THE IMPACT OF HEAT ISLAND REDUCTION STRATEGIES ON HEALTH-DEBILITATING OPPRESSIVE AIR MASSES IN URBAN AREAS

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Introduction

As part of the Heat Island Reduction Initiative (HIRI) program, there is interest in determining whether the number and/or severity of days that are detrimental to human health within selected urban areas will decrease if certain heat island reduction measures are instituted. Our previous research has indicated that certain "oppressive air masses" have been historically associated with increasing health problems related to heat, especially respiratory-related mortality, cardiac arrests, stroke, and of course, a variety of direct heat-related illnesses (Kalkstein, 1995). These particular air masses, most commonly an extreme form of dry tropical (DT) and moist tropical (MT), are beyond the human threshold of tolerance in many locales, especially for the elderly and infirm. Each air mass has a differing means of affecting the vulnerable components of the population. DT is the hottest and driest air mass, and its continued presence induces rapid moisture loss from the body, leading to dehydration. MT is not quite as hot but is more humid, inhibiting the ability of sweat to remove heat from the body. In either case, direct exposure to the air masses, or remaining within un-airconditioned indoor environments during their presence can lead to negative health outcomes. Indoors, these conditions are exacerbated in the upper floors of typical row homes, with black tar roofs, brick construction, and windows on only two sides. Of course, these are the urban environments where most heat-related deaths are recorded.

If a heat island reduction program is put in place, such as the "cool homes" project presently underway in Philadelphia (where inexpensive reflective surfaces are installed on the roofs of homes), or if there is an increase in urban vegetation, it is possible that these types of initiatives might significantly alter both the indoor and outdoor climate of an urban area. For example, is it possible that urban temperatures can be reduced significantly to the point that a day that might have been within an oppressive air mass will now be within a non-oppressive air mass? Even if the thermal alteration is not this dramatic, is it possible that a change of only a few degrees in temperature might save a significant number of lives? Our research has indicated that there is a large variation in urban mortality even within oppressive air masses, and a 1-2 degree reduction in outdoor temperature, along with some other meteorological changes, could reduce mortality by 10-20 percent (Chestnut et al., 1998; Kalkstein, 2000). There is every reason to believe that a similar reduction in indoor temperature might have a similar impact; certainly, individuals would not be comfortable, but even subtle temperature changes may mean the difference between life and death.

In addition, it is clear that reductions in nighttime temperature are at least as important in mitigating heat-related health problems as are similar reductions during the daytime (Kalkstein and Greene, 1997). How does the institution of heat reduction programs affect overnight temperatures both inside and outside the home? Finally, is there any detectible change in atmospheric humidity if heat reduction measures are taken? The impacts of cool initiatives and increasing vegetation are less clear as they apply to dew point temperature (a measure of atmospheric humidity); this will be explored as well within this analysis.

The goal of this project is to determine if the number of days within air masses historically associated with high mortality will decrease significantly if heat island reduction initiatives are put in place. In addition, we have developed a means to estimate daily heat-related mortality within these oppressive air masses, and we have calculated algorithms for various cities that forecast heat-related mortality assuming a variety of meteorological and non-meteorological conditions. Thus, an additional goal is an estimate of heat-related mortality reduction assuming heat island reduction measures are instituted.

Methods

Four cities were chosen for examination in this study: Detroit, Los Angeles, New Orleans, and Philadelphia. The cities were selected because they represent diverse climates and potentially react differently to the cool homes initiatives being evaluated here. In addition, two of the four cities are presently utilizing our heat/health watch warning systems as part of their strategy to lessen the negative health impacts of heat (Kalkstein et al., 1996). For each of the cities examined, the weather – mortality relationship was determined by the past response of the local population to different weather conditions. The initial step in this process was the standardization of both mortality and weather data.

Mortality data are available for the entire US in digital format for the period 1975 to 1998 (National Center for Health Statistics, 2001). As this research focuses on heat, only the "summer" period, May 1 to September 30, was analyzed for each year. For each day, total mortality across the city's metropolitan area was summed. These mortality totals were then standardized to account for demographic changes in the population characteristics over the 24-year period, including population aging and growth or a decline in the overall death rate for reasons unrelated to weather (e.g. in Rome, people leave the city in August to go on holiday, lowering the daily mortality significantly – this decrease must be included in standardization as it represents non-meteorological "noise").

Standardization proceeded on two levels. First, mean daily summer mortality was evaluated for the 24-year period, and a trend line was fit to these data. If there was a statistically significant trend, the data were standardized about this trend line, which generally reflects population growth in the urban area. For the four cities in this study, only Los Angeles required this type of standardization. At this level, nothing was done to determine whether an increasingly aging population is increasing general demographic sensitivity to heat; clearly, this is an addition to be made in the future. Second, an inter-seasonal standardization of mean daily mortality was developed. There is often a sizable inter-seasonal change in mortality that has to do with social/cultural factors, such as vacations and holidays (such changes are considered "noise", as they pollute the trends associated with weather). These are accommodated for by fitting a cubic spline to the trend existing in the inter-seasonal mean daily mortality data.

Standardization yielded a value of "anomalous mortality" above or below the established trend lines described above for each day in the period of record for each city. Thus, with considerable non-meteorological noise removed from the mortality data, evaluations proceeded using the newly-created anomalous mortality variable.

The weather data were supplied by NOAA's National Environmental Satellite, Data, and Information Service (2000) and are standardized by an air-mass classification procedure. This procedure determines which of several air masses has occurred over a particular city on a particular day, and accounts for the time of year by standardizing for seasonal variability in meteorological conditions. For this research, the Spatial Synoptic Classification (SSC) was utilized (Sheridan, 2002), which represents our latest iteration to develop a state-of-the-art air mass classification procedure. The SSC places every day into one of a number of air mass types listed below. The procedure commences by selecting "seed days", or days in each locale that are most representative of each air mass type. This requires a priori information about the meteorological character of each air mass, something that we, as synoptic climatologists, have considerable knowledge about. Thus, each air mass type is represented by a small subset of days that we know best represent each of the types at each locale.

Once the seed days are selected, all of the remaining days are placed into an air mass group based on a "nearest neighbor" approach described in Sheridan (2002). Thus, through tests of similarity, we determine which group of air mass seeds a particular day is closest to. The procedure even has the ability to determine how good a fit the particular day is; for example, is a day very close to the typical meteorological character of a particular air mass, or is it somewhere between two air mass types?

The SSC procedure required the input of observations of the following weather parameters at each city, four times a day:

- Temperature,
- Dew point,
- Barometric Pressure,
- Wind Speed and Direction, and
- Cloud Cover.

Each of these parameters is weighed somewhat similarly (i.e. there is no exposure to procedures like principle components analysis to determine the role each parameter plays in explaining meteorological variance), and through considerable testing, the final categorization of days is robust both spatially and temporally.

The following are the air mass types within the SSC:

- Dry Polar (DP)
- Dry Moderate (DM)
- Dry Tropical (DT)
- Moist Polar (MP)
- Moist Moderate (MM)
- Moist Tropical (MT)
- Moist Tropical Plus (MT+)
- Moist Tropical Double Plus (MT++; New Orleans only)
- Transition (TR)

The mean meteorological characteristics of these air masses for July are illustrated in Table 1.

TABLE 1

Mean July Air Mass Characteristics for the Evaluated Cities

DETROIT	**DM**	**DP**	**DT**	**MM**	**MP**	**MT**	**MT+**	**TR**
5PM Temperature (°C)	28.3	23.5	34.9	23.4	20.1	28.9	32.3	26.9
5AM Temperature (°C)	16.1	12.7	20.1	19.1	14.7	20.2	22.9	19.1
5PM Dew Point (°C)	14.1	9.9	16.0	17.7	14.0	19.2	22.1	15.5
Wind Direction	SW	N	W	SW	NE	SW	SW	NW
Wind Speed (km/h)	13.0	12.6	15.8	13.7	14.8	*	*	17.3
Cloud Cover (tenths)	3.2	3.3	3.3	8.1	8.3	6.7	5.4	5.7

LOS ANGELES	**DM**	**DP**	**DT**	**MM**	**MP**	**MT**	**MT+**	**TR**
5PM Temperature (°C)	23.2	0.0	30.8	22.0	19.7	26.4	29.2	26.3
5AM Temperature (°C)	17.9	0.0	20.7	17.8	15.7	20.8	22.2	20.3
5PM Dew Point (°C)	15.5	0.0	11.7	16.1	14.7	17.6	18.8	15.0
Wind Direction	SW	SW	SW	W	W	SW	SW	SW
Wind Speed (km/h)	12.6	11.2	10.8	12.6	12.2	*	*	11.5
Cloud Cover (tenths)	3.1	0.0	2.7	6.5	6.8	2.4	3.2	2.8

NEW ORLEANS	**DM**	**DP**	**DT**	**MM**	**MP**	**MT**	**MT+**	**MT++**	**TR**
5PM Temperature (°C)	31.3	27.2	35.0	27.0	0.0	31.1	34.1	35.0	31.1
5AM Temperature (°C)	21.6	22.2	22.8	23.7	0.0	24.1	26.0	26.9	24.7
5PM Dew Point (°C)	20.6	14.4	18.9	22.7	0.0	23.0	23.9	24.3	22.9
Wind Direction	E	NE	W	SW	NE	SW	SW	SW	W
Wind Speed (km/h)	9.0	15.5	6.8	9.7	0.0	*	*	*	11.9
Cloud Cover (tenths)	3.6	0.5	1.0	7.6	0.0	6.6	5.2	5.2	5.7

PHILADELPHIA	**DM**	**DP**	**DT**	**MM**	**MP**	**MT**	**MT+**	**TR**
5PM Temperature (°C)	28.9	25.3	34.5	25.1	19.5	30.0	33.1	27.7
5AM Temperature (°C)	18.4	15.6	22.7	20.9	18.0	21.9	24.2	21.0
5PM Dew Point (°C)	13.9	12.0	17.3	19.7	16.0	19.9	22.4	15.6
Wind Direction	W	NW	W	SW	NE	SW	SW	NW
Wind Speed (km/h)	12.6	12.2	13.7	12.6	15.1	*	*	16.6
Cloud Cover (tenths)	3.4	3.6	3.7	9.3	9.3	6.3	5.1	5.6

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*data not available

The DP air mass is associated with relatively cool, dry weather originating from upper latitudes of continental North America. Overnight temperatures are very comfortable, and humidity is not a problem. Skies are usually clear to partly cloudy. DP air rarely reaches Los Angeles, and as Table 1 indicates, is absent there in the summer.

The DM air mass is generally warmer than DP, and is associated with pleasant dry summer weather. While the DP source region is central Canada, DM air originates west of the Rockies, and it is dried and warmed adiabatically as it travels eastward and descends the mountains. There is little human stress associated with either DM or DP air.

DT is an oppressively hot and dry air mass that originates over desert regions of the U.S. and Mexico. It is transported eastward in summer when there is a more active than normal subtropical jet stream. This permits a relatively unmodified version of DT to make its way to the major metropolitan areas of the Midwest and East. When East Coast temperatures top 100 degrees, DT is the responsible air mass. Low moisture content diminishes the specific heat of the atmosphere, permitting a rapid temperature warm-up similar to that found over deserts.

MM is an uncommon summer air mass often associated with stationary fronts extending east-west across a region. This air mass is associated with rather cool, humid conditions and overcast skies. Often, this air mass is described as “frontal overrunning”, where warm, humid tropical air overlies denser cool and moist air, creating an atmospheric inversion. This air mass is generally non-consequential in summer.

MP is an even cooler version of the MM air mass, and occurs well to the north of a mid-latitude cyclone and associated front. Winds are generally from the east around the southern flank of a cool polar high pressure center. Skies are overcast, and precipitation is often associated with this air mass. It is very rare in summer and quite common in winter; New Orleans has no MP air in July.

The MT air mass is an uncomfortably hot and humid condition frequently occurring during summer. The air mass is often associated with the well-known subtropical “Bermuda high”, and upper level steering currents are weak, often permitting this condition to last for a number of consecutive days.

A more extreme subset of this air mass is MT+, which possesses a higher temperature and dew point than MT. Like DT, this air mass is often associated with statistically significantly higher mortality. Temperatures are not quite at DT levels but are nevertheless warm, with average 5PM readings exceeding 32 degrees C (90 degrees F) at all locations but Los Angeles. Excessive dew points inhibit human sweat evaporation rates, and create very uncomfortable conditions. In New Orleans, an even more uncomfortable air mass, MT++, has been identified. AT 5PM, average temperatures are 35 degrees C (95 degrees F), and paired with dew point temperatures near 27 degrees C (80 degrees F), this air mass is truly the purest form of MT.

The final air mass type is Transition (TR), which is really not an air mass at all, but a transition from one air mass type to the next. TR most frequently occurs with frontal passages. Considerable European research has indicated that the TR air mass has a negative impact on human health (McMichael et al., 1996), but our research has been unable to find any heat-debilitating indications within TR.

Mean anomalous mortality was then calculated for the occurrence of each weather type. In all four cities, the DT and MT+ air masses were associated with the greatest increase in mortality above normal levels, although the degree of increase varied from one city to the next. These same weather types were also associated with the greatest variability in observed mortality, indicating that, although most of the highest mortality days occur during these “offensive” air masses, there are some days within these air masses that do not have elevated mortality. To account for this variability, a stepwise linear regression equation was developed for each offensive air mass in each city to predict excess mortality. These equations accounted for the following:

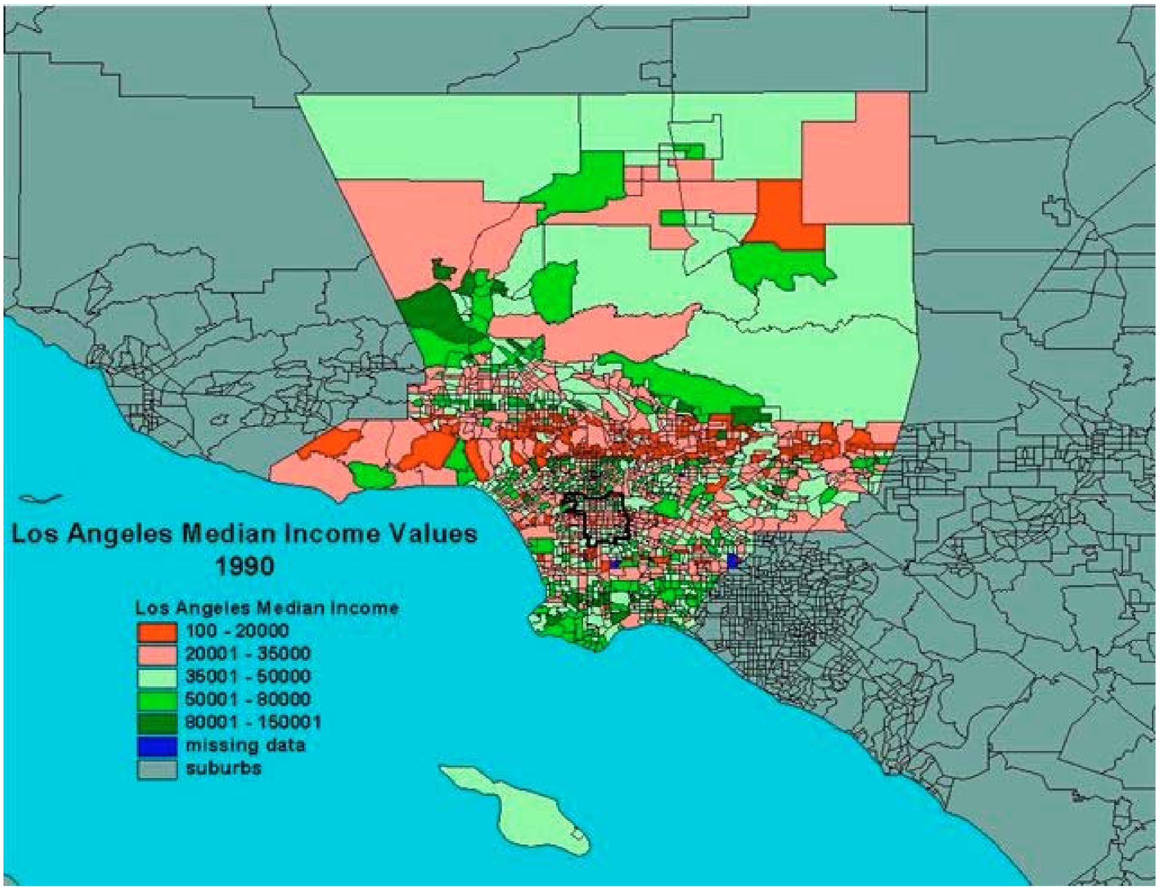
- Time of season,
- Persistence of an oppressive air mass, and
- Air mass character, including temperature, humidity, and cloud cover.

For Detroit, Los Angeles, and Philadelphia, Dry Tropical (DT) and Moist Tropical Plus (MT+) were most “offensive”; for New Orleans, MT+ and Moist Tropical Double Plus (MT++) were most offensive.

To test the impacts of alternate rooftops upon mortality estimates, MM5-derived meteorological model data for several different scenarios were provided by Professor David Sailor of Tulane University (presently at Portland State University) for the cities of Detroit, New Orleans, and Philadelphia, and Dr. Haider Taha of Altostratus for Los Angeles**.** The MM5 derived model data permit us to determine air mass type and character after assumptions are made regarding increased albedo because of the addition of reflective roofs, and changes in surface structure and energy disposition because of added urban vegetation. Variables provided to us from Drs. Sailor and Taha (including temperature, dew point, wind speed and direction, and cloud cover at least four times each day) allowed us to redevelop the air mass classification for each of the cities.

We provided Drs. Sailor and Taha with the locations of urban areas within each city that possessed a majority of the population most vulnerable to heat-related morbidity and mortality (usually the poorest sections of the city in terms of economics and housing stock – refer to Figure 1 for an example).

Figure 1: Isolating Vulnerable Areas in Los Angeles



For each of the four cities, several heat waves between the period 1994 and 2001 were analyzed. Different scenarios were evaluated:

- For Detroit, New Orleans, and Philadelphia, both a “High Albedo” and “High Vegetation” scenario were evaluated. Two exceptions were made
    - for the late July 1999 heat wave in Philadelphia, a “High Albedo” and “Double High Albedo” were run;
    - for the 1995 heat wave in Detroit, five situations were evaluated: “High Albedo”, “High Vegetation”, “High Vegetation and Albedo”, “Double High Albedo”, and “Double High Vegetation” scenarios.
- For Los Angeles, two scenarios were evaluated for all heat waves: “High Albedo” and “Moderate Vegetation and Albedo.”

For Detroit, New Orleans, and Philadelphia, the modeling domains consisted of multiple nests with the finest mesh having 2km resolution over each metropolitan area of interest. Total areas evaluated were within 50-100 km^2. Within these finest nests all urban land was characterized as being residential, commercial/industrial, or urban core. While each of these land use classes has its distinct set of surface characteristics, the application of albedo and vegetation schemes followed a standard approach. Specifically, the "high albedo" modification was accomplished by increasing the albedo of every urban grid cell (whether residential, commercial/industrial, or urban core) uniformly by 0.10 (base is 0.15). The "double-high" albedo modification corresponded to an increase of 0.20. These levels of albedo augmentation are considered realistic and could be achieved in many cities through a combination of roofing and paving projects. The scenarios investigated here, however, do not attempt to model a specific implementation, but rather provide a more general sensitivity analysis. Vegetation modification followed a similar methodology with "high vegetation" corresponding to a nominal increase in vegetative cover by 0.10 for all urbanized cells.

For Los Angeles, the “high albedo” modification assumed the following assumptions for albedo increases:

Residential roofs:	increase of	0.30	(base=0.15)
Commercial roofs:	increase of	0.40	(base=0.20)
Roads:	increase of	0.25	(base=0.10)
Sidewalks/Driveways:	increase of	0.20	(base=0.15)
Parking lots:	increase of	0.25	(base=0.10)

For the “moderate vegetation, moderate albedo” scenario, the albedo increases were more conservative: residential roofs, sidewalks/driveways increase by 0.10, roads and parking lots increase by 0.15, and commercial roofs increase by 0.20. In addition, the following assumptions were made regarding increased vegetation: for all land use classes with the exception of industrial and transportation/communication, there was an increase of four trees per building unit. For industrial, this increase was six trees per building unit, and for transportation/communication, there was no increase of trees.

The grid resolution for the Los Angeles simulation was 5 km, and the evaluation was done over an area of 150 km^2.

All of these scenarios estimate the microscale changes in atmospheric temperature, dew point, and wind in each city due to roof enhancement and increasing vegetation. The modifications were then entered into the weather – mortality model, to predict:

- Whether the day remains within an offensive air mass, and if so,
- The change in estimated anomalous mortality due to different weather conditions.

Air masses are mesoscale meteorological features, and thus, the same air mass virtually always exists over the entire modeled area. There are no scale issues to deal with; any changes in meteorology suggested by the MM5 model are directly inputted into the SSC, and a determination is then made as to whether the changes were significant enough to cause an air mass shift.

Results: Meteorology Changes

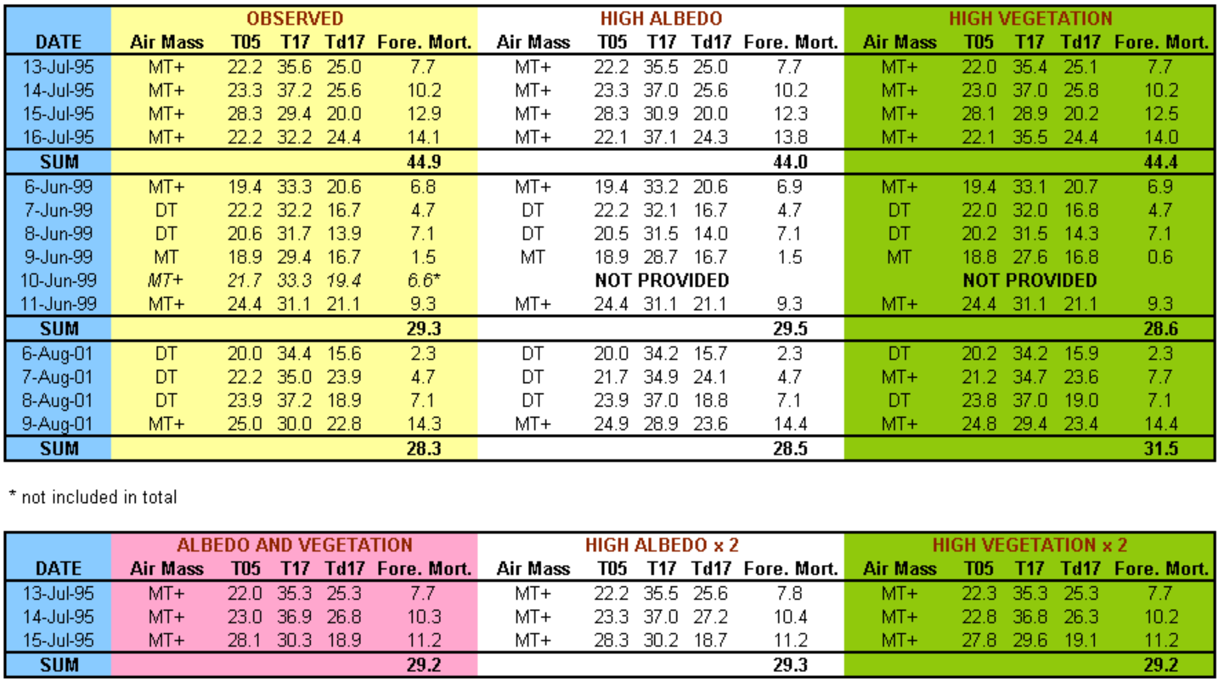
The evaluation methodology for all four cities was identical and based on the procedures outlined above. The only exception was the MM5 assumptions described previously. Since the data were received from two different sources (Sailor for Detroit, New Orleans, and Philadelphia, and Taha for Los Angeles) there were some differences as well in the timing of the data that were sent to us.

The types of heat waves among the cities varied somewhat based on local climatology. For Detroit and Philadelphia, the two major heat wave types are the very warm and humid MT+, and the exceedingly hot but less humid DT. Sometimes both air mass types occurred during the string of days that constituted a heat wave. For example, the June 22-26, 1997 heat wave in Philadelphia consisted of two MT+ days surrounding three DT days. This is not uncommon; as pressure systems shift during a persistent heat wave, it is possible that surface and upper level wind patterns can transport dry desert air on one day and moist tropical air on another. However, the air masses usually do not shift back and forth from one day to the next; it is clear that there are usually consecutive day runs of a certain air mass as seen in Figure 1. As opposed to the two mid-latitude cities in this study, New Orleans almost never has an intrusion of DT air, and thus all of the heat waves are either MT+ or the superhumid MT++, which is generally limited to the Deep South. Los Angeles is rarely impacted by MT+ because it is far from the main source region and resides on a relatively cool water body. Any MT or MT+ air must come from the Gulf of California or even further south. Considering the limited extent of this water body, MT+ air is a rarity. DT heat waves are usually more common, and are associated with the well-known Santa Ana condition, with a large surface anticyclone over the Great Basin and easterly winds over the Los Angeles Basin. The elevation decreases as you travel east through the Basin, creating adiabatic warming conditions and exceedingly hot, dry weather for Los Angeles.

For all four cities, relative changes in both the high albedo and high vegetation scenarios were small during overnight hours (T05; T02 was used for Los Angeles as it was in our available 6 hour dataset for that city and T05 was not), with a general decrease of up to 1°C in afternoon temperatures (T17; T14 was used for Los Angeles), concomitant with a slight increase in dew point (refer to attached figures). It makes intuitive sense that afternoon temperatures may be affected more significantly by cooling scenarios than overnight temperatures. The impact of increasing roof albedo should be more important during daylight hours, when their ability to reflect incoming solar radiation is at a maximum.

There were some important differences in response among the cities. For Detroit (Figure 2), very little change in meteorology was noted during the first two heat waves we evaluated (July, 1995 and June, 1999), and higher albedo and/or increased vegetation only altered temperatures by 0.1 or 0.2°C. During the third heat wave (August, 2001), changes were a bit more significant, with the MT+ day cooling by over 1°C during the afternoon. An additional doubling of the albedo coefficient still did not provide much in the way of temperature modifications in Detroit. Only one day switched air masses in Detroit – August 7, 2001 – which under a high vegetation scenario went from one oppressive air mass (DT) to another (MT+).

FIGURE 2: SCENARIOS FOR DETROIT



	OBSERVED					HIGH ALBEDO					HIGH VEGETATION				
DATE	**Air Mass**	**T05**	**T17**	**Td17**	**Fore. Mort.**	**Air Mass**	**T05**	**T17**	**Td17**	**Fore. Mort.**	**Air Mass**	**T05**	**T17**	**Td17**	**Fore. Mort.**
13-Jul-95	MT+	22.2	35.6	25.0	7.7	MT+	22.2	35.5	25.0	7.7	MT+	22.0	35.4	25.1	7.7
14-Jul-95	MT+	23.3	37.2	25.6	10.2	MT+	23.3	37.0	25.6	10.2	MT+	23.0	37.0	25.8	10.2
15-Jul-95	MT+	28.3	29.4	20.0	12.9	MT+	28.3	30.9	20.0	12.3	MT+	28.1	28.9	20.2	12.5
16-Jul-95	MT+	22.2	32.2	24.4	14.1	MT+	22.1	37.1	24.3	13.8	MT+	22.1	35.5	24.4	14.0
SUM					**44.9**					**44.0**					**44.4**
6-Jun-99	MT+	19.4	33.3	20.6	6.8	MT+	19.4	33.2	20.6	6.9	MT+	19.4	33.1	20.7	6.9
7-Jun-99	DT	22.2	32.2	16.7	4.7	DT	22.2	32.1	16.7	4.7	DT	22.0	32.0	16.8	4.7
8-Jun-99	DT	20.6	31.7	13.9	7.1	DT	20.5	31.5	14.0	7.1	DT	20.2	31.5	14.3	7.1
9-Jun-99	MT	18.9	29.4	16.7	1.5	MT	18.9	28.7	16.7	1.5	MT	18.8	27.6	16.8	0.6
10-Jun-99	*MT+*	*21.7*	*33.3*	*19.4*	*6.6**	**NOT PROVIDED**					**NOT PROVIDED**				
11-Jun-99	MT+	24.4	31.1	21.1	9.3	MT+	24.4	31.1	21.1	9.3	MT+	24.4	31.1	21.1	9.3
SUM					**29.3**					**29.5**					**28.6**
6-Aug-01	DT	20.0	34.4	15.6	2.3	DT	20.0	34.2	15.7	2.3	DT	20.2	34.2	15.9	2.3
7-Aug-01	DT	22.2	35.0	23.9	4.7	DT	21.7	34.9	24.1	4.7	MT+	21.2	34.7	23.6	7.7
8-Aug-01	DT	23.9	37.2	18.9	7.1	DT	23.9	37.0	18.8	7.1	DT	23.8	37.0	19.0	7.1
9-Aug-01	MT+	25.0	30.0	22.8	14.3	MT+	24.9	28.9	23.6	14.4	MT+	24.8	29.4	23.4	14.4
SUM					**28.3**					**28.5**					**31.5**

* not included in total

	ALBEDO AND VEGETATION					HIGH ALBEDO x 2					HIGH VEGETATION x 2				
DATE	**Air Mass**	**T05**	**T17**	**Td17**	**Fore. Mort.**	**Air Mass**	**T05**	**T17**	**Td17**	**Fore. Mort.**	**Air Mass**	**T05**	**T17**	**Td17**	**Fore. Mort.**
13-Jul-95	MT+	22.0	35.3	25.3	7.7	MT+	22.2	35.5	25.6	7.8	MT+	22.3	35.3	25.3	7.7
14-Jul-95	MT+	23.0	36.9	26.8	10.3	MT+	23.3	37.0	27.2	10.4	MT+	22.8	36.8	26.3	10.2
15-Jul-95	MT+	28.1	30.3	18.9	11.2	MT+	28.3	30.2	18.7	11.2	MT+	27.8	29.6	19.1	11.2
SUM					**29.2**					**29.3**					**29.2**

FIGURE 3: SCENARIOS FOR NEW ORLEANS

	OBSERVED					HIGH ALBEDO					HIGH VEGETATION				
DATE	Air Mass	T05	T17	Td17	Fore. Mort.	Air Mass	T05	T17	Td17	Fore. Mort.	Air Mass	T05	T17	Td17	Fore. Mort.
31-May-98	MT+	26.1	34.4	24.4	1	MT+	26.2	33.3	24.7	1	MT+	26.2	35.1	24.7	1
1-Jun-98	MT+	25.6	35.0	23.9	1	MT+	25.6	35.3	23.8	1	MT+	25.6	35.4	23.8	1
2-Jun-98	MT+	25.6	33.3	22.2	1	MT+	25.5	33.2	22.2	1	MT+	25.6	33.2	22.2	1
SUM					**3**					**3**					**3**
16-Jun-98	MT++	27.2	33.9	25.0	4	MT+	27.2	33.4	25.0	1	MT+	27.2	33.0	25.0	1
17-Jun-98	MT+	26.1	33.3	25.0	1	MT+	25.9	32.5	25.1	1	MT+	26.0	32.8	25.6	1
18-Jun-98	MT+	27.2	34.4	23.9	1	MT+	27.2	34.4	24.1	1	MT+	27.1	34.3	23.6	1
SUM					**6**					**3**					**3**
14-Jul-00	MT++	27.2	36.1	24.4	4	MT++	27.2	39.1	23.0	4	MT++	27.0	38.8	23.1	4
15-Jul-00	MT+	26.7	36.1	21.7	1	MT+	26.7	35.8	22.0	1	MT+	26.4	35.6	22.8	1
16-Jul-00	MT+	26.7	36.1	22.8	1	MT+	26.8	35.5	23.0	1	MT+	26.8	35.9	22.8	1
17-Jul-00	MT+	27.2	35.0	22.8	1	MT+	27.2	35.2	22.6	1	MT+	27.2	35.2	22.5	1
18-Jul-00	MT++	27.8	35.0	25.6	4	MT++	27.9	34.9	25.4	4	MT++	27.7	35.0	25.5	4
SUM					**11**					**11**					**11**

	ALBEDO AND VEGETATION					HIGH ALBEDO x 2					HIGH VEGETATION x 2				
DATE	Air Mass	T05	T17	Td17	Fore. Mort.	Air Mass	T05	T17	Td17	Fore. Mort.	Air Mass	T05	T17	Td17	Fore. Mort.
13-Jul-95	MT+	22.0	35.3	25.3	7.7	MT+	22.2	35.5	25.6	7.8	MT+	22.3	35.3	25.3	7.7
14-Jul-95	MT+	23.0	36.9	26.8	10.3	MT+	23.3	37.0	27.2	10.4	MT+	22.8	36.8	26.3	10.2
15-Jul-95	MT+	28.1	30.3	18.9	11.2	MT+	28.3	30.2	18.7	11.2	MT+	27.8	29.6	19.1	11.2
SUM					**29.2**					**29.3**					**29.2**

FIGURE 4: SCENARIOS FOR PHILADELPHIA

	OBSERVED					HIGH ALBEDO					HIGH VEGETATION				
DATE	Air Mass	T05	T17	Td17	Fore. Mort.	Air Mass	T05	T17	Td17	Fore. Mort.	Air Mass	T05	T17	Td17	Fore. Mort.
22-Jun-97	MT+	24.4	30.0	22.8	4.1	MT+	24.3	29.1	22.4	3.3	MT+	24.3	29.8	22.9	3.6
23-Jun-97	DT	20.0	31.1	10.6	5.3	DT	19.8	31.0	10.7	5.4	DT	19.8	30.9	11.0	5.5
24-Jun-97	DT	17.8	31.7	18.3	12.9	DT	17.6	31.2	18.6	13.1	DT	17.7	31.0	18.7	13.2
25-Jun-97	DT	22.2	34.4	18.3	14.6	DT	22.1	34.3	18.3	14.6	MT+	21.9	34.1	18.6	8.9
26-Jun-97	MT+	24.4	30.0	18.3	9.3	MT+	24.3	29.4	19.8	7.1	MT+	24.1	29.7	20.0	7.3
SUM					**46.3**					**43.5**					**38.5**
3-Jul-99	MT+	23.3	32.2	22.8	4.7	MT+	23.3	32.0	23.2	4.0	MT+	23.3	31.9	23.4	3.8
4-Jul-99	DT	25.0	36.1	22.2	15.8	DT	24.8	36.5	22.3	15.9	DT	24.8	36.4	22.4	16.1
5-Jul-99	DT	28.3	37.2	21.1	14.5	DT	28.2	37.0	20.9	14.4	DT	28.2	36.9	21.4	14.8
6-Jul-99	DT	26.7	36.1	22.8	16.2	DT	26.6	35.0	23.2	16.6	DT	26.6	36.0	22.9	16.3
7-Jul-99	DT	27.8	32.2	14.4	7.0	DT	27.8	32.1	14.5	7.1	DT	27.7	31.9	14.8	7.4
8-Jul-99	DT	21.7	32.8	8.9	1.0	DT	21.3	32.7	9.0	1.1	DT	21.3	32.6	9.4	1.5
SUM					**59.0**					**59.1**					**59.9**
23-Jul-99	MT+	24.4	33.9	18.3	9.9	MT+	24.3	33.9	18.3	9.8	MT+	24.2	33.8	18.4	9.6
24-Jul-99	MT+	26.1	32.8	21.7	5.3	MT+	26.0	32.8	21.9	5.1	MT+	25.9	32.6	21.9	4.8
25-Jul-99	DT	24.4	35.0	10.6	2.2	DT	24.2	34.9	11.0	2.7	DT	24.0	35.0	10.8	2.8
26-Jul-99	DT	24.4	32.8	18.9	7.4	DT	24.3	32.5	19.1	7.6	DT	24.1	32.4	19.2	7.8
27-Jul-99	MT+	24.4	33.9	22.2	7.9	MT	24.3	33.5	22.4	1.3	MT	24.2	32.9	22.4	1.5
28-Jul-99	DT	26.1	33.3	20.0	5.4	DT	26.0	32.8	20.6	5.8	DT	26.0	31.9	20.9	6.3
29-Jul-99	MT	22.2	32.2	19.4	0.6	MT	21.5	32.4	19.3	1.1	MT	22.0	32.4	19.1	0.7
SUM					**38.6**					**33.4**					**33.5**

*Note mint color represents Double High Albedo

FIGURE 5: SCENARIOS FOR LOS ANGELES

DAY	OBSERVED					Case 20					Case 11				
	Air Mass	T02	T14	Td14	Fore. Mort	Air Mass	T02	T14	Td14	Fore. Mort	Air Mass	T02	T14	Td14	Fore. Mort
10-Aug-94	MT	21.7	27.8	15.6	8.1	DM	21.6	26.8	15.3	6.0	MT	21.7	27.5	15.5	7.4
11-Aug-94	MT	21.7	27.2	16.1	6.7	DM	21.5	25.9	15.7	4.0	MT	21.7	26.9	15.8	6.1
12-Aug-94	MT	20.0	28.9	18.6	10.3	MT	19.9	29.0	18.3	10.5	MT	20.0	28.5	18.1	9.4
13-Aug-94	MT+	24.4	31.1	17.2	28.9	MT+	24.4	30.2	16.9	25.7	MT+	24.4	30.8	17.1	27.8
14-Aug-94	MT+	23.3	28.9	20.0	17.9	MT	23.0	27.8	19.7	14.3	MT+	23.3	28.5	19.9	16.5
15-Aug-94	MT	22.2	29.4	16.7	11.2	MT	22.1	28.4	16.5	9.1	MT	22.2	29.1	16.6	10.5
Total					**83.1**					**69.5**					**77.9**
8-Oct-94	DT	17.8	33.9	4.4	5.4	DT	17.7	33.1	4.1	5.1	DT	17.8	34.1	4.5	5.4
9-Oct-94	DT	22.2	35.6	4.4	20.4	DT	22.0	34.6	4.1	19.7	DT	22.2	35.7	4.4	20.4
10-Oct-94	DT	23.3	31.1	5.0	24.1	DT	23.4	30.0	4.8	24.5	DT	23.4	30.2	4.8	24.5
Total					**49.9**					**49.2**					**50.3**
14-Oct-97	DT	20.6	35.0	-0.6	14.9	DT	20.6	33.8	-0.9	14.9	DT	20.6	35.3	-0.6	14.9
15-Oct-97	DT	23.3	34.4	2.8	24.1	DT	23.1	33.0	2.5	23.4	DT	23.3	34.4	2.8	24.1
16-Oct-97	DT	23.9	31.1	8.3	26.2	DT	23.3	29.9	8.0	24.1	DT	23.9	31.2	8.3	26.2
Total					**65.2**					**62.5**					**65.2**
8/29/1998	MT	20.0	28.9	16.7	9.3	MT	20.0	27.5	16.3	6.3	MT	19.9	28.6	16.6	8.6
30-Aug-98	MT	22.8	29.4	18.9	10.3	MT	22.6	28.4	29.1	8.2	MT	22.7	29.2	18.8	9.9
31-Aug-98	MT	21.1	27.2	19.4	5.5	MT	20.9	25.8	19.0	2.6	MT	21.1	26.8	19.3	4.7
1-Sep-98	MT+	22.2	28.3	20.0	12.6	MT	22.0	27.3	19.7	8.7	MT	22.2	27.5	19.8	9.0
2-Sep-98	MT	22.2	27.2	20.0	5.4	MT	22.1	26.4	19.7	3.7	MT	22.2	26.1	19.8	3.1
3-Sep-98	MT+	22.2	29.4	19.4	16.5	MT+	22.1	29.4	19.1	16.2	MT+	22.1	29.3	19.3	15.8
Total					**59.6**					**45.6**					**51.1**

New Orleans and Philadelphia results were more interesting. In New Orleans (Figure 3), there were some significant thermal changes induced by increasing albedo and vegetation. Although morning temperature changes were minimal (T05), afternoon temperatures (T17) were altered somewhat. For example, May 31, 1998 showed a temperature decrease of about 1.1°C with the high albedo scenario. A reduction of 0.8°C occurred on June 17, 1998 in the afternoon. However, several days showed some increases in afternoon temperature, the biggest occurring on July 14, 2000. The high vegetation scenario demonstrated smaller temperature changes than the high albedo scenario in New Orleans. Only one day switched air masses in New Orleans – June 16, 1998, which went from a very oppressive MT++ to a less oppressive MT+.

In Philadelphia (Figure 4), the high albedo scenario generally led to modest decreases in temperature. This was especially true in the afternoon. However, on many days, this was compensated by increases in dew point temperature, especially for the high vegetation scenario. There was one day that exhibited a major air mass shift – July 27, 1999, where the day was altered from an oppressive MT+ to a less oppressive MT. June 25, 1997 also demonstrated an air mass change from DT in the control and high albedo situation to a less oppressive MT+ in the high vegetation scenario. Based on mortality forecasts, it is clear that DT is the most oppressive air mass in Philadelphia.

The results in Los Angeles (Figure 5) were most unique in that there were two different “types” of heat wave evaluated. The August 1994 and 1998 heat waves were warm and humid (MT type air masses), while the October 1994 and 1997 heat waves were hot and dry (DT type air masses). The changes in atmospheric conditions were generally more pronounced with high albedo than with moderate vegetation and albedo. In a number of cases, afternoon temperature decreased by over 1 degree C in the high albedo case, regardless of the air mass. This was a larger decrease than was recorded for the other three cities. Morning temperature decreases were considerably more modest.

The conditions during the hot and dry heat waves were so extreme that neither albedo nor vegetation changes modified any of the days’ air masses into different categories. In contrast, the more humid heat waves were more significantly altered in terms of air mass type; this was particularly true with the August 1994 heat wave, where three of six days in the high albedo scenario changed air mass designation to more benign categories.

Results: Mortality Changes

Mean daily mortality for offensive air masses (assuming no heat island reduction initiatives are in place) in all four cities are well above the summer baseline (Table 2). For Detroit, during MT+ days (these occur about 6 percent of the time during a typical summer), mortality averages almost 8 deaths above the baseline. The impact of DT air (2.8 percent summer frequency) is somewhat less, but daily mortality is still statistically significantly above the long-term summer baseline. In Los Angeles, DT (0.9 percent during an average summer) appears to have a slightly greater impact than MT+ (1.5 percent) in terms of increasing mortality. In New Orleans, MT+, which occurs rather commonly (14 percent), increases mortality by about one death, while the more extreme MT++ (3.5 percent) contributes to greater mortality. For Philadelphia, DT (4.5 percent of typical summer days) and MT+ (9.5 percent) both contribute over 3 excess deaths above the baseline. Thus, these air masses are truly dangerous with regard to increasing mortality in all the cities.

TABLE 2
Mean Daily Mortality Above Baseline Values for Offensive Synoptic Categories

CITY	AIR MASS TYPE	EXCESS MORTALITY
Detroit	DT	4.7
	MT+	7.7
Los Angeles	DT	18.0
	MT+	14.0
New Orleans	MT+	1.0
	MT++	4.0
Philadelphia	DT	3.4
	MT+	3.4

Initial results when instituting the MM5 models suggest that a sharp decrease in mortality occurred if a day “jumped” from an offensive air mass to a non-offensive one, since no anomalous mortality would be calculated for the non-offensive day. To remedy this situation, a separate mortality regression equation was also calculated for non-offensive days that bordered on the offensive.

In Philadelphia, some decreases in expected mortality of around 5 deaths per heat wave were observed in two of the three heat waves (Figure 4). During the hottest of the three heat waves, July 3-8, 1999, when temperatures exceeded

100°F with a dew point of 70°F, virtually no change in mortality was observed. Every day but one during this heat wave was represented by a DT air mass. Differences among the heat waves suggest that, on days that are not quite as hot but already humid (MT+), mortality generally decreases. For example, on July 27, 1999, a hot, humid MT+ air mass was present, and based on the high albedo and high vegetation scenario, the day was modified to a less oppressive MT. This resulted in a mortality reduction of approximately 6 deaths. On hot and dry days however, the added moisture (as represented by a slightly higher dew points under the higher albedo and higher vegetation scenarios) offsets the slightly lower, but still very high, temperature, yielding minimal if any changes in mortality. In fact, in some cases, slight increases in mortality are noted. Only when temperatures are reduced enough to remove the day from the DT category do we find any mortality reductions, as explained below.

Comparing the different model runs, the comparative benefits of white roofs versus that of greater vegetation is uncertain. During the 1997 heat wave, mortality decreased more significantly in the high vegetation scenario (-8 deaths) than the high albedo scenario (-3 deaths). However, the high vegetation scenario was forecast to have an increase of +1 death during the early July 1999 heat wave, compared with no change in the high albedo run. In Philadelphia, the comparison of high albedo with double high albedo scenarios during the later July 1999 heat wave provided little distinction: both were associated with a forecast decrease of 5 deaths. It appears that, of the three cities, higher vegetation in Philadelphia had the greatest mitigating effect on mortality. This is because a lowering of temperature (to remove a day from the deadliest DT category) more than compensated for any increase in dew point that the high vegetation induced (MT+ was less offensive, from a mortality standpoint, than DT).

Thus, for Philadelphia, it appears that major reductions in mortality occur on a few days when the modified scenarios produce a change in air mass type.

During the three heat waves evaluated, this occurred on two days, June 25, 1997 and July 27, 1999. Thus out of 18 total days evaluated, 2 experienced air mass changes that led to significant mortality decreases. This represents 11 percent of total heat wave days evaluated.

It appears that during the very hottest DT heat wave, neither mitigation activity seems to yield much improvement in Philadelphia. However, during heat waves when the more humid MT air masses are present, there appear to be some significant benefits, and both heat waves with more MT representation showed mortality decreases averaging 15-20 percent. Higher vegetation seemed most beneficial during the somewhat cooler 1997 heat wave, and higher albedo was of greater importance during the hotter late July, 1999 heat wave.

Results for Detroit (Figure 2) suggest that alternate roofs and increased vegetation have a lesser effect upon meteorological conditions than in Philadelphia, as differences in temperature and dew point are generally within 0.5°C. Mortality differences are similarly minimal, with no difference of greater than one death in any of the high albedo or high vegetation runs, except for an increase of 3 deaths with high vegetation during the 2001 heat wave. The 1995 heat wave was also run with three additional scenarios, as described above. All three of these were associated with an estimated decrease in mortality of 1.5 deaths, attributable to a considerable dew point decrease on July 15th. This response is unlike what we found in Philadelphia, where modified scenarios led to slight dew point increases. The negative impact of dew point increases is dramatically demonstrated on one of the heat wave days, August 7, 2001, where the increased vegetation scenario led to an air mass change from DT to MT+. Unlike Philadelphia, where such a change led to a mortality decrease, this change in Detroit was associated with a mortality increase of about three deaths. Some of these differences between the two cities may be due to the different housing stock; row homes represent a much smaller proportion of the housing than they do in Philadelphia. Finally, none of the changes in Detroit led to a shift in air mass type except for one counterproductive shift on 7 August 2001 from DT to MT+. This is clearly a difference from the Philadelphia result, where two days exhibited air mass shifts and associated significant drops in mortality.

Results for New Orleans (Figure 3) are different than those obtained for the two mid latitude cities above. First, Dry Tropical weather virtually never occurs in New Orleans, and the two offensive air masses are merely more extreme versions of the typical hot and humid conditions. Second, the human mortality response to these air masses is not as significant as in the northern cities, largely because of population adaptation to consistent heat and housing that is more amenable to hot conditions. Last, temperature and moisture changes predicted by the model are minimal, in most cases less than 0.5°C. It appears that roof and vegetation modification have only a minor effect on meteorology, and hence, mortality, in New Orleans. It is also interesting to note that, in some of the cases, the mitigation techniques were actually associated with higher temperatures and dew points in New Orleans. For example 14 July 2000 showed an important increase in afternoon temperature from the baseline in both the high albedo and high vegetation runs. Fortunately, this was associated with a moderate decrease in dew point, or the result on mortality would have most certainly been negative.

As a result, mortality remained the same regardless of scenario in two of the three heat waves studied. In the third (June 16-18, 1998), both high vegetation and high albedo were associated with a decrease in three deaths; in both cases, the first day (June 16, 1998) was categorized into a less offensive air mass. Thus, of a total 11 heat wave days evaluated in New Orleans, one resulted in an air mass change that led to decreased mortality on that day.

When comparing the results for Los Angeles to the other cities (Figure 5), it must be considered that the meteorological modeling for L.A. was provided by another source. This noted, the impact of increased albedo is very significant, and mortality reductions appear to be sizable within the humid heat waves, with reductions of 14 deaths in August 1998 (approximately 25 percent), and a similar number (approximately 17 percent) in the August 1994 heat wave. Moderate albedo increases coupled with increasing vegetation appear to have a more limited (but still notable) impact on reducing mortality during these humid heat waves. This lesser effect might be attributed to the impact of increasing vegetation upon dew points, which seem to be relatively unchanged from the baseline within the higher vegetation scenario.

During the hot and dry heat waves, mortality changes appear to be minimal, fewer than 3 deaths, and the thermal changes associated with both increasing albedo and vegetation seem very small during DT air mass days in Los Angeles. Comparing the two different scenarios during DT heat waves, the high albedo scenario is associated with a greater reduction of mortality than the vegetation/moderate albedo scenario. This is similar to the result during the humid heat waves, and appears to suggest that increasing albedo has a more significant mitigating effect than increasing vegetation.

There were several important air mass changes that occur under the high albedo scenario. During the August 1994 heat wave, three of the days changed to less oppressive air mass types, and this significantly lowered the mortality totals for this heat wave. However, under the moderate albedo/high vegetation scenario, these days shifted back to the offensive air mass because of temperature and dew point increases. For Los Angeles, this reinforces the effectiveness of the higher roof albedo, and may speak against the potential positive ramifications of higher vegetation.

Concluding Remarks and Potential Future Work

Table 3 summarizes the results of this study, and compares the responses among the four cities. We are struck by the differing response in the cities when roof albedo and vegetation conditions are modified. In Philadelphia and Los Angeles, there appeared to be some significant downward change in mortality, mainly because some days demonstrated air mass alterations due to the modified conditions (particularly in Los Angeles during humid heat waves). In Detroit, changes were more modest, with some slight mortality decreases

Table 3
A Summary of Results

Attribute	Detroit	Los Angeles	New Orleans	Philadelphia
Scenarios Constructed	High Albedo High Vegetation High Albedo + High Vegetation	High Albedo Moderate Albedo + High Vegetation	High Albedo High Vegetation	High Albedo High Vegetation
Offensive Air Masses	DT MT+	DT MT+	MT+ MT++	DT MT+
Meteorological Changes with Cooling Scenarios	very little, some minor morning temperature decreases especially with high vegetation	significant temperature decreases especially afternoon with high albedo scenario, some dewpoint decreases with high albedo	very little, with some minor increases and decreases	some moderate afternoon temperature decreases especially with high vegetation
Number of days with air mass changes	1 change to more oppressive air mass (17 total days)	4 changes to less oppressive air mass (all high albedo), 1 change to less oppressive air mass (moderate albedo plus high vegetation) (18 total days)	1 change to less oppressive air mass (11 total days)	2 changes to less oppressive air mass (18 total days)
Mortality Changes	very little, some minor decreases, some minor increases	significant for 2 or 4 heat waves with high albedo scenario, moderate for the third heat wave, results less impressive with moderate albedo/high vegetation	very little, one air mass day change reduced mortality by 3	moderate decrease for 2 or three evaluated heat waves; reductions about 15%

noted except for one day where the higher vegetation scenario led to an air mass change to a more humid MT+ and associated mortality increases. Interestingly, an air mass change in Philadelphia from DT to MT+ led to mortality decreases; in Detroit, the one example when this happened led to a mortality increase. In New Orleans, responses were minimal except for one day that experienced an air mass change from MT++ to a less offensive MT+.

To summarize, it appears that the high albedo scenarios are more effective in lowering mortality than the high vegetation scenarios in three of the four cities, but high vegetation seemed more effective in Philadelphia. Neither produced the dramatic results that we would have hoped in New Orleans and Detroit, but nevertheless, in both Philadelphia and Los Angeles, several of the days demonstrated air mass changes, particularly on days that were originally hot and very humid, that led to significant decreases in mortality. We were particularly impressed with the Los Angeles results, especially for the high albedo scenario.

One interesting finding is the differential inter-regional responses to the modifications among the locales. Since we only evaluated one city within each region (East, Midwest, South, West), it is not known if this inter-regional differentiation is attributed to the general meteorology of each region or some specific factor inherent to each city evaluated. With this in mind, before the results of this study can be taken seriously, we recommend a duplication of the analysis in four additional cities within the same regions. For example, if this evaluation is replicated in New York City, and if responses are similar to those that were already found in Philadelphia, we can say with more certainty that there is a particular response in the East that is constant throughout the region. This would be an important finding, since the Philadelphia evaluation seems to suggest that increasing albedo and vegetation leads to some significant mortality reductions. The same holds for the other cities; in New Orleans, we found little mortality response regardless of albedo or vegetation conditions. Is it possible that the South responds less dramatically than the East? Or is it possible that New Orleans represents some kind of anomaly? If we replicate this study in a city with a similar summer climate as New Orleans, for example, Houston, we may gain the answer. We also suggest a replication for Detroit (possibly Chicago?) and for Los Angeles (possibly San Diego or San Francisco).

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