-	-
14-Aug-92	93.9	57.9	94.6	93.3	58.2	94.0	93.4	57.8	94.1	-	-	-
15-Aug-92	95.9	61.9	98.5	95.4	62.2	98.1	95.5	61.6	97.9	-	-	-
16-Aug-92	99.0	59.0	100.1	98.3	59.3	99.6	98.5	58.9	99.6	-	-	-
17-Aug-92	99.9	59.0	101.0	99.1	59.3	100.4	99.3	59.2	100.6	-	-	-
18-Aug-92	95.0	59.0	96.2	94.3	59.4	95.7	94.5	59.4	95.8	-	-	-
Event Average	**97.3**	**59.1**	**98.5**	**96.6**	**59.4**	**98.0**	**96.8**	**59.1**	**98.0**	-	-	-
10-Aug-94	95.9	54.0	95.0	95.3	54.2	94.5	95.5	53.9	94.5	-	-	-
11-Aug-94	99.0	54.9	98.4	98.2	55.1	97.8	98.4	55.1	97.9	-	-	-
12-Aug-94	100.9	55.9	100.8	100.3	56.2	100.3	100.5	55.9	100.3	-	-	-
13-Aug-94	99.9	59.0	101.0	99.2	59.3	100.5	99.4	58.5	100.3	-	-	-
14-Aug-94	93.9	61.9	96.5	93.1	62.2	95.8	93.3	62.0	95.9	-	-	-
Event Average	**97.9**	**57.1**	**98.3**	**97.3**	**57.4**	**97.8**	**97.4**	**57.1**	**97.8**	-	-	-
12-Aug-94	100.9	55.9	100.8	100.3	56.2	100.3	100.5	55.9	100.3	99.4	55.8	99.2
13-Aug-94	99.9	59.0	101.0	99.1	59.2	100.4	99.3	58.9	100.4	98.6	58.8	99.7
14-Aug-94	93.9	61.9	96.5	93.4	62.0	96.0	93.5	61.7	96.0	92.7	61.7	95.2
15-Aug-94	97.0	56.8	97.2	95.9	57.2	96.2	96.0	56.8	96.2	94.8	55.9	94.7
16-Aug-94	90.9	61.9	93.4	90.2	61.8	92.8	90.4	61.6	92.8	89.3	61.4	91.7
17-Aug-94	88.9	63.9	92.5	88.0	64.4	91.9	88.2	64.1	91.9	87.0	64.7	91.1
Event Average	**95.2**	**59.9**	**96.9**	**94.5**	**60.2**	**96.3**	**94.7**	**59.8**	**96.3**	**93.7**	**59.7**	**95.3**
22-Jul-06	108.0	57.0	108.2	107.1	57.3	107.5	107.3	57.2	107.6	-	-	-
23-Jul-06	91.0	66.9	96.4	90.3	67.2	95.8	90.4	67.0	95.8	-	-	-
24-Jul-06	90.0	68.0	96.0	89.1	68.3	95.3	89.3	68.0	95.3	-	-	-
25-Jul-06	91.0	66.9	96.4	90.4	67.2	95.9	90.6	67.0	96.0	-	-	-
26-Jul-06	95.0	68.0	101.0	94.3	68.2	100.4	94.5	68.1	100.5	-	-	-
Event Average	**95.0**	**65.4**	**99.6**	**94.2**	**65.6**	**99.0**	**94.4**	**65.5**	**99.1**	-	-	-

Table 12: Air mass type on each of the days during the heat events in Los Angeles. Darkened air mass types indicate scenario-induced changes from the observed conditions.

	Air Masses			
Scenario	*Obs*	*Alb1Veg1*	*Alb1*	*Alb2*
13-Aug-92	**DT**	DT	DT	-
14-Aug-92	**DT**	DT	DT	-
15-Aug-92	**DT**	DT	DT	-
16-Aug-92	**DT**	DT	DT	-
17-Aug-92	**DT**	DT	DT	-
18-Aug-92	**DT**	DT	DT	-
10-Aug-94	**DT**	DT	DT	-
11-Aug-94	**DT**	DT	DT	-
12-Aug-94	**DT**	DT	DT	-
13-Aug-94	**DT**	DT	DT	-
14-Aug-94	**DT**	DT	DT	-
12-Aug-94	**DT**	DT	DT	DT
13-Aug-94	**DT**	DT	DT	DT
14-Aug-94	**DT**	DT	DT	DT
15-Aug-94	**DT**	DT	DT	DT
16-Aug-94	**DT**	DT	DT	**MT**
17-Aug-94	**MT**	MT	MT	MT
22-Jul-06	**DT**	DT	DT	-
23-Jul-06	**DT**	DT	DT	-
24-Jul-06	**DT**	DT	DT	-
25-Jul-06	**MT++**	MT++	MT++	-
26-Jul-06	**MT++**	**MT+**	MT++	-

As part of this research, the modeled results in the city of Los Angeles and surrounding regions were mapped to determine when and where the greatest temperature reductions at 2m heights would take place under the scenarios. ALB2 scenarios for Aug 12th and Aug 13th 1994 at 3:00p.m. are displayed in Figures 4 and 5 as an example, with full mapping of all scenarios is found in Appendix B. The unique geography of Los Angeles, with the ocean to the west and mountains to the east and the hot and dry Santa Ana winds in the late summer and into the fall season, complicates the modeling of local weather and climate to a greater degree than in the other cities studied. The maps showing the temperature reductions in Los Angeles demonstrate that most of the cooling is over the center of the city and in the eastern populated areas, including the some of the most disadvantaged areas of the city. The cooling extends outside the city boundaries in the direction of the wind. The strong air flow off the ocean from the west (indicative of a sea breeze) displaces the cooling to the east, where the most vulnerable populations are located. Moreover, with a less dense built up area and lower population density (7,358 people per sq. mile) as compared to others (e.g., New York = 27,000 people per sq. mile) (eRepublic, 2014), the impacts of the UHI mitigation strategies produce less alterations in the air mass. Therefore, in a less dense location, a greater amount of urban modification is needed to alter the thermal regime, as compared to very dense urban areas.

Table 13: Estimated mortality for days within the evaluated heat events in Los Angeles.

	Mortality Estimates			
Scenario	***Obs***	***Alb1Veg1***	***Alb1***	***Alb2***
13-Aug-92	13.8	13.7	13.7	-
14-Aug-92	14.7	14.5	14.6	-
15-Aug-92	18.1	17.9	18.0	-
16-Aug-92	21.8	21.6	21.6	-
17-Aug-92	22.1	21.8	21.9	-
18-Aug-92	20.5	20.3	20.4	-
Event Total	**111.1**	**109.9**	**110.2**	**-**
10-Aug-94	12.7	12.5	12.5	-
11-Aug-94	16.4	16.1	16.2	-
12-Aug-94	19.7	19.5	19.6	-
13-Aug-94	22.1	21.9	22.0	-
14-Aug-94	20.3	20.0	20.1	-
Event Total	**91.1**	**90.1**	**90.4**	-
12-Aug-94	19.7	19.5	19.6	19.3
13-Aug-94	22.1	21.9	22.0	21.7
14-Aug-94	20.3	20.1	20.1	19.9
15-Aug-94	21.2	20.8	20.9	20.5
16-Aug-94	19.3	19.1	19.1	0.0
17-Aug-94	0.0	0.0	0.0	0.0
Event Total	**102.6**	**101.4**	**101.7**	**81.4**
22-Jul-06	16.7	16.5	16.5	-
23-Jul-06	14.2	14.0	14.0	-
24-Jul-06	16.6	16.4	16.4	-
25-Jul-06	19.7	19.5	19.6	-
26-Jul-06	20.9	20.7	20.8	-
Event Total	**88.2**	**87.0**	**87.3**	-
All Events	**393.0**	**388.4**	**389.6**	

Table 14: Temperature changes (°F) from actual conditions under each of the scenarios in Los Angeles.

🟦	0.3 to 0.5 reduction	🟥	0.3 to 0.5 increase
🟦	0.6 to 1 reduction	🟥	0.6 to 1 increase
🟦	>1 reduction	🟥	>1 increase

Scenario	**Alb1Veg1 (°F)**			**Alb1 (°F)**			**Alb2 (°F)**		
	Ta	***Td***	***AT***	***Ta***	***Td***	***AT***	***Ta***	***Td***	***AT***
13-Aug-92	-0.6	0.3	-0.5	-0.4	0.1	-0.4	-	-	-
14-Aug-92	-0.7	0.2	-0.6	-0.5	-0.2	-0.6	-	-	-
15-Aug-92	-0.5	0.3	-0.4	-0.4	-0.3	-0.5	-	-	-
16-Aug-92	-0.7	0.3	-0.5	-0.5	-0.1	-0.6	-	-	-
17-Aug-92	-0.7	0.3	-0.6	-0.5	0.2	-0.5	-	-	-
18-Aug-92	-0.7	0.4	-0.5	-0.5	0.4	-0.3	-	-	-
Event Average	**-0.6**	**0.3**	**-0.5**	**-0.5**	**0.0**	**-0.5**	-	-	-
10-Aug-94	-0.6	0.2	-0.5	-0.4	0.0	-0.4	-	-	-
11-Aug-94	-0.7	0.3	-0.6	-0.6	0.3	-0.4	-	-	-
12-Aug-94	-0.6	0.3	-0.5	-0.5	-0.1	-0.5	-	-	-
13-Aug-94	-0.7	0.3	-0.5	-0.5	-0.5	-0.7	-	-	-
14-Aug-94	-0.8	0.3	-0.6	-0.6	0.1	-0.6	-	-	-
Event Average	**-0.7**	**0.3**	**-0.5**	**-0.5**	**0.0**	**-0.5**	-	-	-
12-Aug-94	-0.6	0.3	-0.5	-0.5	0.0	-0.4	-1.5	-0.1	-1.5
13-Aug-94	-0.7	0.2	-0.6	-0.5	-0.1	-0.6	-1.2	-0.2	-1.3
14-Aug-94	-0.5	0.2	-0.5	-0.4	-0.1	-0.5	-1.3	-0.1	-1.3
15-Aug-94	-1.1	0.4	-1.0	-0.9	-0.1	-1.0	-2.1	-0.9	-2.5
16-Aug-94	-0.7	0.0	-0.7	-0.5	-0.3	-0.6	-1.5	-0.4	-1.8
17-Aug-94	-0.9	0.5	-0.6	-0.7	0.3	-0.6	-1.8	0.8	-1.4
Event Average	**-0.8**	**0.3**	**-0.6**	**-0.6**	**-0.1**	**-0.6**	**-1.6**	**-0.2**	**-1.6**
22-Jul-06	-0.9	0.3	-0.7	-0.7	0.2	-0.6	-	-	-
23-Jul-06	-0.8	0.3	-0.6	-0.6	0.1	-0.6	-	-	-
24-Jul-06	-0.8	0.3	-0.7	-0.6	0.0	-0.6	-	-	-
25-Jul-06	-0.6	0.3	-0.5	-0.5	0.1	-0.4	-	-	-
26-Jul-06	-0.7	0.2	-0.6	-0.5	0.1	-0.5	-	-	-
Event Average	**-0.8**	**0.3**	**-0.6**	**-0.6**	**0.1**	**-0.5**	**-**	**-**	**-**

Figure 4. Temperature reductions (Alb2 – Observed) at 2m using the ALB2 scenario on Aug 12, 1994 at 3:00p.m. in Los Angeles. Dashed red line indicates city limits.

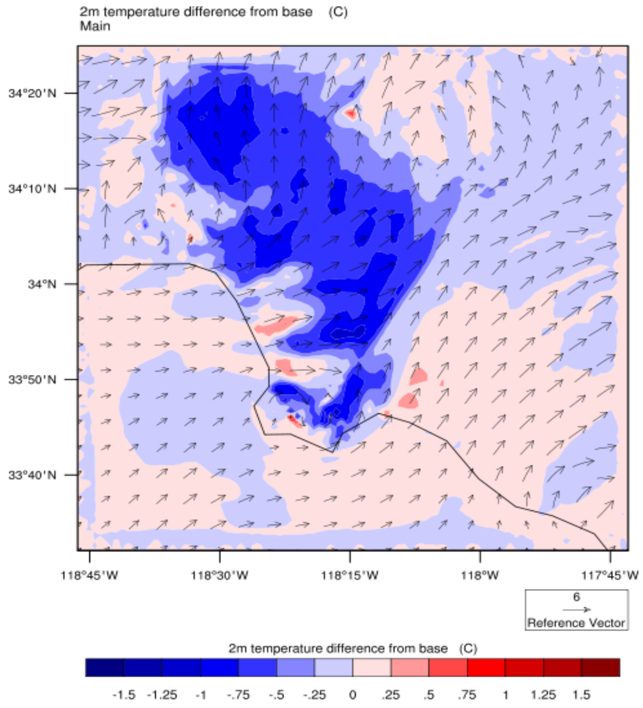
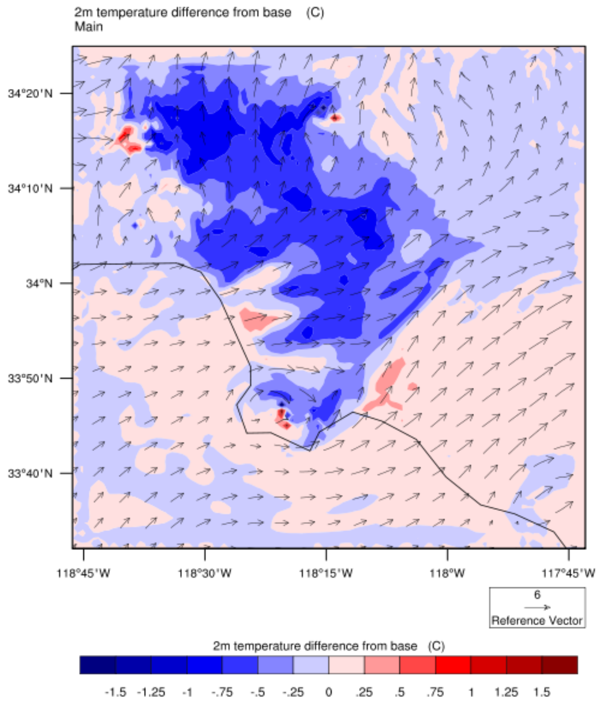


Figure 5. Temperature reductions (Alb2 – Observed) at 2m using the ALB2 scenario on Aug 13, 1994 at 3:00p.m. in Los Angeles. Dashed red line indicates city limits.



C. New York

New York showed the greatest reductions in mortality as a result of the UHI mitigation strategies (Table 17). All scenarios resulted in reductions of air temperatures similar to that of Baltimore (approximately 0.4 to 0.6^{o}F lower) (Table 15). However, New York did not undergo an increase in dew point temperature, as observed in the other cities, thus resulting in lower apparent temperature values. Temperature reductions in the ALB1VEG1 and the ALB1 scenarios were similar within each heat event. The intervention of a larger increase in albedo (ALB2) for July 1995 and 1999 heat events resulted in temperature reductions of approximately 0.1 to 0.3^{o}F, which also led to air mass changes. The greatest reduction occurred on August 3, 1995, where both the apparent temperature and dew point temperature dropped by almost a full degree. The July 1999 and August 2006 events were the most intense, with the city experiencing some MT++ (extremely hot and humid) and MT+ days. Apparent temperatures extended many degrees above the historical average for the air mass. Such intense events occurring over many days, in conjunction with high nighttime temperatures, are most worrisome for human health, and occur frequently during the summer in New York.

Air mass changes occurred in two of the four New York heat events examined in this study. The first day of the July−August 1995 heat wave changed from a DT air mass to the benign DM air mass for all three scenarios. In addition, the July 2006 event demonstrated a reduction on two days: Day 1, with MT+ switching to MT, and Day 2 with a DT air mass switching to MT. These results are more pronounced than those of the other cities studied. The outcomes indicate that albedo alterations can have great impact on temperature, and potentially mortality reduction, in a densely populated city like New York. In fact, the city's population density of over 27,000 per square mile makes it the densest city in terms of population in the country (eRepublic, 2014). Therefore, the same urban modification – even just a 10 percent change – can produce a greater impact on the thermal regime than the same modifications in a less dense area, such as Los Angeles. This is because a more dense urban area also commonly results in a large proportion of dry, impervious surfaces, and a lesser amount of urban vegetation that holds moisture. Thus, a 10% increase in vegetation in a dense city like New York is more likely to result in a smaller increase in humidity – and associated dew point temperature – as moisture sources are already very limited. A recent study shows that New York City has the largest proportion of impervious surface (61 percent) and among the lowest proportion of vegetated surface (19 percent) among 20 large cities studied, including Los Angeles and Baltimore (Nowak and Greenfield, 2012). A less dense city such as Washington, DC is likely to have more existing vegetation, and hence moisture sources, to add to the 10% increase in vegetation.

Table 15: Temperature (T), dew point (Td) and apparent temperature (AT) at (5:00 p.m. local time) for the four New York heat events. "Observed" represents the actual event.

Scenario:	**Observed (°F)**			**Alb1Veg1 (°F)**			**Alb1 (°F)**			**Alb2 (°F)**		
Temperature Variable:	**T**	**Td**	**AT**	**T**	**Td**	**AT**	**T**	**Td**	**AT**	**T**	**Td**	**AT**
28-May-91	89.1	62.1	91.7	88.9	62.1	91.6	89.0	62.0	91.6	-	-	-
29-May-91	86.0	63.0	89.2	85.4	62.9	88.5	85.5	62.9	88.6	-	-	-
30-May-91	82.0	66.9	87.4	81.8	66.9	87.2	81.9	66.9	87.3	-	-	-
31-May-91	77.0	66.9	82.4	76.8	67.0	82.2	76.8	67.0	82.3	-	-	-
1-Jun-91	84.9	55.9	84.8	85.1	55.5	84.8	85.2	55.4	84.8	-	-	-
Event Average	**83.8**	**63.0**	**87.1**	**83.6**	**62.9**	**86.8**	**83.7**	**62.8**	**86.9**	**-**	**-**	**-**
31-Jul-95	90.0	60.1	91.7	89.7	59.9	91.3	89.8	59.8	91.4	89.4	59.7	90.9
1-Aug-95	91.0	62.1	93.7	90.6	62.2	93.4	90.7	62.2	93.5	90.4	62.3	93.1
2-Aug-95	93.0	72.0	101.6	92.6	72.1	101.2	92.7	72.1	101.3	92.2	72.3	101.0
3-Aug-95	91.0	72.0	99.6	90.9	71.6	99.2	91.0	71.6	99.3	90.7	71.2	98.8
4-Aug-95	95.0	66.9	100.3	94.8	66.9	100.1	94.9	66.9	100.2	94.6	66.9	99.9
Event Average	**92.0**	**66.6**	**97.4**	**91.7**	**66.5**	**97.0**	**91.8**	**66.5**	**97.1**	**91.4**	**66.5**	**96.7**
03-Jul-99	89.1	71.1	97.0	88.9	71.0	96.9	89.0	70.9	96.9	88.9	70.9	96.8
04-Jul-99	93.0	73.9	103.0	92.8	74.0	102.8	92.9	74.0	102.9	92.8	74.0	102.7
05-Jul-99	98.1	72.0	106.6	97.8	72.0	106.4	97.9	72.0	106.5	97.7	72.0	106.3
06-Jul-99	100.9	71.6	109.2	100.7	71.7	109.0	100.8	71.6	109.1	100.5	71.7	108.9
07-Jul-99	91.9	48.0	89.1	91.8	48.2	89.0	91.9	48.1	89.0	91.7	48.2	88.9
Event Average	**94.6**	**67.3**	**101.0**	**94.4**	**67.4**	**100.8**	**94.5**	**67.3**	**100.9**	**94.3**	**67.4**	**100.7**
30-Jul-06	89.1	64.0	92.8	88.9	64.2	92.7	89.0	64.1	92.7	-	-	-
31-Jul-06	89.1	66.9	94.4	88.8	66.9	94.2	89.0	66.8	94.3	-	-	-
1-Aug-06	98.1	73.0	107.3	97.9	73.1	107.2	97.9	73.1	107.2	-	-	-
2-Aug-06	99.0	70.0	106.2	98.7	70.0	106.0	98.8	70.0	106.0	-	-	-
3-Aug-06	90.0	69.1	96.6	89.7	69.1	96.4	89.8	69.1	96.5	-	-	-
Event Average	**93.0**	**68.6**	**99.5**	**92.8**	**68.7**	**99.3**	**92.9**	**68.6**	**99.4**	**-**	**-**	**-**

Table 16: Air mass type on each of the days during the heat events in New York. Darkened air mass types indicate scenario-induced changes from the observed conditions.

	Air Masses			
Scenario	***Obs***	***Alb1Veg1***	***Alb1***	***Alb2***
28-May-91	DT	DT	DT	-
29-May-91	MT+	MT+	MT+	-
30-May-91	MT+	MT+	MT+	-
31-May-91	MT+	MT+	MT+	-
1-Jun-91	MT+	MT+	MT+	-
31-Jul-95	DT	**DM**	**DM**	**DM**
1-Aug-95	DT	DT	DT	DT
2-Aug-95	MT+	MT+	MT+	MT+
3-Aug-95	MT+	MT+	MT+	MT+
4-Aug-95	MT+	MT+	MT+	MT+
3-Jul-99	MT+	MT+	MT+	MT+
4-Jul-99	MT++	MT++	MT++	MT++
5-Jul-99	DT	DT	DT	DT
6-Jul-99	DT	DT	DT	DT
7-Jul-99	DT	DT	DT	DT
30-Jul-06	MT+	**MT**	**MT**	
31-Jul-06	DT	**MT**	**MT**	
1-Aug-06	DT	DT	DT	
2-Aug-06	DT	DT	DT	
3-Aug-06	DT	DT	DT	

Table 17: Estimated mortality for days within the evaluated heat events in Los Angeles.

	Mortality Estimates			
Scenario	***Obs***	***Alb1Veg1***	***Alb1***	***Alb2***
28-May-91	24.5	24.3	24.4	-
29-May-91	31.1	30.6	30.7	-
30-May-91	38.5	38.2	38.3	-
31-May-91	43.2	43.0	43.1	-
1-Jun-91	48.4	48.4	48.4	-
Event Total	**185.6**	**184.6**	**184.9**	**-**
31-Jul-95	43.8	0.0	0.0	0.0
1-Aug-95	45.3	45.1	45.1	44.9
2-Aug-95	51.4	51.2	51.2	51.0
3-Aug-95	49.8	49.5	49.5	49.1
4-Aug-95	50.2	50.1	50.1	49.9
Event Total	**240.6**	**195.7**	**196.0**	**194.9**
3-Jul-99	24.7	24.5	24.5	24.5
4-Jul-99	38.1	38.0	38.0	37.9
5-Jul-99	49.7	49.5	49.6	49.4
6-Jul-99	60.5	60.3	60.4	60.2
7-Jul-99	44.4	44.3	44.4	44.3
Event Total	**217.3**	**216.7**	**216.9**	**216.3**
30-Jul-06	0.0	0.0	0.0	-
31-Jul-06	28.4	0.0	0.0	-
1-Aug-06	47.3	47.2	47.2	-
2-Aug-06	55.1	54.9	55.0	-
3-Aug-06	47.4	47.3	47.3	-
Event Total	**178.2**	**149.3**	**149.5**	**-**
All Events	**821.7**	**746.3**	**747.3**	

Heat-related mortality estimations for New York (Table 17) show the most significant reductions of the three cities. Moreover, these estimates of potential live saved are greater than the results recently found in Washington, DC, which indicated a 7 percent reduction in heat-related mortality (Kalkstein et al., 2013). The heat events that experienced air mass modifications also demonstrated the greatest decline in estimated mortality. For example, for the August 1995 heat event, the mortality estimate was reduced by approximately 45 lives (19 percent) in all three scenarios. Furthermore, the dramatic decrease was also found in the July 2006 heat event, where the altered air mass and lowered temperatures resulted in 29 fewer deaths (11 percent) for both ALB1 and ALB1VEG1. For the May 1991 and the July 1999 scenarios, minimal reductions were found, with the greatest on July 7th, 1999 where a decrease of 1 death was found.

As part of this research, the city of New York and surrounding regions were mapped to determine when and where the greatest temperature reductions at 2m heights would take place under the scenarios. ALB2 scenarios for July 3rd 1999 at 9:00a.m and 3:00p.m are displayed in Figures 6 and 7 as an example, with full mapping of all scenarios found in Appendix C. The maps showing the temperature reductions in New York demonstrate that most of the cooling is over the Brooklyn and Queens, with some cooling in the Bronx. The greatest temperature decreases occur in midday and continue into the afternoon. This cooling extends outside the city boundaries and in the direction of the wind.

Table 18: Temperature changes (°F) from actual conditions under each of the scenarios in New York.

🟦	0.3 to 0.5 reduction	🟥	0.3 to 0.5 increase
🟦	0.6 to 1 reduction	🟥	0.6 to 1 increase
🟦	>1 reduction	🟥	>1 increase

Scenario	Alb1Veg1			Alb1			Alb2		
	Ta	Td	AT	Ta	Td	AT	Ta	Td	AT
28-May-91	-0.2	0.0	-0.2	-0.1	0.0	-0.1	-	-	-
29-May-91	-0.6	-0.1	-0.7	-0.5	-0.1	-0.5	-	-	-
30-May-91	-0.3	0.0	-0.3	-0.1	-0.1	-0.2	-	-	-
31-May-91	-0.2	0.1	-0.2	-0.2	0.0	-0.1	-	-	-
1-Jun-91	0.2	-0.5	0.0	0.2	-0.5	0.0	-	-	-
Average	**-0.2**	**-0.1**	**-0.3**	**-0.1**	**-0.1**	**-0.2**			
31-Jul-95	-0.3	-0.2	-0.4	-0.2	-0.2	-0.3	-0.6	-0.4	-0.8
1-Aug-95	-0.4	0.1	-0.3	-0.3	0.1	-0.3	-0.7	0.2	-0.6
2-Aug-95	-0.5	0.2	-0.3	-0.4	0.1	-0.3	-0.8	0.4	-0.6
3-Aug-95	-0.1	-0.4	-0.4	-0.1	-0.4	-0.3	-0.3	-0.8	-0.8
4-Aug-95	-0.2	0.0	-0.2	-0.1	0.0	-0.2	-0.4	0.0	-0.4
Average	**-0.3**	**-0.1**	**-0.3**	**-0.2**	**-0.1**	**-0.3**	**-0.6**	**-0.1**	**-0.6**
03-Jul-99	-0.2	0.0	-0.2	-0.1	-0.1	-0.2	-0.1	-0.2	-0.2
04-Jul-99	-0.2	0.1	-0.1	-0.1	0.0	-0.1	-0.3	0.1	-0.2
05-Jul-99	-0.2	0.0	-0.2	-0.1	0.0	-0.1	-0.3	0.0	-0.3
06-Jul-99	-0.3	0.1	-0.2	-0.2	0.0	-0.1	-0.4	0.1	-0.4
07-Jul-99	-0.2	0.1	-0.1	-0.1	0.0	-0.1	-0.3	0.2	-0.2
Average	**-0.2**	**0.1**	**-0.2**	**-0.1**	**0.0**	**-0.1**	**-0.3**	**0.0**	**-0.3**
30-Jul-06	-0.2	0.2	-0.1	-0.1	0.1	0.0	-	-	-
31-Jul-06	-0.2	0.0	-0.2	-0.1	-0.1	-0.1	-	-	-
1-Aug-06	-0.2	0.1	-0.2	-0.1	0.0	-0.1	-	-	-
2-Aug-06	-0.2	0.1	-0.2	-0.2	0.0	-0.2	-	-	-
3-Aug-06	-0.2	0.0	-0.2	-0.1	0.0	-0.1	-	-	-
Average	**-0.2**	**0.1**	**-0.2**	**-0.1**	**0.00**	**-0.1**			

Figure 6: Temperature reductions (ALB2 – Observed) at 2m using the ALB2 scenario on July 3, 1999 at 9:00 a.m. in New York City

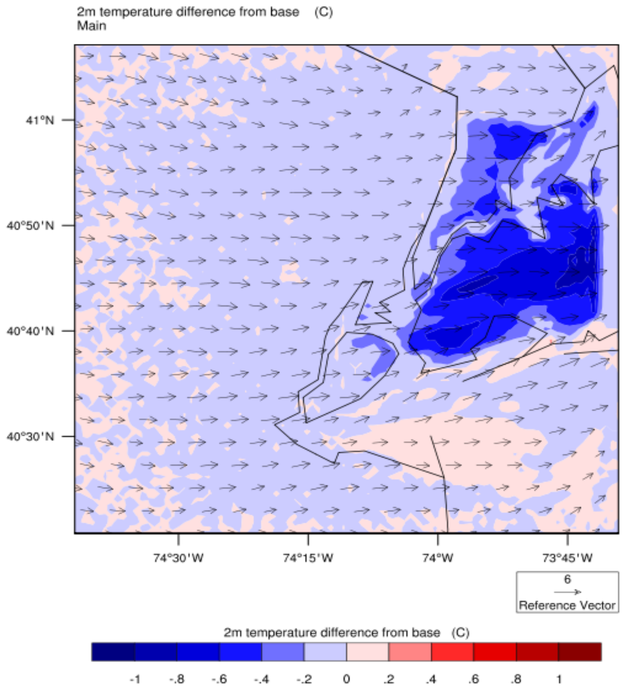
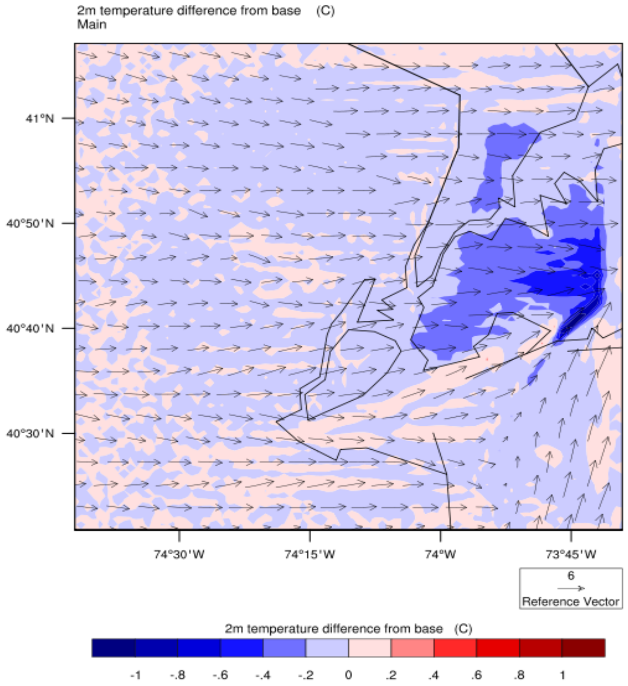


Figure 7: Temperature reductions (ALB2 – Observed) at 2m using the ALB2 scenario on July 3, 1999 at 3:00p.m. in New York city.



Conclusions

This study highlights the health and safety benefits of UHI mitigation policies, and also demonstrates the role that strategies aimed at reducing urban heat accumulation can play to achieve greater urban resiliency by improving weather conditions on extremely hot days. The results reveal that altering the landscape of Baltimore, Los Angeles, and New York in a manner that increases albedo and vegetation cover will lead to some ambient cooling of the urban area, often in the sections of the cities where the most vulnerable people reside. New York's results were quite impressive, and during two of the four heat events, the models estimated significant decreases in mortality by up to 21% from observed heat wave conditions. Results were less dramatic for Baltimore and Los Angeles, although the greatest benefit from the cool technologies occurred in the poorest areas of both cities, much like they did in our earlier analysis of Washington, DC (Kalkstein et al., 2013).

All four heat events in each city were modeled with assuming 1) a 10 percentage point reflectance increase (ALB1); and 2) a 10 percent increase in reflectance and vegetation together (ALB1VEG1). Both scenarios resulted in modest air and dew point temperature changes (commonly <1^{o}F), yet those decreases were significant enough to contribute to the reduction of deaths for heat events. With added vegetation, the air temperature decrease was often greater than albedo alone, but was often accompanied by an increase in atmospheric water vapor (as reported in dew point temperature). These factors partially offset themselves and led to similar apparent temperature results between the two scenarios. However, there was also a slightly greater mortality decrease under the ALB1VEG1 scenario.

The third scenario, representing a 20 percent increase in reflectance (ALB2) with no change in vegetation, resulted in the greatest average decrease of both apparent temperature and heat related mortality in all cities for the four heat events. In Los Angeles and New York, this mitigation strategy resulted in a favorable air mass change, with an oppressive air mass dropping into a benign air mass that is not shown to harm human health. Policies requiring cool roofs are already in place in both cities and this level of reflectivity increase achievable. This type of change in air mass results in the largest decline of heat-related mortality. In the long run, urban modifications that would allow for ALB2 conditions would likely lead to even more lives being saved. As only 1 to 2 heat events were modeled under the ALB2 scenario in each city, further assessments may be needed to understand the modification effects under various air mass and heat event situations.

In addition, there is sufficient cooling in two of the three evaluated cities (New York and Los Angeles) to shift days into less oppressive air masses for two heat events. This shift contributes to the 21% and 18% average reductions in heat-related mortality totals for the given heat events in New York and Los Angeles, respectively. Based on our previous work in Baltimore, Los Angeles, and New York, during the presence of oppressive air masses approximately 572, 185, and 1,842 individuals die of heat-related causes during an average decade (in the summer months of Jun-Jul-Aug) (Kalkstein et al., 2011). A 21% decrease in New York results brings the city's number down to 1,445 per decade, and the 18% reduction in Los Angeles decreases the decadal estimate to 151. Hence, the warm climate of Los Angeles may be almost as vulnerable as northeast cities to extreme heat. Even minimal reductions in mortality can the decadal death total down by over 10 lives in New York. Moreover, estimates based on past decades may be conservative for Baltimore and New York, as the oppressive air mass days per summer when comparing the periods of 1950–2000 versus 2000–2012 have increased by 3.7% and 10.3%, respectively, with minimal to no change found in Los Angeles between the two periods.

While the urban heat island mitigation technologies, as modeled in this analysis, did not appear to contribute to large urban-scale reductions in temperature during heat events, the study demonstrates that by decreasing temperatures during heat events a single degree for much of a day can in certain instances lead to a favorable air mass category change, which may also result in significant reductions in mortality. Both reflectivity and vegetation scenarios led to similar reductions in outdoor ambient temperature and mortality.

The study's scope was limited to the impact on outside temperature alterations. Incorporating the impact of albedo/vegetation modifications on indoor temperature reductions would very likely significantly increase the estimates of lives saved; we hope to follow up with a study of this type. Likewise, broadening future studies to include negative health impacts less severe than death would greatly increase the estimates human and economic benefits of UHI mitigation.

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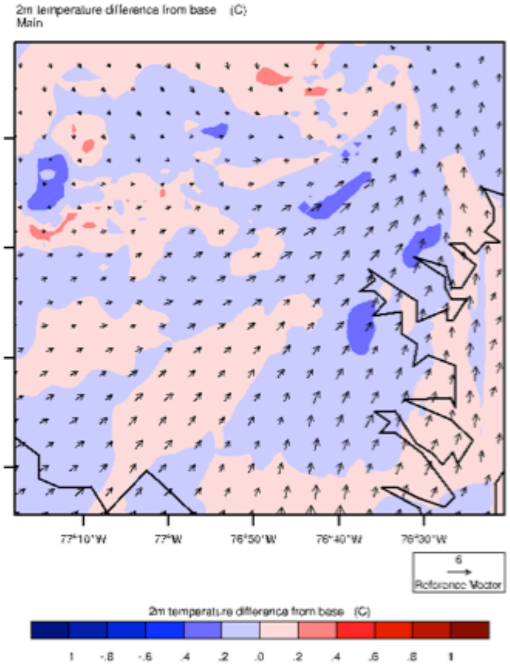
Appendix A. Selected Maps of Temperature Change Resulting from Increasing Reflectivity and Vegetation in Baltimore

Temperature change on June 16, 1994 between base and ALB1

7am



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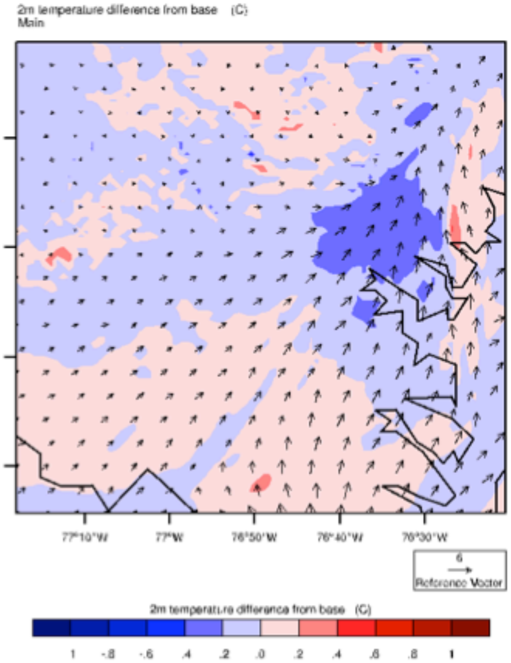

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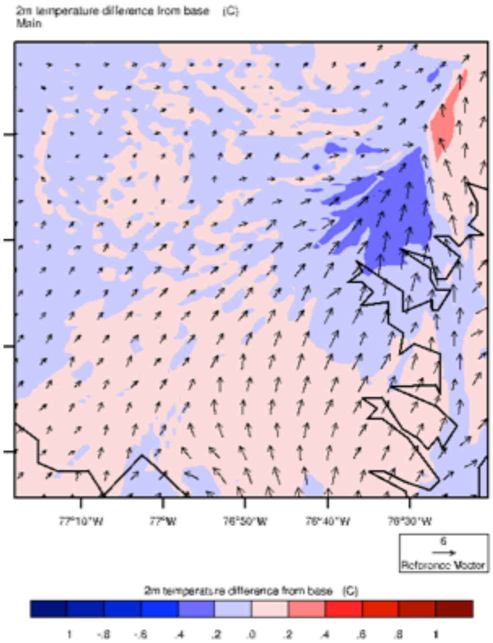

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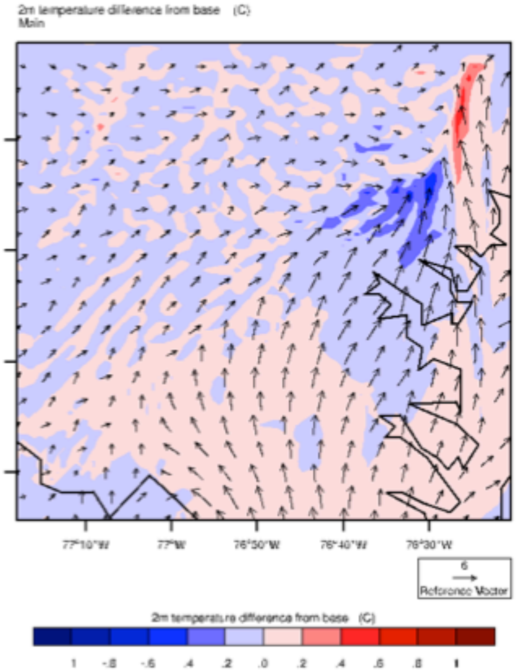

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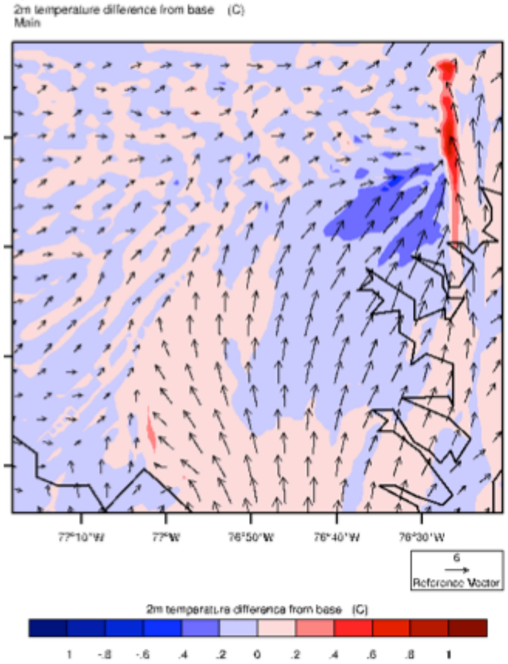
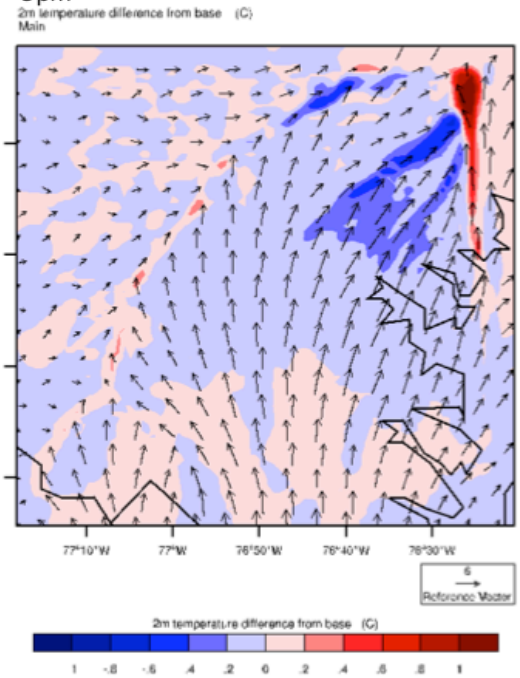

2m temperature difference from base (C)
Main
77°10'W
77°W
76°50'W
76°40'W
76°30'W
6
Reference Vector
2m temperature difference from base (C)
1
-.8
-.6
.4
.2
0
.2
.4
.6
.8
1

5pm

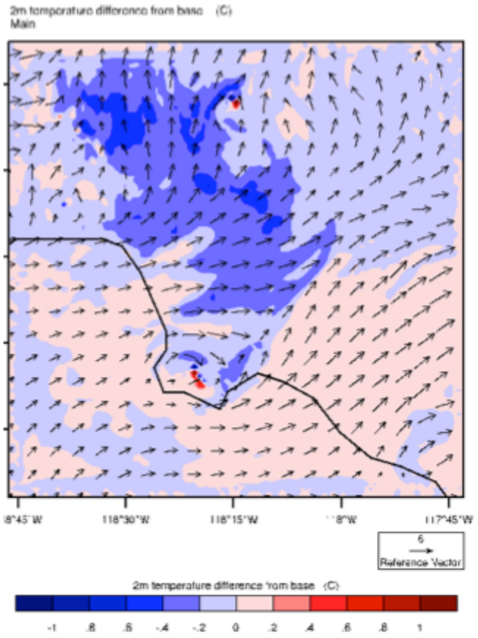

2m temperature difference from base (C)
Main
77°10'W
77°W
76°50'W
76°40'W
76°30'W
6
Reference Vector
2m temperature difference from base (C)
1
-.8
-.6
.4
.2
0
.2
.4
.6
.8
1

Appendix B. Selected Maps of Temperature Change Resulting from Increasing Reflectivity and Vegetation in Los Angeles

We have done a complete mapping of temperature changes and wind flow for all heat events in each city. Appendices A, B, and C are selected maps depicting an urban cooling scenario over the course of a full day.

Temperature change between base and ALB1VEG1 on August 12, 1994

3 pm



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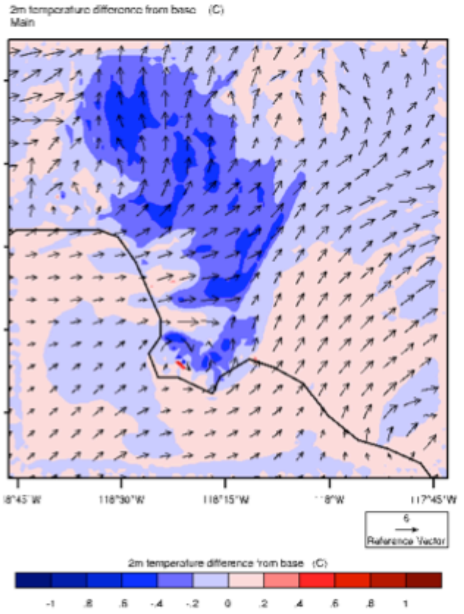
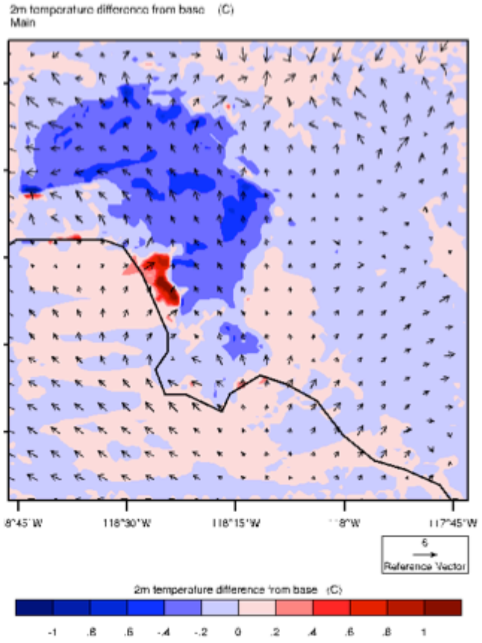
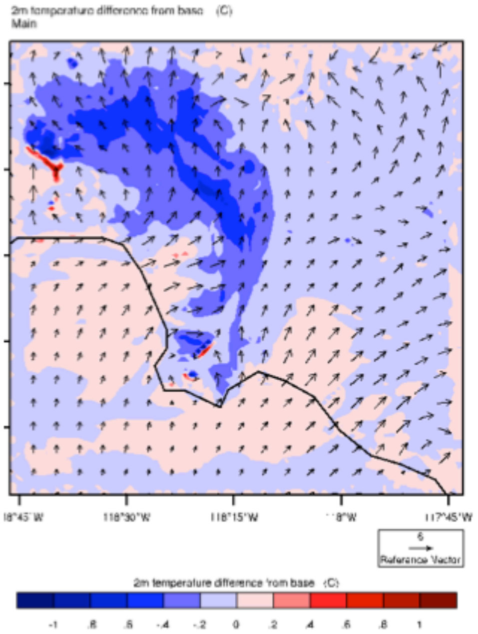


11 am



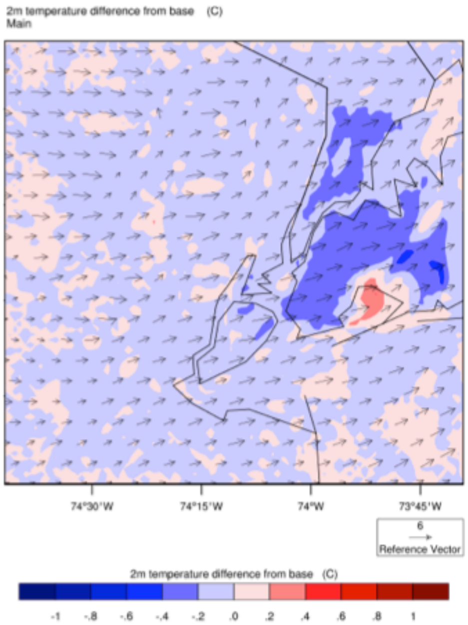
1 pm



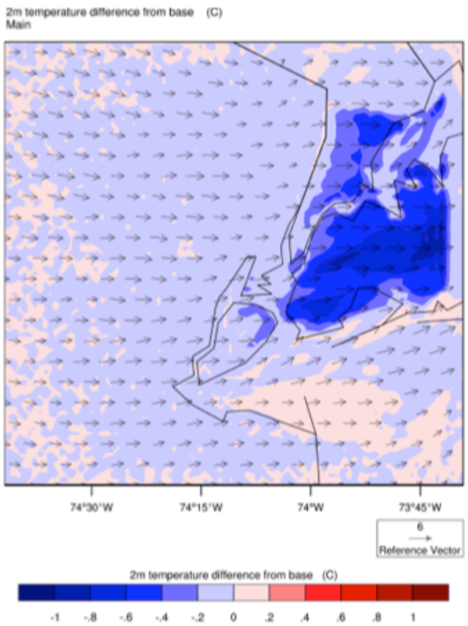
Appendix C. Selected Maps of Temperature Change Resulting from Increasing Reflectivity and Vegetation in New York

Temperature change on July 3, 1999 between base and ALB2

7am



9am



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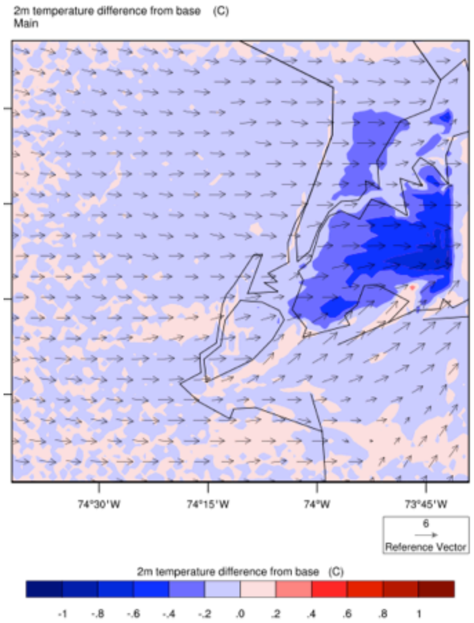

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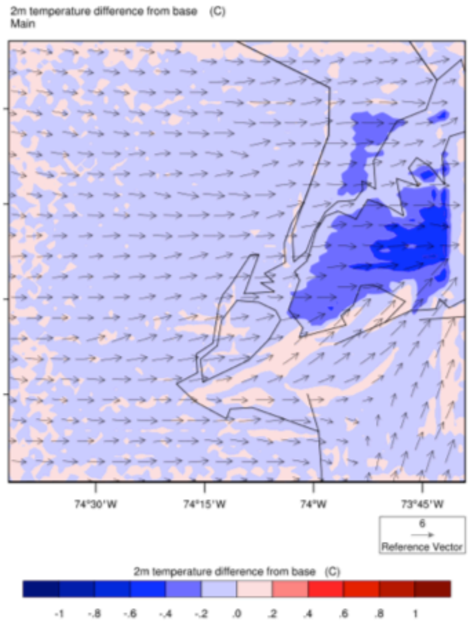

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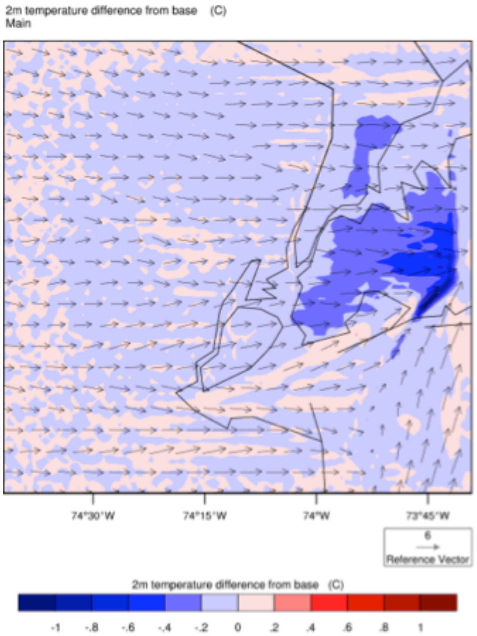
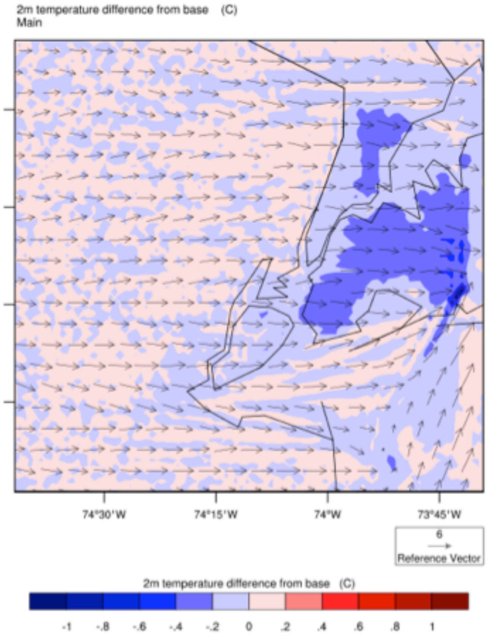

2m temperature difference from base (C)
Main
74°30'W
74°15'W
74°W
73°45'W
6
Reference Vector
2m temperature difference from base (C)
-1
-.8
-.6
-.4
-.2
0
.2
.4
.6
.8
1

5pm


2m temperature difference from base (C)
Main
74°30'W
74°15'W
74°W
73°45'W
6
Reference Vector
2m temperature difference from base (C)
-1
-.8
-.6
-.4
-.2
0
.2
.4
.6
.8
1