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Improving Heat-Related Health Outcomes in an Urban Environment with Science-Based Policy

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Abstract: We use the Northeast US Urban Climate Archipelago as a case study to explore three key limitations of planning and policy initiatives to mitigate extreme urban heat. These limitations are: (1) a lack of understanding of spatial considerations—for example, how nearby urban areas interact, affecting, and being affected by, implementation of such policies; (2) an emphasis on air temperature reduction that neglects assessments of other important meteorological parameters, such as humidity, mixing heights, and urban wind fields; and (3) too narrow of a temporal focus—either time of day, season, or current vs. future climates. Additionally, the absence of a direct policy/planning linkage between heat mitigation goals and actual human health outcomes, in general, leads to solutions that only indirectly address the underlying problems. These issues are explored through several related atmospheric modeling case studies that reveal the complexities of designing effective urban heat mitigation strategies. We conclude with recommendations regarding how policy-makers can optimize the performance of their urban heat mitigation policies and programs. This optimization starts with a thorough understanding of the actual end-point goals of these policies, and concludes with the careful integration of scientific knowledge into the development of location-specific strategies that recognize and address the limitations discussed herein.

Keywords: urban climate; urban heat island; heat-related mortality; heat island mitigation

1. Introduction

Urban planning and management strategies are increasingly addressing the challenges associated with local climate effects on human health and well-being. Although the science underpinning the relationships among urban form, anthropogenic activities, and the urban climate system are still developing, local and regional governments are acting on limited information to mitigate these problems. Such planning activities, however, fall short in three key respects. First, problems or solutions generated within one urban center have complex spatial signatures both within and downwind of the city—affecting, and being affected by, neighboring urban centers. Second, despite the tendency to focus on one climate variable (e.g., air temperature), in reality, complex problems in the urban environment (e.g., human health, energy, water, etc.) are intricately tied to multiple meteorological drivers. Finally, analysis of likely impacts of mitigation efforts often provides a limited assessment of their performance during a specific temporal window (e.g., a focus on typical current-climate summer daytime conditions). As a result, the temporal variation in the consequences of mitigation efforts is not completely understood [1].

This manuscript uses the mesoscale Weather Research and Forecasting Model (WRF) to explore the regional interconnectedness and importance of spatial and temporal scales in the urban climate system. WRF is a numerical weather prediction system designed both for atmospheric research and operational forecasting needs, with a worldwide community of more than 30,000 registered users across more than 150 countries. Several cities in the Northeast United States (Washington DC-Baltimore-Philadelphia-New York) are used as a case study of an urban climate archipelago (UCA). Regional-scale simulations investigate cases in which each city is modeled in isolation, as well as cases involving simultaneous representation of multiple urban centers within the region. Such simulations provide insight into how the UCA modifies the thermal and hydroclimate regimes of the region. These simulations include modeling of historical heat wave episodes to demonstrate how variable characteristics of regional weather conditions influence the cooling effectiveness of urban heat mitigation strategies. We also use WRF simulations of future climates with projected land cover changes and greenhouse-induced warming, combined with the Environmental Protection Agency's (EPA) BenMAP health impacts modeling tool (an open-source computer program that calculates the number and economic value of air pollution and heat-related deaths and illnesses) to explore the effectiveness of heat mitigation strategies under climate change.

We synthesize the results of these modeling efforts to explore how discrete aspects of the built environment and urban climate system interact, thereby affecting human health and well-being. We also discuss physical and social factors that can lead to very different individual-level exposures. As an organizing principle, we explore the human health concerns associated with these aspects of the urban climate and discuss interactions among the systems and consequences for human health and well-being. This perspective on the analysis of urban heat mitigation strategies represents a novel and important step in urban climate science that will enable policy-makers to develop and deploy more effective location-specific urban climate interventions.

2. Shortcomings of Planning for Improved Urban Climate Outcomes

City and regional governments have growing concerns about the challenges posed by extreme urban heat. Often, however, efforts in this realm actually focus more broadly on strategies that address global climate change, as opposed to the more local challenges posed by urban warming. National-level efforts to address health effects of climate change typically focus on human response to an imposed climate signal, rather than on modifying that signal. For example, the CDC's Climate-Ready States and Cities initiative is currently helping 16 states and several cities improve their ability to anticipate and respond to the health risks imposed by a warming climate. Somewhat surprisingly, recommended action at the municipal level also tends to focus more on mitigating global climate change. For example, many cities are developing climate action plans and related sustainability frameworks that establish a baseline of greenhouse gas emissions, as well as targets and strategies for reducing such emissions into the future. While laudable, such efforts may have limited direct effects on the local urban environment. An analysis of climate action plans from 50 cities [2] found only 12 of these plans explicitly address urban heat mitigation, either through programs that increase surface albedo or vegetative cover. Efforts to increase vegetative cover or albedo are sometimes driven by building energy savings or storm water runoff concerns. The case for action, however, is strengthened by arguments related to other environmental factors, including the reduction of urban heat islands [3].

More commonly, mitigation efforts tend to be implemented through specific, frequently short-term or one-time initiatives, such as tree planting programs led by city planning or sustainability offices (e.g., Los Angeles, CA, USA; New York, NY, USA). One limitation of urban tree planting campaigns is that they often have insufficient plans for long-term maintenance. As a result, the longevity of the average street tree may be less than a decade [4], in which case, the full benefits that would be achieved upon maturity are never realized, and are over-predicted by modeling efforts that assume a fully mature urban tree canopy.

A more fundamental problem with urban heat mitigation efforts is that they are often developed based on an incomplete understanding of the actual desired goals. Specifically, the stated goal is often phrased in terms of the scope of implementation (e.g., plant a million trees) or in terms of some arbitrary average impact on temperature (e.g., reduce summer air temperatures by 1 °C). Ultimately, however, the real driving force for considering mitigation strategies is not as simple as suggested by these goals. Rather, the actual endpoint of interest is improving the health and well-being of urban inhabitants, either through a reduction in heat-related illnesses/deaths, or simply by improving quality of life (e.g., improved thermal comfort, reduced ambient air pollution, or lowered energy bills). Of course, progress toward these goals is often moderated by economic and political concerns.

A review of two centuries of urban planning and climate science in Manchester [5] argues that one of the oldest and most persistent problems plaguing the successful integration of urban climate science and planning is the lack of communication between planners and climatologists who "do not speak the same language". Furthermore, scientists tend to formulate science questions based on their own limited understanding of the true issues facing city managers and planners, i.e., only involving the key stakeholders at the end of the scientific process through dissemination of their answers to an inadequate set of questions. A fuller integration of stakeholders throughout the scientific research process is a necessary step to assure that results will be more relevant and readily implemented by policy-makers.

2.1. Spatial Scales

Urban climate problems and solutions do not obey the spatial boundaries of governance. Specifically, a policy implemented in a specific city has the potential to affect adjacent and downwind communities. When cities implement strategies directly aimed at affecting their own urban climate, these strategies directly impact that city's climate, as well as having downwind implications. This interconnection of proximal cities is quite evident in the field of air pollution. There is an obvious relation between emissions from industry in the Pearl River Delta of China and nearby downwind cities [6]. Similar "chain-flow" effects between Japanese cities have also been reported [7]. This downwind effect on pollution has been demonstrated to operate, not only at regional, but also at continental, scales, including transport from Asia to North America [8].

When a city implements a sustainability strategy of any sort, both positive and negative downwind effects are likely. For example, any major reduction in air temperature over a city, if not accompanied by a concomitant reduction in pollution emissions, can actually result in adverse air quality effects downwind. Taha [9] for example, found that simulated temperature reductions in Sacramento, CA had large-scale benefits for ozone concentrations locally, but with clearly evident downwind pockets of increases in ozone.

The location and spatial extent of heat mitigation strategies also lead to complicated outcomes. For example, the vertical scale of the implementation of any heat mitigation strategy will significantly affect both the magnitude and location of its benefits. High albedo rooftops certainly reduce the solar energy absorbed by the urban area, but if these rooftops are 50 to 100 m above the street level, then it is likely that any temperature reduction is largely diffused through mixing at the roof-level, having no measurable effect at the street level in nearby neighborhoods, and a very diluted effect further downwind of the city (cf. [10]).

Since mitigation strategies directly impact the local surface energy budget, their direct effect is to cool the air in and around their deployment area. However, as noted above, the resulting pool of cooled air is advected downwind. As a result, the benefits of any mitigation strategy accrue locally and downwind of the application. As such, it is interesting to note that most mitigation strategies are quite broad in their intended implementation (e.g., planting trees throughout the city) without regard for the importance of downwind advection. Thus, both the size of an urban park and where it is located relative to its potential downwind benefits should be considered.

2.2. Interactions within the Climate System

One challenge of developing effective policies for urban heat mitigation is that urban climate problems and solutions are both regional in nature and highly interdisciplinary. So, while an agency may be pursuing deployment of green roofs or rain gardens for storm water management, it may miss the implications of such technologies for urban heat, building energy, and air quality. Taking urban vegetation as an example, there is ample empirical and modeling evidence of the potential for urban vegetation to significantly reduce urban air temperatures (e.g., [11–13]), although water availability is a key determinant of performance [14]. Some important implementation issues, however, are often not considered. For example, vegetation emits varying amounts of hydrocarbons that interact with other pollutants in the urban atmosphere to produce photochemical smog. Green roofs are widely touted for their storm water benefits. However, these roofs also have the potential to affect urban climate and heating/cooling requirements of buildings through evaporative cooling and thermal storage in their growing media. Optimizing green roof designs and implementation plans for storm water management likely miss opportunities to optimize their co-benefits. There may also be adverse unintended consequences. For example, the addition of vegetation in the urban system will increase atmospheric moisture. If the target of this mitigation is really to reduce heat-related morbidity and mortality (which depends both on air temperatures and humidity), then it is possible that this increased atmospheric moisture may partially counteract, or even overwhelm, the benefits of the decreased air temperatures. Even mitigation strategies involving albedo modification may have unintended health consequences because such atmospheric cooling results in a reduction of mixing heights and an increase in concentrations of pollutants (and moisture) emitted at the surface [15]. This effect was demonstrated by [16], which showed that high albedo and high-vegetation strategies implemented in Philadelphia, PA have the potential to decrease predicted heat-related mortality during some heat waves while increasing it during others. Furthermore, high albedo surfaces alter the balance between longwave and shortwave radiative exchange and can lead to higher mean radiant temperatures in urban canyons under sunny conditions [17].

2.3. Temporal Scales

Urban heat mitigation has several important temporal aspects. One aspect is the period of time over which the strategy evolves. While the installation of a white roof will have immediate effects on the surface energy balance, any new building codes requiring highly reflective roofs will take years or decades to impact the urban energy balance as new buildings are built and existing roofs replaced. Likewise, the effects of a green roof or a street tree evolve over multiple growing seasons.

Another important temporal aspect of heat mitigation that is often overlooked is the differing effects of such mitigation either over the course of a day or seasonally over the course of a year. Most planners tend to focus on reducing mid-day summer air temperatures. Although this goal has numerous potential benefits, this narrow focus also limits the overall effectiveness, and may obscure potential adverse unintended consequences. For example, if the true goal of a mitigation strategy is energy savings or reduction of greenhouse gas emissions, then one must consider not only summer air conditioning energy savings, but also any potential winter heating penalties [18]. Likewise, if one is focused on reducing heat-related mortality and morbidity, then the focus should not be on an arbitrary average summer air temperature reduction. Rather, strategies for heat-related health improvements should consider performance with respect to weather patterns responsible for the most significant heat wave events. Likewise, these strategies should include not only considerations of daytime high temperatures, but also nighttime lows and humidity levels.

3. The Northeast Urban Climate Archipelago as a Case Study Region

Having articulated the potential shortcomings of urban heat mitigation planning efforts we now present three related regional case studies to provide a more in-depth exploration of such issues. The literature is fairly conclusive on urban modifications to dynamical flow, temperature, and precipitation (e.g., [19]). However, the mid-Atlantic region of the United States has been inadequately studied within these contexts. Notable exceptions include studies of New York City's influence on precipitation systems (e.g., [20,21]) and research into the role of the Baltimore-Washington, D.C. urban area on urban heat island development and hydrometeorological responses [22].

3.1. Interactions among Climates of Proximal Cities

Based on current and predicted trends, urban areas will increasingly influence weather phenomena [23]. During 1973–2000, the developed land area increased 33% in the United States [24]. In the Northeast US, the developed land area increased 800,000 hectares over 1982–1997; approximately 12% of the total land area is developed [25]. By 2025, the developed land area is projected to increase 73% in the Northeast [25]. Lin et al. [26] suggest that by 2100 future urban expansion in the northeast megalopolis may increase average annual temperature by 2 °C to 5 °C in new urban areas. However, the authors also project temperature decreases (−0.40 °C to −1.20 °C) in the southern part of the megalopolis.

Rosenzweig et al. [27] defined very small urban archipelagoes within a city, whereas Shepherd and colleagues [28] proposed a much more expansive concept, linking the climates of proximal cities. Previous studies primarily focused on case studies of individual cities; however, the expansion and agglomeration of cities may have unique impacts on the climate, and the interaction with air quality. In introducing the UCA concept [27] posed several questions to the research community. What are the thermal impacts of UCAs on weather, climate, and related applications? What are the policy and stakeholder implications of UCAs? What observational and modeling frameworks will be required to study UCAs? Here, we are interested in addressing these questions based on the Northeast Corridor Urban Climate Archipelago (NE-UCA) depicted in Figure 1.

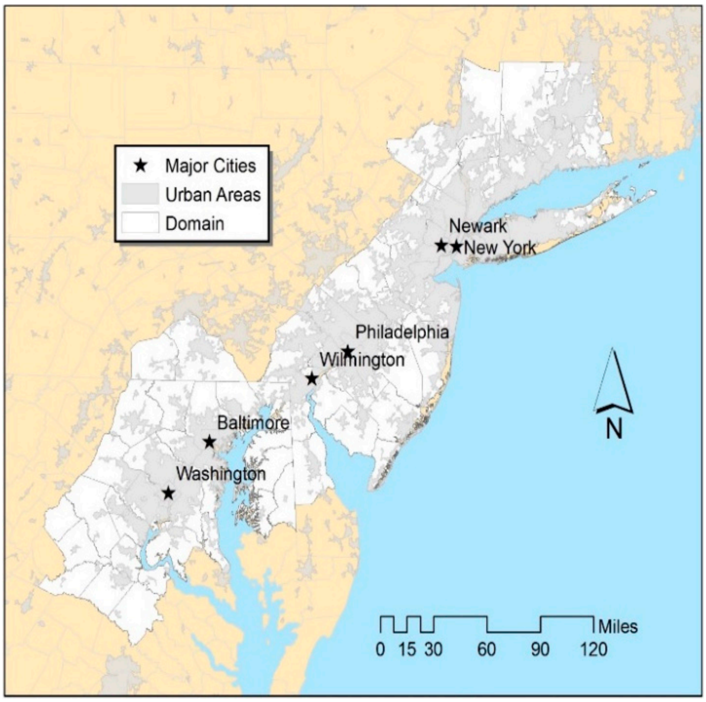

Figure 1. Northeast Corridor Urban Climate Archipelago. Figure courtesy of B. Johnson/UGA. Data courtesy of ESRI/U.S. Census.

The proximity of cities within the NE-UCA may result in independent and synergistic impacts on the regional thermal, dynamic, and microphysical systems. For example, WRF simulations of the region (Figure 2) with and without urbanization (URBAN and NOURBAN, respectively) reveal notably higher air temperatures overnight (particularly in the northeastern portion of the domain) due to the heat island effect, which can adversely affect health outcomes. The figure also suggests that cities in the NE-UCA perturb the regional wind fields possibly affecting convergence, transport, and dispersion.

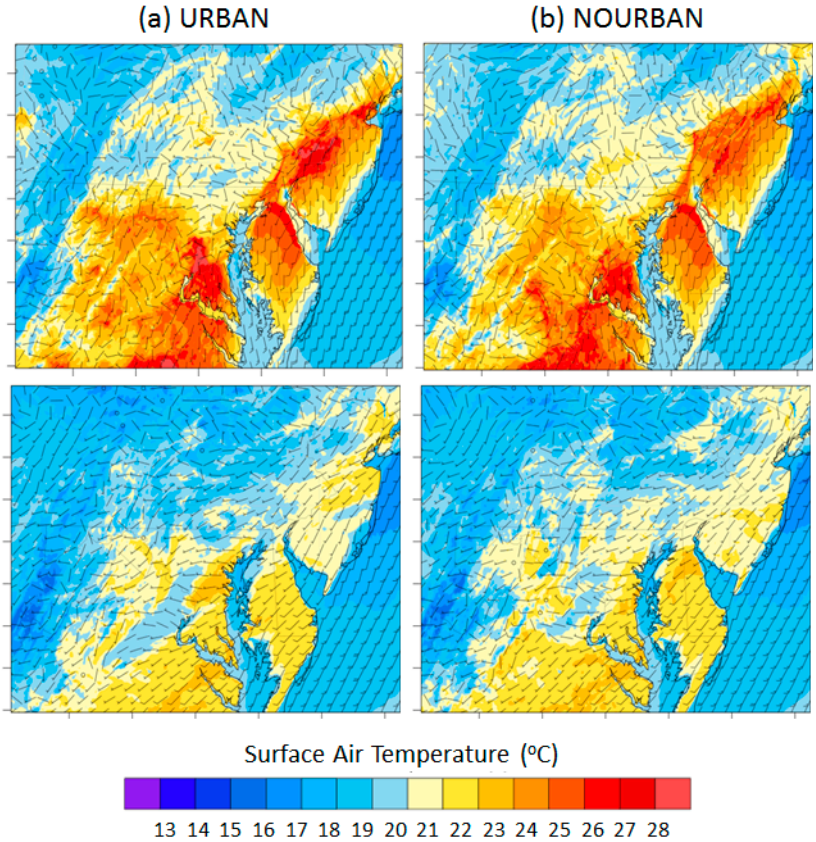

Figure 2. The surface air temperature (°C) and winds for the (**a**) URBAN; and (**b**) NOURBAN simulations. Valid for the early evening (**top**) 2 June 00 UTC, and early morning (**bottom**) 2 June 12 UTC.

3.2. Climatic Factors Affecting the Efficacy of UHI Mitigation

In considering factors that may influence the potential benefits of urban heat mitigation strategies, it is important to understand the underlying goals of heat mitigation. If mitigation is targeting reductions in urban energy consumption, then evaluations of strategies must look beyond the common focus of a summer reduction in air conditioning (AC) loads and consider annual tradeoffs between AC energy savings and potential winter heating penalties [29]. If an underlying goal is to reduce the incidence of excess mortality due to extreme heat, then heat mitigation necessarily should target and be evaluated by its performance during summer heat waves. This may include the extent to which conditions of high humidity coexist with high temperatures and the rates of nocturnal cooling.

Related to this line of inquiry is the notion that underlying weather conditions during the periods of interest for urban heat mitigation may influence the performance of specific strategies in different ways. For example, vegetation strategies, such as urban street trees, green walls, or green roofs, all perform better under conditions of low humidity and high soil moisture availability. Urban albedo strategies perform best when the role of radiant solar heating is largest. Thus, albedo strategies will be less effective during heat waves that are coincident with cloud/haze or highly polluted atmospheres.

As a case study of the importance of underlying weather conditions in affecting the performance of heat mitigation strategies, consider the case of reducing heat-related mortality in Baltimore, MD. As noted above, the periods of interest are major heat waves, either in terms of extreme temperatures alone, or high temperatures combined with high humidity. One of the most notable recent heat waves occurred 15–18 July 2013. During this heat wave at least five deaths in Baltimore were attributed directly to the heat [30]. The temperature only reached 36 °C during this heat wave, but the high humidity and multiple power outages in the region contributed to heat-related morbidity and mortality. Most of the episode coincided with scattered to partly-cloudy skies, a relatively common characteristic of heat events in the region. Over the past decade (based on National Weather Service data from the Baltimore-Washington International Airport) there have been 21 days with maximum temperatures reaching 38 °C; many of these days were characterized by significant cloud cover, suggesting that cloud cover may adversely affect the performance of albedo-based heat mitigation strategies on very hot days.

To explore this issue further, we selected two historic heat waves in Baltimore with contrasting levels of cloudiness. One heat wave occurred on 5 July 2010, when the sky was clear all day and the maximum and minimum temperatures were 37 °C and 21 °C, respectively. The second episode was 21 July 1991, a day with clouds present every hour and a drizzle observed during much of the day. The maximum and minimum temperatures were 37 °C and 25 °C, respectively. These episodes were selected based on the severity and length of unusual heat and the underlying synoptic weather patterns (moist, tropical air mass) that are known to be correlated with heat-related mortality [31].

To explore how the two Baltimore heat waves interact with albedo-based heat mitigation strategies we conducted nested mesoscale atmospheric model simulations with WRF. We used the single-layer urban canopy model (UCM) parameterization 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 WRF UCM is used to represent the physical processes involved in the exchange of heat, momentum, and water vapor in the urban environment by simulating shadowing from buildings, the reflection of shortwave and longwave radiation, wind profiles in the canopy layer, and multilayer heat transfer equations for roof, wall, and road surfaces [32].

We represented the simulation domain using a nested structure with grid resolutions of 1 km, 3 km, 9 km, and 27 km. The outermost domain covers a region of approximately 1900 km (east-west) by 1600 km (north-south). The atmosphere is represented vertically using 31 variably-spaced vertical levels; the terrestrial input data (topography and land-cover) is the 30-s (0.0083 degrees lat/lon or nominally 1 km) resolution data. USGS 24-category land cover data were used to characterize all land cover in all domains. This database uses a single category to represent urban areas (LU = 1). Using a subjective classification approach, we modified this representation using recent aerial images to create a first-order refinement that included designations of urban areas as commercial/industrial, low-intensity residential, and high-intensity residential. Each simulation was initiated with NCEP/NCAR reanalysis data (NNRP) and conducted for 144 to 160 h, with output saved for only the finest grid at hourly increments. Script files were used to identify locations of interest (local airports, downtown areas) and to extract temperature, wind, and humidity results from the simulations. WRF was run with a five-layer soil model, the Yonsei Planetary Boundary Layer scheme, and one-direction feedback among grid nests.

For each heat wave, we created an urban heat island (UHI) perturbation case in which the overall albedo of all urban cells was increased from 0.15 to 0.25 by increasing road and roof albedos.

The results clearly showed the importance of the local synoptic scale weather conditions in urban heat mitigation efforts. Specifically, for the clear sky day of 5 July 2010, increasing the albedo of urban surfaces resulted in an average modeled reduction of 0.23 °C in the air temperature in downtown Baltimore. However, for the cloudy episode of 21 July 1991 increasing the albedo only reduced the daytime downtown temperatures by an average of 0.08 °C. Furthermore, it was found that increasing surface albedo reduced the mixing heights and, therefore, had the general effect of increasing the near-surface humidity.

3.3. Reducing Heat-Related Mortality in Future Climates

While an extensive amount of literature has examined the influence of land cover changes in cities on heat island formation [1,3,14], and the health impacts of high temperatures [31], few studies have explicitly sought to link UHI formation directly to human health outcomes. One of the first studies to address this question [33] used a global circulation model (GISS) coupled with a regional climate model (MM5) to assess the impact of globally- and regionally-driven warming on heat-related mortality in New York by 2050. The results of this work find mortality from rising urban temperatures to increase by between 47% and 95% over the present-day baseline. Building on this work [34] employed a similar approach to estimate heat-related mortality across the entire US, finding national mortality to increase by 3500 to 27,000 deaths per year due to heat-related causes from both the global greenhouse effect and the urban heat island effect.

The association between rising urban temperatures and heat-related mortality suggests the potential for urban governments to lessen the health impacts of climate change through urban heat mitigation. Specifically, urban policies designed to enhance the area of vegetative cover and cool materials can reduce annual heat-related mortality in large urbanized regions. Through an analysis of specific urban heat management strategies and projected heat-related mortality, [35] estimated the benefits of land cover changes in Philadelphia, Pennsylvania, for reducing heat-related deaths by mid-century. Here, we re-examine this dataset to better understand how health benefits of heat mitigation strategies vary across different patterns of urbanization.

One component of a study sponsored by the US Centers for Disease Control (5U01EH000432-02) focused on urban climate change and health. The data examined here for the Philadelphia metropolitan region combined information on land cover change, land development patterns (rural, suburban, urban), population demographics, near-surface air temperature, and estimated heat-related mortality for the year 2050. A key aspect of climate adaptation planning concerns the extent to which heat mitigation across different metropolitan development patterns can yield health benefits. Specifically, how should limited resources for heat mitigation be invested—in suburban zones, where the majority of metropolitan populations now reside, or in urban zones—where population densities and heat island intensity are greatest? This question is particularly relevant in the context of growing urban climate archipelagos, as the impacts of a continuum of land uses across UCAs require better understanding. To address this question, we modify the area of vegetation and cool materials in rural, suburban, and urban zones of Philadelphia using the MM5 regional climate model and associate these changes with heat-related mortality in the year 2050. Future scenarios were developed using census-tract level population data trends and corresponding estimates of how seven classes of land cover, including forest, grass, barren land, water, wetlands, and impervious surfaces, are expected to change by 2050.

The results of three heat management scenarios are presented in Figure 3. Through the first of these (ALBEDO), the albedo/reflectivity of all building roofing and street paving surfaces is increased across the Philadelphia metropolitan region to assess how projected heat-related mortality changes relative to a business-as-usual (BAU) land cover scenario during the 2050 warm season. The resulting area of high albedo materials is presented by the development type (rural, suburban, urban) and by the resulting change in the estimated heat-mortality relative to the BAU scenario. Under the GREEN scenario, the area of vegetation—tree canopy and grass cover—is increased to meet the minimum green cover targets by zoning class, while the COMBINED scenario reports the land cover change and avoided mortality resulting from the combination of the ALBEDO and GREEN scenarios (see [35] for further details of the methods employed).

Three principal conclusions are drawn from this assessment of future land cover change and mortality in Philadelphia. First, vegetation strategies are found to be more effective overall in reducing heat-mortality than albedo strategies. This outcome occurs even though a greater total land area is converted to highly-reflective materials, suggesting that green cover yields more health protection per unit of land area conversion. A combination of vegetation and albedo-enhancement was found to be more effective in reducing future mortality than either single approach.

Second, the majority of avoided deaths under all scenarios occurs in suburban zones of the Philadelphia metropolitan region; 18 of the 32 avoided deaths under the COMBINED scenario are attributed to these zones. Given that more than half of the metropolitan population resides in suburban census tracts, heat management should not be limited to urban zones alone.

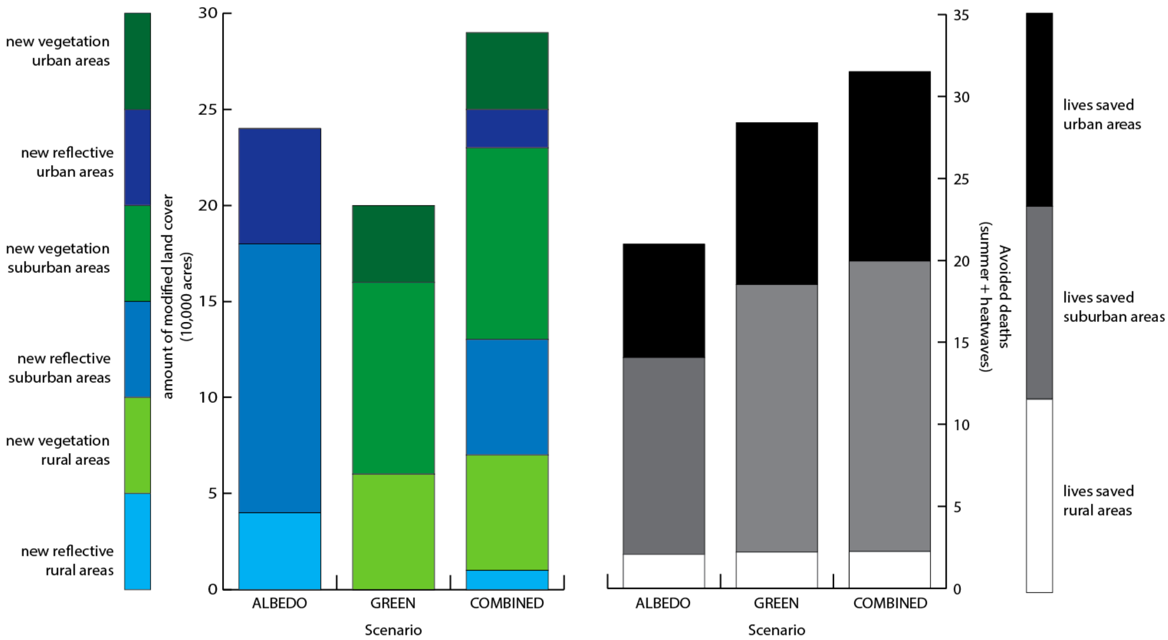

Figure 3. Projected land cover change and avoided mortality by a heat management scenario in Philadelphia in 2050.

Third, heat management strategies in urban zones are disproportionately protective of health relative to suburban or rural zones. While 20% of the total land cover changes were directed to urban zones under the COMBINED scenario, 37% of the avoided deaths are located in urban census tracts. By contrast, while about 55% of the total lives saved are located in suburban zones, about 54% of the land cover changes are directed to these zones. These results suggest that each unit of heat management intervention in urban zones to yield almost twice the health benefits of each unit of heat management intervention in suburban zones. Although urban heat mitigation is effective in reducing heat-related mortality throughout the Philadelphia metropolitan region, the limited climate adaptation resources should be directed to the highest density zones to maximize public health benefits.

4. Implications for Science-Based Urban Climate Policy to Improve Health Outcomes

Each negative human health outcome associated with oppressive summer heat is unique. A person's inability to regulate his/her thermal balance can be related to physiological factors, such as a deterioration of heat regulation due to age, medical conditions, or medications [36]. Behavioral mechanisms, such as maintaining hydration or refraining from overexertion, can be crucial. Socioeconomic factors may affect access to cooler environments and their microclimates, as studies have shown those of lower socio-economic status inhabit areas with a stronger urban heat islands [37]. Furthermore, recent research that has monitored individually-experienced temperatures [38] has shown vastly different thermal environments experienced by persons within the same neighborhood depending upon their housing and lifestyle. Ultimately, these outcomes are all affected by the larger urban environmental conditions discussed above.

The research presented herein has implications for urban climate policy on several scales. Our research suggests that climate policy should go beyond the individual city level, as clear synergistic benefits can be identified with broad-scale modification across conurbations. This may involve coordination among city governments or in the context of regional or state-level planning authorities. Although we demonstrate this conclusion in the NE-UCA, opportunities are most substantial in the developing world, where urban population and land area growth is most heavily concentrated, and where there are the most opportunities to shape the form of urban growth to mitigate climate hazards.

Climate policy geared towards large-scale modification of the urban environment must consider the many impacts on thermal conditions for human health outcomes. As shown above, in the Northeastern US, both drier, sunnier heat waves and more humid, hazier heat waves occur, with varying effects on human health. Some urban modifications increase humidity and/or nighttime temperatures. The temperature-mortality relationship appears stronger with afternoon temperatures in some cities and with morning temperatures in others [39]. Many studies suggest that the relationship with apparent temperature (a metric of human thermal stress, which includes the combined effects of temperature, humidity, and wind speed) is stronger than that with temperature [40]. Thus, urban policy should be tailored to the extreme events local to the environment, so that thermal stress is most appropriately mitigated. Humidity increases may aggravate thermoregulatory stress more than any decreases in temperature would alleviate it, especially in humid, tropical locations.

Further, as evidenced by individually-experienced temperatures, climate policy should also endeavor to produce a microclimate space that is more thermally beneficial. This space can include parks or recreational areas where restful, shaded green space is available; full thermoregulation models account for incident solar radiation and work performed [41]. Thus, benefits within a person's individual environment are important. As most people spend the vast majority of their time indoors, particularly in developed economies, the ancillary benefits of urban modifications to indoor conditions are substantial [42,43], yet relatively under-studied, with a few exceptions (e.g., [44]).

Ultimately, the climate policy implications from this research should be viewed in a broader context. Our results show the importance of urban modifications in reducing impacts of future heat events, which will very likely be more intense and longer lasting than present-day events. Further, metropolitan areas of the future will face additional challenges; particularly in rapidly urbanizing areas of the world, where populations are increasing, and across many developed cities, where demographic transitions are resulting in a greater percentage of elderly residents, who are the most vulnerable to heat illness.

5. Conclusions

Clearly, heat—as measured by air and surface temperatures—is just one important aspect of the urban climate system. For policy-makers to develop effective strategies for improving climate-related health outcomes they must first have a thorough understanding of the challenges facing their population and the pathways through which climate factors influence these challenges. Specifically, while elevated ambient air temperature is a contributing factor to adverse health outcomes, other environmental factors, such as humidity, surface temperatures, wind speeds, and air pollution must also be considered.

Furthermore, as urban residents spend the vast majority of their time indoors, building construction characteristics, indoor conditions, access to air conditioning, and adaptive capacity are all crucial factors in determining health consequences in a major heat wave [45]. Thus, policies that focus exclusively on reducing urban outdoor air temperatures may underperform expectations in terms of measurable health outcomes. Hence, efforts to "mitigate the urban heat island", while well-intentioned, may be targeting a metric that is only loosely associated with the actual desired goals. It is, therefore, crucial that city managers first define the climate-related problems facing their cities, and then set policy goals that are directly tied to mitigating these problems. This may require moving away from heat island reduction targets, focusing instead on policies whose success is measured in terms of actual health, air quality, or energy outcomes. As such, it is equally important for mitigation efforts to consider not only summertime peak temperatures, but also thermal conditions diurnally and throughout the year. Furthermore, these policies must take into account other weather factors and possible unintended consequences across all urban sustainability challenges.

It must also be emphasized that urban climate problems and solutions do not respect political or geographical boundaries. Namely, any strategy is likely to have implications for downwind neighborhoods and communities. This suggests the need for neighboring cities within urban archipelagos to work together in addressing their urban climate challenges.

Finally, by focusing on desired health outcomes, planners may be able to identify areas within cities that are most vulnerable. They can then design more effective mitigation strategies by using spatially- and temporally-targeted policy solutions that focus on improving the adverse conditions for the most at-risk populations. Such targeting of mitigation efforts may result in greater benefits at significantly reduced costs as compared to less-targeted city-wide programs.

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Author Contributions: David Sailor performed some of the WRF modeling and was co-lead on writing manuscript. Marshall Shepherd led the research on UCA/UCA modeling with Theresa Andersen and was a co-lead on writing manuscript. Scott Sheridan was a co-lead on writing manuscript. Brian Stone developed UHI mitigation scenario data and was a co-lead on writing manuscript. Laurence Kalkstein performed some of the heat-related mortality analysis and assisted in editing manuscript. Armistead Russell performed some WRF modeling and assisted in editing manuscript. Jason Vargo performed health impact modeling and assisted in editing manuscript. Theresa Andersen provided text and WRF modeling results in Figure 1 and assisted in editing manuscript.

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