

# Cool Cities: Counteracting Potential Climate Change and its Health Impacts

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Published online: 16 July 2015  
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**Abstract** Cool cities can produce a range of multi-scale, multi-dimensional impacts on the atmospheric environment. One area of increasing interest is the potentially beneficial impacts of cool cities in reducing heat stress and improving air quality health during hot weather and heat events. While the overriding effects of cool cities are beneficial in terms of thermal environment, cooling-energy use, air pollutant emissions, atmospheric chemistry, and air quality, some inadvertent effects can also arise. The goal of this paper is to present and compare the magnitudes of local heat and air quality effects induced by (1) climate change, (2) urban heat islands, and (3) cool cities. From the review of past and more recent findings, this paper concludes that cool cities have the potential to offset the negative local health impacts of climate change and/or their exacerbation by urban areas. To achieve these benefits, the measures must be tailored to region-specific characteristics and needs.

**Keywords** Air quality · Air quality index · Atmospheric modeling · Climate change · Cool cities · Heat health · Heat index · Heat island control · Urban climate · Urban cooling · Urban heat islands

## Introduction

One anticipated outcome of climate change is an increase in frequency and duration of heat events [1, 2]. While these events are defined differently in different regions [3], all require certain temperature thresholds to be exceeded, the compounding effect of humidity be considered, and that they have certain intensity, duration, and spatial-extent characteristics [4]. Many studies project significant health implications from such conditions. For example, a study of 12 U.S. cities estimates that by the end of the century, up to 200,000 heat-related deaths will occur in these urban areas because of climate change [5, 6]. During the California heat wave of 2006, there was a 9 % increase in daily mortality rate for each 5.5 °C (10 °F) increase in apparent temperature [7].

The climate change impacts on heat stress, emissions, and atmospheric pollution can be further exacerbated by urban heat islands (UHIs) because of the higher canopy- and boundary-layer temperatures, transport of heat and pollutants, reduced surface moisture, and modified cloudiness. These pathways, separately and synergistically, impact heat and air quality health.

UHIs can be defined or diagnosed in different manners including, for example, as instantaneous or cumulative metrics, point-specific or area-averaged, relative to fixed or time-varying (wind-dependent) temperature reference points, and with or without pre-defined temperature thresholds. UHIs also vary in intensity and diurnal/seasonal profiles as well as in spatiotemporal characteristics. Instantaneous UHIs are most often in the range of 0.5–3 °C [8, 9, 10, 11, 12]. Larger UHIs, e.g., 4–8 °C, have been observed [13, 14] but are not considered typical. Cool islands (UCI), when cities are cooler than non-urban surroundings, can occur during certain parts of the day, e.g., early morning [11], or on seasonal time scales [15], but UHIs occur much more frequently [8]. And while UHIs

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This article is part of the Topical Collection on *Climate Change and Human Health*

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can be an asset in high-latitude climates, they are a liability in terms of energy, heat, emissions, and air quality in the mid- and low latitudes. Thus, where UHIs exist in these regions, it is desirable to mitigate them.

Presently, there exists a global interest in implementing cool cities [16]. Whether these measures can offset part or all of the urban and local climate effects will depend on each region's characteristics. However, cool cities can produce desired environmental benefits (cooling) regardless of the existence of a UHI, i.e., even when urban areas are UCIs [11].

Figure 1 depicts the general pathways discussed in this paper. While climate change will impact all local meteorological fields, the main focus in this paper is on the changes in air temperature. Urban areas can locally exacerbate (+) the climate effects and increase temperature further. Cool cities can lower temperatures (–) and mitigate the health effects. The dashed line suggests that cool cities can also indirectly impact the global climate via reducing emissions of greenhouse gases and their subsequent intercontinental transport.

## Cool Cities Measures

While many technologies could be considered part of the cool cities portfolio of strategies, Table 1 lists some of the more common ones, along with their influence pathways [17•, 20•]. These measures, whether standalone or in combinations, can affect regional meteorology, microclimate, emissions, and chemistry in varying degrees and, thus, directly and/or indirectly heat and air quality health.

Thus, urban areas or neighborhoods that deploy some or all of these measures are defined as cool cities. In terms of atmospheric and environmental impacts, cool cities are defined as the horizontal and vertical domains within which the effects from these measures are detected, e.g., on micrometeorology (temperature, moisture, and wind), emissions (anthropogenic and biogenic), and chemistry (air quality).

The beneficial effects (cooling and improved air quality) of the measures in Table 1 are mainly localized effects, i.e., experienced directly at and near where cool cities measures are deployed. Downwind of the modified areas, effects are generally positive but sometimes also negative, e.g., warming and/or increased ozone [8, 11]. Furthermore, the effectiveness of cool cities varies significantly from one geographical area to another, depending on climate, emissions profiles, technical potential, and size of modified urban area. Accordingly, the deployment of these technologies should be tailored to area-specific characteristics so as to maximize health benefits.

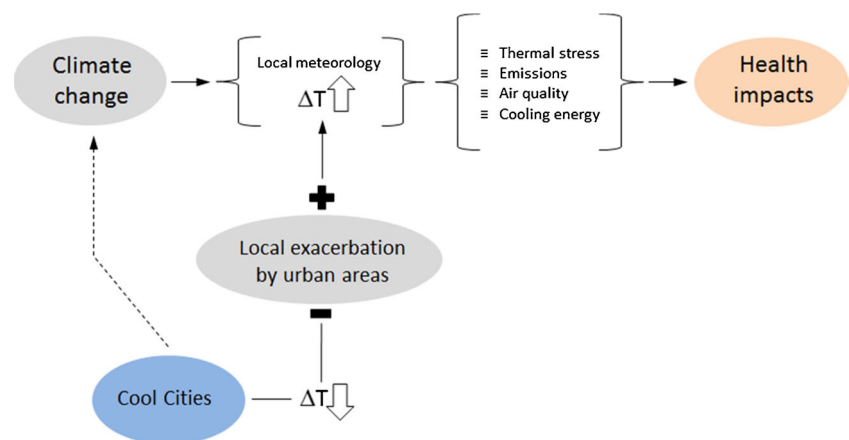
## Positive and Negative Impacts of Cool Cities

As with many environmental control measures, cool cities can exert both positive (beneficial) and negative (inadvertent) effects. The benefits include reduced cooling energy demand, improved thermal comfort, reduced emissions of air pollutants, and improved air quality [35]. Inadvertent effects include winter heating energy penalties and increased temperature and/or pollutant concentrations downwind of cool cities [18].

## Regional Scale

Modeling studies at the regional, urban, and microscales [11, 18, 23] show that the inadvertent effects are smaller than the beneficial ones and limited in spatial extent. For example, the implementation of various cool cities measures (e.g., those listed in Table 1) in California could lead to typical decreases of 0.5–3.0 °C in daytime air temperature and average reductions of ~6 degree-hour per day ( $\text{dh day}^{-1}$ ) above 15 °C [36]. The decreases in 1-h average ozone can reach up to 10–15 ppb. The negative effects, mostly downwind of cool cities, include (1) increased temperature (up to ~0.3 °C) due to inhibited mixing and (2) increased ozone (2–3 ppb) due to reduced venting, higher temperatures, and shallower boundary layers, although the latter can cause both increases and

**Fig. 1** Pathways discussed in this paper



**Table 1** Cool cities measures

Measure	Health-relevant pathways	
Cool roofs	<ul style="list-style-type: none"> <li>• Decreased surface, air, and apparent temperatures</li> <li>• Decreased anthropogenic and biogenic emissions</li> <li>• Reduced photochemical reaction rates</li> </ul>	[11, 17•, 18, 19]
Cool pavements	<ul style="list-style-type: none"> <li>• Decreased surface<sup>a</sup>, air, and apparent temperatures</li> <li>• Decreased anthropogenic and biogenic emissions</li> <li>• Reduced photochemical reaction rates</li> </ul>	[11, 17•, 18, 20•, 21, 22]
Urban forests	<ul style="list-style-type: none"> <li>• Increased deposition of pollutants</li> <li>• Increased cooling (evapotranspiration<sup>b</sup>) and shading</li> <li>• Decreased anthropogenic and biogenic emissions</li> <li>• Reduced photochemical reaction rates<sup>c</sup></li> </ul>	[23–26]
Solar photovoltaics	<ul style="list-style-type: none"> <li>• Increased effective albedo<sup>d</sup></li> <li>• Decreased surface, air, and apparent temperatures</li> </ul>	[27]
Green roofs/walls	<ul style="list-style-type: none"> <li>• Decreased surface, air, and radiant temperatures</li> </ul>	[25, 28, 29]
Anthropogenic-heating control	<ul style="list-style-type: none"> <li>• Decreased air and apparent temperatures</li> <li>• Decreased anthropogenic emission rates</li> <li>• Reduced photochemical reaction rates</li> </ul>	[30, 31]
Runoff/surface-water control	<ul style="list-style-type: none"> <li>• Decreased air temperature<sup>b</sup></li> <li>• Decreased anthropogenic and biogenic emissions</li> <li>• Reduced photochemical reaction rates</li> </ul>	[32–34]

<sup>a</sup> Can increase radiant heat if not implemented properly

<sup>b</sup> Increases atmospheric moisture to some extent

<sup>c</sup> Low-emitting species assumed

<sup>d</sup> Unless implemented on highly reflective roofs or surfaces

decreases in ozone depending on the local ratios of precursor concentrations. In another study of California [37•], it was found that cool roofs implemented per state regulations for commercial buildings will cause mean radiative forcing of  $-1.38 \text{ W m}^{-2}$  per 0.01 increase in albedo.

To date, there have been no observational studies of large urban areas or regions actually implementing cool cities measures, i.e., where surface modifications have been carried out intentionally for this purpose on a large scale. However, there exist limited observational data that could provide some real-world indications to the potential large-scale effects of the proposed measures. For example, an observational study [38] in White Sands National Monument ( $\sim 400 \text{ km}^2$ ) in New Mexico showed that air temperature over the sandy areas (albedo  $\sim 0.55$ ) can be up to  $6 \text{ }^\circ\text{C}$  lower than surrounding areas (albedo  $\sim 0.20$ ) with  $-2 \text{ }^\circ\text{C}$  being a more representative observed difference. An observational study in Spain [39] has documented negative radiative forcing and a cooling trend ( $-0.3 \text{ }^\circ\text{C decade}^{-1}$ ) because of land conversion into greenhouse farming over an area of  $\sim 260 \text{ km}^2$  (with an annual mean albedo that is 0.09 higher than over the surroundings).

### Global Scale

At the global scale, a study [40] estimates that increasing albedo by 0.1 in major urban areas worldwide

would decrease the global average temperature by  $0.008 \text{ }^\circ\text{C}$  during the boreal summer. A similar effort [41•] found that deployment of cool roofs and pavements throughout urban areas in the USA can cause the domain-wide annual average outgoing radiation to increase by  $0.16 \pm 0.03 \text{ W m}^{-2}$  and afternoon summertime urban air temperatures to decrease by  $0.11\text{--}0.53 \text{ }^\circ\text{C}$ . Some rural locations could warm up ( $\sim 0.27 \text{ }^\circ\text{C}$ ) because of reduced cloud cover.

Another study [42] finds positive (cooling) effects from global implementation of cool roofs. Averaged over all urban areas, the annual mean heat island is decreased by 33 % (from 1.2 to  $0.8 \text{ }^\circ\text{C}$ ) and the daily urban maximum temperature reduced by  $0.6 \text{ }^\circ\text{C}$ . The daily minimum temperature is lowered by  $0.3 \text{ }^\circ\text{C}$ . On the other hand, a global modeling study [43•] found that while urban albedo increase can result in urban-specific cooling (an average of  $0.02 \text{ }^\circ\text{C}$ ), the global temperature can increase by  $0.07 \text{ }^\circ\text{C}$ .

However, these global studies did not account for other potentially beneficial effects of cool cities, such as the impacts on energy use, emissions, and chemistry. Thus, again, the implications of these and similar findings are that cool cities measures must be optimized specifically to each region and are not “one-size-fits-all” measures.

## Health Implications

For heat, the impacts of cool cities can be quantified via (1) changes in meteorological variables, (2) changes in heat indices, and (3) modifications to local air mass classification. At the synoptic scale, an air mass classification system was established to characterize heat health impacts and mortality [44, 45]. Of 8 spatial synoptic categories in the system, the hot and humid Moist Tropical (MT+, MT++) and hot Dry Tropical (DT) air masses cause the most increase in mortality [44]. Thus from this perspective, one goal of cool cities is to decrease the occurrences and/or durations of these oppressive weather types. Indeed, a few studies suggest that cool cities can impart effects that are significant enough to shift the local air mass types to more benign ones [46, 47].

At the local scale, several indicators can be used to translate the effects of urban heat and its potential exacerbation of background climate effects and, by same token, the potential of cool cities in locally mitigating these effects. Excess mortality ( $M$ ) due to heat can be estimated as [48, 49]:

$$M = c_1 + c_2D + c_3t + c_4T \quad (1)$$

where  $D$  is day sequence during an offensive weather type,  $t$  is time of season, and  $T$  is afternoon air or apparent temperature. The constants  $c_1$  through  $c_4$  are city- and air-mass-type-specific.

Generally, cool cities measures tend to affect (reduce) daytime more than nighttime temperatures [11, 18, 36] and can thus help reduce mortality, since  $T$  (in Eq. 1) is an afternoon temperature.<sup>1</sup> While the daytime effects sometimes carry over to nighttime temperatures, daytime cooling is generally larger than at night for measures that involve modifying surface albedo. Several modeling studies of increased urban albedo indicate significant daytime cooling but smaller changes in nighttime air temperature [11, 17, 18, 42].

On the other hand, the impacts of vegetation-cover increase can differ from one situation to another. For example, one study shows that nighttime cooling (0.7–2.8 °C) from an urban park in Athens can be larger than daytime cooling [24] whereas a U.S. study shows some urban parks to be up to 7 °C cooler than surrounding urban areas at night but only about 3 °C cooler during the day [50]. In other situations, vegetation canopies can be warmer at night [51] because of the smaller sky-view factor than in surroundings. This highlights the need for region and site specificity in developing cool cities measures to maximize the heat health benefits. For example, at the regional scales, drier climates generally favor both urban forest and albedo control measures, whereas relatively more humid climates favor reflective surfaces. Variations in microclimates within each region can further dictate the measures that

would be most effective, depending on available sunshine (cloudiness/fogginess), temperature, humidity, wind patterns, anthropogenic and biogenic emissions, soil moisture availability, urban morphological characteristics, technical potential for deployment of control measures, and other considerations. Based on these factors and on the indirect atmospheric impacts of mitigation techniques, it is possible to prioritize and rank the measures in Table 1 per site- region-specific characteristics [20, 52].

In terms of air quality,<sup>2</sup> there are similarly several ways to evaluate the potential health impacts. These include (1) evaluation of changes in concentrations, (2) changes relative to established thresholds and standards, and (3) changes in the air quality index (AQI). In “Air Quality” section, examples are provided.

A number of studies have evaluated the impacts of ozone on health and mortality. One study analyzed impacts in 95 U.S. urban areas and found a 0.25 % increase in mortality for each 10 ppb increase in 24-h average ozone (1-day lag) [53]. It was also found that mortality ranges from 0.52 to 0.64 % per 10 ppb increases in prior-week ozone concentrations (1-week lag). Another study found an increase in mortality risk of 0.8 % per 10 ppb increase in ozone [54]. For long-term exposure, the relative risk of mortality from respiratory causes was found to be 1.040 for each 10 ppb increase in ozone [55].

An aspect of interest is whether air quality and heat should be evaluated separately or as confounding factors [56]. This is of relevance to cool cities because urban cooling affects meteorology (heat), emissions (air quality), and chemistry (air quality) simultaneously and, thus, quantifying health benefits would be more realistic, and possibly larger, if heat and air quality impacts are accounted for simultaneously. A review [57] found mixed results in terms of air pollution ( $O_3$ ,  $PM_{10}$ ,  $PM_{2.5}$ ,  $CO$ ,  $NO_2$ , and  $SO_2$ ) as a confounder or modifier to heat-mortality associations. Some studies found no confounding effects whereas others suggested impacts from  $PM_{10}$  and  $O_3$ .

In a study of the heat discomfort index (DI) and air quality index (AQI) under heat-wave and non-heat-wave conditions, it was found that the two indices correlated during hot conditions [58]. Similarly, researchers in a Mediterranean climate found that when the common air quality index exceeded 76, the DI was highest [59].

The compounding effects of air pollution on heat stress during different weather types were evaluated in 12 Canadian cities [48]. It was found that within air mass types DT and MT+ [45, 46] there was a 4-fold and 2-fold increase,

<sup>1</sup> Other formulations include both nighttime (0300 LST) and daytime (1700 LST) temperatures.

<sup>2</sup> Climate change, UHI, and their mitigation affect many pollutants. The focus in this paper is on ozone because most studies of cool cities to date have evaluated this pollutant and health studies show that ozone and particulate matter are the most influential.

respectively, in likelihood of extreme pollution events.<sup>3</sup> It was also found that single-pollutant impacts on mortality depended on the air mass type. For example, the average pollutant-induced increases in mortality within DT and MT+ weather types were respectively 14.9 and 11.9 % higher than for other weather types. In Adelaide, Australia, a study developed temperature thresholds for heat while accounting for ozone and PM<sub>10</sub>. After adjusting for the effects of pollutants, it found a 6-fold increase in emergency department presentation per 10 °C increase in maximum air temperature [60].

## Impacts of Climate and Heat Islands

### Heat

Global temperatures, expected to rise 2–5 °C by the end of the century [6], can be locally exacerbated by UHIs. To evaluate the synergistic interactions between climate and UHI, studies have examined the response in urban and non-urban temperatures to heat waves. In one study, observational data from Baltimore, MD, show that heat waves increase the UHI intensity because of low urban surface moisture and wind speeds [61]. The data show that the 2008 heat wave increased the nighttime UHI from 0.5 to 2.5 °C and the daytime UHI from 0.25 to 1.5 °C. Since such conditions could become more common under climate change, it can be expected that UHI intensities will increase in the future.

In a modeling study of several U.S. regions [9], it was found that urban temperatures would increase between 0.5 and 1.2 °C which is additional exacerbation to the background climate effect. In Houston, TX [62], the urban area could get 2 °C hotter because of changes in climate and land use. Another study [63] found that urbanization between 1993 and 2004 increased the daytime UHI by 0.6 °C and nighttime UHI by 1.4 °C in the Pearl River and Yangtze River delta regions in China. That study also showed an increase in UHI intensity over time. For example, in Shanghai, the UHI was found to increase by 0.025 °C year<sup>-1</sup>. The urban exacerbation can also be seen in heat health impacts and mortality rates. A study of the 1998 heat wave in Shanghai [64] found that excess mortality was 27.3 per 100,000 in urban areas but only 7.0 per 100,000 in non-urban surroundings. These additional ~20 deaths per 100,000 are caused mainly by the UHI. Similarly, a study of Hong Kong [65] found that a 1 °C increase in background temperature above 29 °C caused 4.1 % increase in mortality in areas within heat islands but only 0.7 % increase in non-heat island areas, thus an urban contribution (exacerbation) of 3.4 %.

<sup>3</sup> Extreme pollution events are defined as occurrences of top 5 % pollutant concentrations.

A study of Tokyo using the A1B scenario [66] suggests that temperature in 2070 will be 2 °C higher than in 1990. Urban exacerbation contributes 0.6 °C to the current heat island of 1 °C—thus the study predicts a future UHI contribution of 1.6 °C. In Israel, the difference in discomfort index between an urban area (Beer Sheva) and non-urban surrounds increases by 0.022–0.024 years<sup>-1</sup> and the physiological equivalent air temperature (PET) increases by 0.048–0.063 C°years<sup>-1</sup> due to urban exacerbation of the background climate effect on heat stress [67].

In a study of climate change impacts on Korean cities [46], conservative model scenarios for the city of Busan show that occurrences of DT weather type would increase from less than 1 % in early twenty-first century to 3 % by end of the century. The occurrences of MT++ would increase from 0.24 % presently to 9.33 % by 2090. Conversely, there may be regions where the UHI could decrease with climate change. For example, Paris, France, under scenarios A1B and A2 could warm up slower than its non-urban surrounds because of the latter's lower soil moisture [68]. Furthermore, the study suggests larger reductions in the nighttime UHI than in daytime UHI.

Thus, the magnitudes and tendencies of the UHI in a changing climate will depend on the differences in thermo-physical properties of urban areas relative to those of their non-urban surroundings. However, in terms of mitigation, it is expected that urban cooling will be equally effective regardless of whether UHIs increase or decrease in the future.

### Air Quality

Many studies have evaluated the future air quality implications of a changing climate including or separately from the effects of emission controls. Findings suggest that the local effects of climate change can in some cases offset the benefits of planned emission-reduction measures [69, 70]. Hence, from this perspective, cool cities can help offset the urbanization and local climate effects on meteorology and provide benefits in parallel to traditional emission-control strategies.

Climate change will worsen air quality by (1) increasing emissions, (2) increasing production of ozone, and (3) lengthening the ozone season and poor air quality episodes. A study of the USA [71] projects an increase of 2–15 ppb in the maximum 8-h average ozone by 2050 due to climate change (A1B scenario). It is also likely that by the end of the century, stagnation events will become more frequent. Using an air stagnation index, a study [72] projects an increase of up to 40 days per year with stagnation events by the late twenty-first century in the tropics and sub-tropics as well as some mid-latitude regions.

In European suburban areas, climate change could cause an increase in ozone such that the annual mean and average daily ozone maxima are increased by up to 1.5 ppb, and the number



of high ozone days increased by 5–30 % [73]. In China [63], a study showed that the meteorological consequences of urbanization between 1993 and 2004, i.e., the UHI, increased ground level ozone by 4.7–8.5 % at night and 2.9–4.2 % during the day. Other studies indicate that climate change will cause an increase of 1–10 ppb in ozone in urban areas driven mainly by higher temperatures (UHI), whereas background ozone might decrease somewhat because of increased water vapor [74].

Fine-resolution meteorological, emissions, and photochemical modeling of downscaled IPCC scenarios for California found that the 1-h peak ozone concentrations can increase by up to 11 ppb in the Los Angeles Basin and 9 ppb in the Sacramento Valley by 2090 assuming controlled emissions (meaning future emission controls are in place) [70]. The study also found that the correlation between changes in ozone and temperature is (1) 0.67 ppb °C<sup>-1</sup> for peak ozone at times and locations of present-day peaks, (2) 4.61 ppb °C<sup>-1</sup> for the largest increase anytime anywhere in the domain, and (3) 8–10 ppb °C<sup>-1</sup> (up to 15 ppb °C<sup>-1</sup>) for the largest ozone increase anywhere any time in the domain but with uncontrolled emissions [70]. In Houston, TX, a modeling study [62] evaluated the A1B scenario and found that the impacts of climate change alone would be to increase ground level 8-h maximum ozone by 2.6 ppb. When urbanization effects are also accounted for, the increase in the 8-h maximum reaches up to 6.2 ppb.

Another study [75] indicated a range of effects from climate change including increased ozone production of 2–15 ppb °C<sup>-1</sup>, similar in magnitude to the results above [70]. Analysis by the U.S. EPA [76] suggests that climate change will increase summer-time average ozone by 2–8 ppb in many regions and also lengthen the ozone season.

### Potential of Cool Cities to Counteract Urban and Climate Change Effects

In this section, the potential impacts of cool cities on health are discussed (1) in terms of changes in variables of relevance to heat and/or air quality, (2) modifications to heat and/or air quality metrics relative to thresholds or standards, and (3) modifications to classification of health impacts. This is summarized in Table 2 which is expanded into BOX H1 through H3 for heat and BOX AQ1 through AQ3 for air quality. Each box shows the changes in the indicator (column 1), a description of the changes (column 2), the cool cities measures causing the changes (column 3), and references (column 4). The effects are for cool roofs (CR), cool pavements (CP), urban forestation (UF), conversion of impervious to pervious surfaces and runoff control (IM/P), vegetation and/or structural shade (V/S), and green roofs (GR).

The amount of cooling achievable with these measures is strongly dependent on (1) the size of the urban area to be modified, (2) deployment and technical potentials in each area, as well as (3) the local climate characteristics [11, 17•, 18, 20•]. Results presented below and in “Conclusions” section show that, in general, the magnitudes of effects from cool cities are significant and sufficiently large to mitigate the effects of heat islands and locally offset some of the effects of climate change on heat and/or air quality health.

### Heat Health

Several formulations of the heat index have been developed to translate environmental conditions into quantifiable health metrics [83]. One of the more commonly used indexes is that of the National Weather Service (NWS) [83, 84]. More recent formulations include the Universal Thermal Climate Index (UTCI) which is an equivalent-temperature model that also includes clothing and adaptation models of the urban population [85].

Taking the commonly-used NWS heat index (*HI*) and partially differentiating with respect to temperature (*T*), we obtain:

$$\frac{\partial HI}{\partial T} = c_2 - c_4 H - 2c_5 T + 2c_7 T H + c_8 H^2 - 2c_9 T H^2 \quad (2)$$

where  $c_2=2.04901$ ,  $c_4=0.224755$ ,  $c_5=0.006837$ ,  $c_7=0.001228$ ,  $c_8=0.000852$ , and  $c_9=0.00000199$ , and where *HI* and *T* are in degree °F, and *H* (relative humidity) is in percent. At the milder end of a heat event, for example, 85 °F (29.4 °C) and 40 % relative humidity,  $\partial HI/\partial T$  from Eq. 2 is 1.06 °F °F<sup>-1</sup> (1.9 °F °C<sup>-1</sup>) whereas during a relatively more severe event, say 94 °F (34.4 °C) and 70 % relative humidity,  $\partial HI/\partial T$  is 3.53 °F °F<sup>-1</sup> (6.4 °F °C<sup>-1</sup>). Considering that cooling of 1–3 °C is achievable with cool cities (see column 1 in BOX H1), the reductions in *HI* can amount to up to 19 °F (10.6 °C) in the relatively more severe event. This is comparable to BOX H2 where the heat index ranges from 3.5 to 10 °C. Even if cool cities achieved only a 0.5–1 °C reduction in air temperature (e.g., some of the lower values in BOX H1), the effects will still be significant, e.g., 1.9–6.4 °F (1–3.6 °C) and, in some cases, can shift the local air mass classification to a less severe one, as seen in BOX H3, for example.

In a study of increased urban albedo (+0.1) and vegetation cover (+10 %) [47], it was found that in Baltimore, Los Angeles, and New York, the average change in air temperature is -0.5, -0.7, and -0.2 °C, respectively, with an increase of between 0.1 and 0.3 °C in dew point temperature for the case with vegetation cover modification. The corresponding effects on health are reductions in mortality of 2, 1, and 9 %, respectively.

**Table 2** Framework for discussion of cool cities impacts

	Changes in relevant variables:	Changes in relevant metrics:	Changes in class or category:
Heat	<ul style="list-style-type: none"> <li>• Air temperature</li> <li>• Apparent temperature<sup>a</sup></li> <li>• Degree-hours</li> </ul>	• Heat index value	<ul style="list-style-type: none"> <li>• Air mass classification</li> <li>• Synoptic conditions</li> <li>• Heat index bracket or category</li> </ul>
Air quality	BOX H1 <ul style="list-style-type: none"> <li>• Concentrations</li> <li>• Population weighted exceedance</li> <li>• Emissions</li> <li>• Emission equivalents</li> </ul> BOX AQ1	BOX H2 <ul style="list-style-type: none"> <li>• 1-h average</li> <li>• 8-h average</li> <li>• AQI value</li> </ul> BOX AQ2	BOX H3 <ul style="list-style-type: none"> <li>• AQI category or class (bin)</li> </ul> BOX AQ3
Change	Notes	Measure	Reference
BOX H1			
0.11–0.53 °C $T_{air}\downarrow$	Summer afternoon average over several U.S. urban areas (continental scale)	CR + CP	[41•]
2.00–3.75 °C $T_{air}\downarrow$	Maximum daytime decrease, Southern California, USA (mesoscale)	CR + CP + UF	[18]
1.50–2.00 °C $T_{air}\downarrow$	Maximum daytime decrease San Francisco—Sacramento region, USA (mesoscale)	CR + CP + UF	[18]
0.30–0.50 °C $T_{air}\downarrow$	Average daytime air temperature, Philadelphia, USA	CR + CP	[77]
1.00–4.00 °C $T_{air}\downarrow$	Nighttime heat-island reduction, London, UK	UF	[78]
0.20–2.60 °C $T_{air}\downarrow$	Urban forest/park daytime cooling (UCI), Athens, Greece	UF	[24]
2.5 °C $T_{air}\downarrow$	Peak daytime air temperature, Atlanta, USA	CR + CP	[10•]
2.0 °C $T_{air}\downarrow$	Largest reduction in UHI, Stuttgart Germany	CR	[79]
0.8–2.0 °C $T_{air}\downarrow$	Range of largest changes for several U.S. urban regions	CR + GR	[9•]
3–6 dh $day^{-1}\downarrow$	Relative to 15 °C, range of average over monitor locations in central California, USA	CR + CP	[20•, 36]
6–7 dh $day^{-1}\downarrow$	Relative to 15 °C, range of average over monitor locations in southern California, USA	CR + CP	[20•, 36]
BOX H2			
UTCI 10 °C $\downarrow$	From average UTCI 33 to 23 °C, shading, Canada and Korea	V/S	[26]
HI 4.3 °C $\downarrow$	Imperviousness 71.9 to 12.8 %, Florence, Italy	IM/P	[32]
UTCI 3.5 °C $\downarrow$	Evaporation from urban surfaces, summer, Zurich, Switzerland		[80]
UTCI 4.3 °C $\downarrow$	Albedo increase, summer, Zurich, Switzerland	CP + CR	[80]
BOX H3			
UTCI “moderate-strong” to “no stress-moderate”	Heat stress, shading, Canada and Korea (microscale)	UF/shade	[26]
Air mass MT++ to MT+ or DT to either DM or MT	Several U.S. cities	CR + CP + UF	[47, 49•, 81]
BOX AQ1			
66–185 mtpd VOC $\downarrow$ (3–9 %)	Anthropogenic emission equivalents of increased albedo, Central California, USA	CR + CP	[20•, 36]
51–77 mtpd VOC $\downarrow$ (5–8 %)	Anthropogenic emission equivalents of increased albedo, Los Angeles, USA	CR + CP	[20•, 36]
5–10 ppb [O <sub>3</sub> ] $\downarrow$	Representative changes in 1-h and 8-h average ozone, California urban areas, USA	CR + CP	[11, 36]
BOX AQ2			
5.5 ppb [O <sub>3</sub> ] $\downarrow$	Daily 1-h average maximum ozone, several urban areas, Southern California, USA	CR + CP + UF	[18]
3.5 ppb [O <sub>3</sub> ] $\downarrow$	Daily 8-h average maximum ozone, several urban areas, Southern California, USA	CR + CP + UF	[18]
2.4 ppb [O <sub>3</sub> ] $\downarrow$	Peak daylight ozone decrease, Washington DC—Massachusetts, USA	UF	[73]

**Table 2** (continued)

	Changes in relevant variables:	Changes in relevant metrics:	Changes in class or category:
12.0 ppb [O <sub>3</sub> ] ↓	Average changes in 1-h peak, San Francisco—Sacramento, USA	CR + CP + UF	[18]
1–5 ppb [O <sub>3</sub> ] ↓	1-h peak, multi-seasonal range, urban areas in California, USA	CR + CP	[20•]
13 % [O <sub>3</sub> ] ↓	Maximum 8-h average, Sacramento, USA	CR + CP	[11]
1 % [O <sub>3</sub> ] ↓	Average 8-h, Washington DC—Massachusetts, USA	UF	[82]
BOX AQ3			
“Very unhealthy” to “unhealthy”	Daily 8-h maximum ozone, several urban areas, Southern California, USA	CR + CP	[36]
“Unhealthy” to “unhealthy for sensitive population”	Daily 8-h maximum ozone, several urban areas, Central and Southern California, USA	CR + CP	[36]

CR cool roofs, CP cool pavements, UF urban forest, PV solar photovoltaic, GR green roofs, GW green walls, QF anthropogenic heat control, IM/P runoff and soil moisture control, V/S vegetation or structural shading, AQI air quality index, HI heat index, UTCI universal thermal climate index ([www.utci.org](http://www.utci.org)) [76],  $T_{air}$  air temperature,  $dh \text{ day}^{-1}$  degree-hours per day, mtpd metric tons per day, ppb parts per billion

<sup>a</sup> To also account for effects of relative humidity, wind speed, and solar radiation

respectively. A related study [49•] showed that for the District of Columbia, a 0.1 increase in urban albedo could reduce mortality by an average of 6 % during excessive heat events.

In New York City, urban greening (converting impervious surfaces to tree canopies) can decrease air temperatures by an average of 1.9 °C and up to 4.8 °C [25]. A study of the USA [9•] suggests that implementation of green and reflective roofs can reduce air temperature in urban areas by 1.5–2 °C. The study estimates that whereas future urban expansion in the USA could contribute 1–2 °C to the regional climate, cool cities could locally offset that warming.

A fine-resolution meso-urban modeling study of increasing urban albedo in the Sacramento Valley found a decrease in air temperature of up to 2–3 °C [11] for an increase in albedo of up to 0.4 on roofs and 0.15 on pavements. Another study [12] found that cool cities measures in Canada could reduce urban air temperatures by 0.5–1 °C (with highs as large as 3 °C possible). In the city of Stuttgart, Germany, the implementation of reflective roofs can decrease the heat island by up to 2 °C [79]. A review of studies evaluating the effects of reflective surfaces on air temperature reports an average decrease of 0.3 °C for an increase of 0.1 in albedo of urban areas around the world [17•]. If only cool roofs were considered, the mean decrease in average urban air temperature would be 0.2 °C. The review also reports an average decrease in peak temperatures of 0.9 °C across several studies and regions.

A study of Atlanta, Philadelphia, and Phoenix estimates that by 2050, heat-related mortality could be decreased by 40–99 % if increased vegetation cover and surface albedo were implemented [86]. The study concluded that cool cities could help in adaptation to a changing climate. An analysis of the 2002 Beijing heat wave estimated that air temperature could be reduced by

1.4 °C on the peak day of the heat event (an offset of ~59 %) [87]. In the city of Melbourne, Australia, researchers suggest that urban forestation can help reduce average summer temperatures by up to 2 °C [88]. They also suggest that doubling vegetation cover in the city would reduce heat-related mortality by 5–28 %.

The foregoing discussion and the information in BOX H1–H3 show that cool cities can have a significant beneficial impact on temperature (H1), heat index (H2), and even weather type (H3).

### Air Quality Health

Air quality health benefits from cool cities are achieved by (1) reducing emissions, (2) reducing emission equivalents, and (3) slowing photochemical production of ozone:

- *Reduced emissions* result from (1) reduction in power generation because of direct (building) and indirect (atmospheric) effects on cooling energy demand, (2) reduction in temperature-dependent biogenic and anthropogenic emissions, and (3) reduction in fugitive/evaporative emissions [18];
- *Emission equivalents* represent the anthropogenic VOC and/or NO<sub>x</sub> emission reductions (or avoided emissions) that produce ozone reductions equal to those from cool cities impacts on atmospheric chemistry [20•, 36], for example, BOX AQ1; and
- *Slower photochemical production of ozone* results from (1) smaller temperature-dependent reaction rates and (2) PAN chemistry (reduction of NO<sub>2</sub> pool) [11, 18], as in BOX AQ2.



The U.S. EPA's air quality index (*AQI*) is often used in operational forecasting for ozone (e.g., [89]). Differentiating *AQI* with respect to pollutant concentrations within the *AQI* range of 51–200 and using ozone as example, we obtain:

$$\frac{\partial AQI}{\partial c_i} = \frac{AQI_1 - AQI_2}{bP_1 - bP_2} = 2.57 \text{ ppb}^{-1} \quad (3)$$

where  $c_i$  is the 8-h concentration of ozone and  $bP_1$  and  $bP_2$  are the concentration break points corresponding to  $AQI_1$  and  $AQI_2$ , respectively. Thus a change of 1 ppb in the 8-h averaged (maximum) ozone is equivalent to an *AQI* change of 2.57 points. Considering that ozone concentration decreases of 3–5 ppb in 8-h averages are realistically possible with cool cities [11, 36], as also suggested in BOX AQ2, the *AQI* could be reduced by up to 8–13 points, which is significant. In some cases, as shown in BOX AQ3, the reductions in ozone concentrations from cool cities can shift the *AQI* class altogether to a more benign one.

A fine-resolution urban meteorological and photochemical modeling study shows that in Sacramento, CA, ozone can be decreased by 5–11 ppb (1-h average) during the daytime as a result of increased surface albedo [11]. These decreases correspond to 2–4.5 ppb °C<sup>-1</sup>. Compared with the effects of climate change of 0.67–10 ppb °C<sup>-1</sup> [70] and 2–15 ppb °C<sup>-1</sup> [75], this would suggest that cool cities can offset about 30–50 % of the local climate impacts in Sacramento. In terms of the daily maximum 8-h average, the relative reduction factor (RRF) corresponding to these increases in albedo ranges from 4 to 9 % [11, 36]. Since, as discussed earlier, an increase of 10 ppb in ozone would result in an increase in mortality of 0.8 % [52], the above reductions of 5–11 ppb from cool cities [11] would be roughly equivalent to a reduction of 0.8 % in mortality.

In central California, the maximum 8-h ozone can be decreased by 1–2 % and in southern California by 2–3.6 % as a result of cool cities (increased urban albedo) [20•, 36], which is comparable to other results, e.g., BOX AQ2. This can also shift the *AQI* from one class to another, as discussed above. In terms of urban greening, a study estimates decreases of up to 2.4 ppb in daytime ozone concentrations as a result of urban forestation in northeastern USA [82]. However, the nighttime ozone can increase because of reduced mixing and non-urban areas can also experience an increase (~0.25 ppb) during the daytime. In another modeling study [12], it was shown that deployment of cool cities measures in Canada could reduce ozone by 2–4 ppb (1-h average).

A multi-seasonal modeling evaluation of cool cities impacts on air quality found that in Central California, the 1-h peak ozone can be decreased by 1.2–5.2 ppb [20•, 36]. Since cool cities can also cause increases in ozone, e.g., downwind of modified areas, the study [36] also evaluated the ratio of cumulative (ppb-hrs) decrease-to-increase (RDI) in ozone. It

was found that RDI reaches up to 62, an overwhelmingly positive effect. There was one episode out of 25 where the average RDI was about 1. For Southern California, the study found that cool cities measures decrease the 1-h peak ozone by 4.8–8.4 ppb and that the RDI ranges from 19 to 99 (thus a larger impact than in Central California). These studies [18, 20•, 36] also show that heat island control can impact all regions, downwind included, in a beneficial way. In other words, upwind implementation of mitigation measures can also benefit those areas downwind regardless of whether or not mitigation measures are implemented in the downwind regions [8, 11, 18].

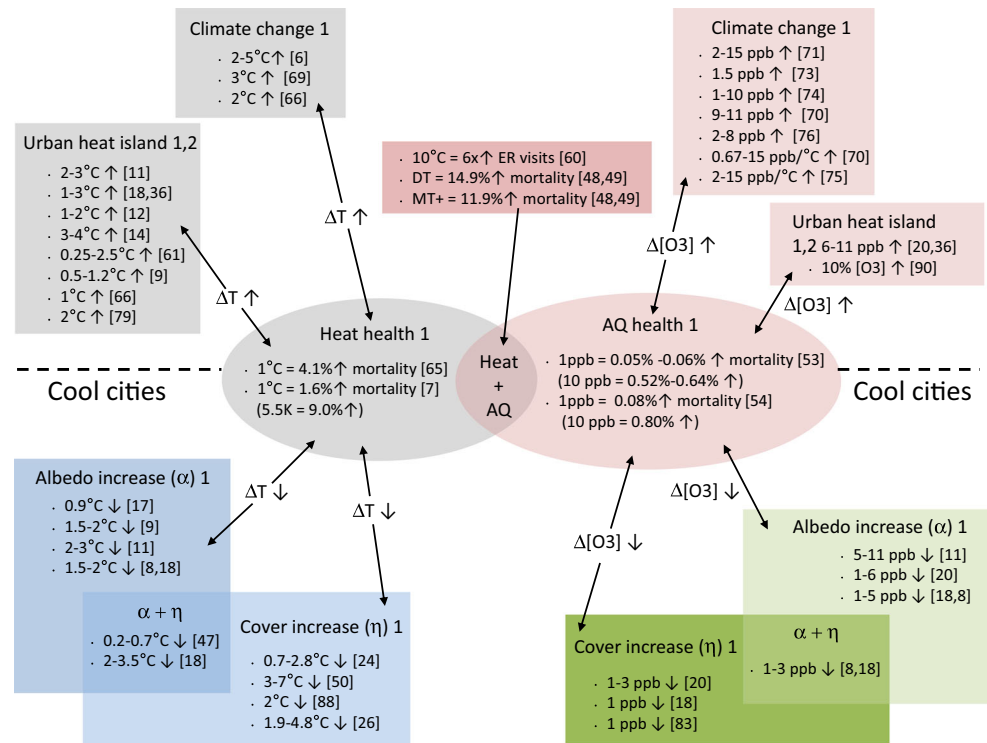
In a study of regulatory episodes [18, 36], it was shown that the 1-h peak ozone can be reduced by up to 16 ppb as a result of deployment of cool cities measures in central California. Compared to 0.52–0.64 % increase in mortality per 10 ppb for 1-week lag [53] discussed earlier, this yields a 0.83–1.02 % reduction in mortality. The study [18] also shows that cool cities can reduce the 24-h average ozone in Southern California (averaged over urban regions) by up to 2 ppb. As discussed earlier [53], a 0.25 % increase in mortality was estimated for each 10 ppb increase in 24-h average (1-day lag). Thus the above 2-ppb decrease in the 24-h average from cool cities would translate into a decrease of 0.05 % in mortality. If monitor-specific (not area-averaged) ozone changes were considered (which can reach up 8 ppb), the reductions in mortality risk will be dramatically larger (i.e., quadruple).

## Conclusions

Results reviewed in this paper suggest that effects of cool cities are similar in magnitude (and opposite in direction) to those of UHI and/or local effects of climate change. While there are regional disparities in the magnitudes and sometimes even different directionalities, an overriding number of studies point to the conclusion that cool cities, if optimally deployed, have the potential to mitigate health effects of UHI and climate.

Figure 2 presents a sampling summary of such effects. The two ovals in the center equate the changes of 1 °C and 1 ppb (ozone) to health as a basis for comparing the negative (above dashed line) and positive effects (below dashed line). The area of overlap between the ovals (darker pink) represents the combined effects of heat and air quality. The upper half of the figure depicts the negative effects of climate change and UHI on heat (grey) and ozone air quality (light pink). The bottom half shows the potential of cool cities in mitigating heat (blue) and air quality (green) effects. Areas of overlap (darker shades) represent the combined effects of reflective surfaces and vegetation measures ( $\alpha + \eta$ ). The cool cities examples in this figure are reflective roofs and increased canopy cover and the pollutant is ozone.

**Fig. 2** Sampling of magnitudes of heat and air quality impacts and mitigation potentials. *Note 1:* The numbers provided in *parentheses* (in the *ovals*) are the original form (as in the source/reference). Thus, linearity is assumed within the given range, which may or may not be a reasonable assumption. *Note 2:* The figure is for temperature and ozone and local effects only. The units “ppb” in the figure refer to ozone concentrations. *Note 3:* The *arrows* next to temperature or ozone changes indicate whether the variable is increasing (↑) or decreasing (↓). <sup>1</sup>Various regions. <sup>2</sup>Current UHI contributions



The figure depicts data from different regions and scenarios and, thus, is not intended as an exact one-to-one correspondence among the various variables and effects but, rather, a qualitative comparison of their magnitudes.

Figure 2 suggests that the magnitudes of climate change and UHI impacts on heat are more or less in the range of 1–5 °C and their localized effects on ozone in the range of 1–15 ppb (1-h averages). The counteracting effects of cool cities on heat are in the range of 1–4 °C and on air quality, 1–11 ppb. This suggests that cool cities measures have the potential to locally offset most, if not all, of the local heat and air quality effects (ozone) of climate change and/or urban heat islands. This also suggests that the benefits of cool cities are significant enough, warranting further research to tailor the strategies for region specifics, maximize their local benefits, and minimize inadvertent effects.

Future efforts in optimizing the design and deployment of heat island control measures and analyzing their effects should also consider that the effectiveness of cool cities depends on geographical, microclimate, and regional weather characteristics as well as other physical properties, including size of urban areas, spatial characteristics, density of urbanization, and deployment potential for mitigation measures. The effectiveness of heat island control will also depend on interactions among the various measures (sometimes in a highly non-linear manner) with both positive and negative net effects as possible outcomes from these processes. Thus, it is useful to prioritize and rank the measures based on their indirect

impacts on the atmosphere and the consideration of all of these site-specific, local factors [20, 52]. Furthermore, feedbacks from chemistry to meteorology, e.g., radiative forcing, should also be examined further. For example, heat island control measures that can reduce air pollutant concentrations, such as NO, NO<sub>2</sub>, VOC, O<sub>3</sub>, and PM directly (e.g., deposition in vegetation canopies or reduction in emissions) or indirectly (e.g., slowing photochemical production of ozone because of lowered air temperatures) can also affect heating or cooling of the atmosphere because of changes in radiative forcing that result from changes in concentrations of gases and PM [8, 18, 36, 91].

Finally, future research on the effects of cool materials should also distinguish between and quantify the different effects of ground-based increases in albedo (pavements, parking lots, etc.) and the elevated canopy- or boundary-layer effects of roof- or wall-based increases in albedo. Current modeling capabilities and recent urban parameterizations in atmospheric models allow for fine-scale vertical resolution and distinction between these effects (elevated versus coupled to the ground). This is important in developing mitigation measures that are tailored to local-scale and site-specific characteristics in addition to general regional properties.

**Conflict of Interest** The corresponding author states that there is no conflict of interest.

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