

URBAN HEAT ISLANDS

Opportunities and Challenges for Mitigation and Adaptation

David J. Sailor, Director

South Central Regional Center of the

National Institute for Global Environmental Change

School of Engineering, Tulane University

New Orleans, LA

ABSTRACT

The impact of urbanization on local climate, pollution, and human health is a problem that has been recognized and documented for centuries. The observation that cities can be significantly warmer than their rural surroundings is a phenomenon widely referred to as the urban heat island (UHI) effect. The causes of the UHI include generally lower urban reflectivity to solar radiation; lower surface moisture availability; lower vegetative cover; and substantial levels of waste heat release in cities. While modern tools have greatly improved our ability to monitor and document the effects of urbanization, the underlying problems and challenges remain. The causes of the UHI, however, have led researchers and policy makers to propose potential solutions such as increasing urban reflectivity and vegetative cover. Quantifying the costs and benefits of large-scale implementation of these strategies and assessing how to overcome the associated barriers to implementation is now the subject of intensive research.

The following paper summarizes opening remarks that I presented to the North American Urban Heat Island Summit. These remarks provide a brief background on the causes of the UHI phenomenon, and discuss the current state of knowledge with respect to large-scale mitigation strategies. The goal of the presentation, however, was to provide an overview of the key challenges for UHI and serve as a common point of departure for participants in the North American Urban Heat Island Summit.

Early Observations of the Urban Environment

Environmental concerns associated with the impacts of urban development have just started to receive significant attention in the policy and research communities over the past few decades. The roots of these problems, however, extend back hundreds, if not thousands, of years. A good overview of the history of urban climate-environment interactions can be found in (Landsberg 1981). For the present paper I provide a brief summary of this history. The interested reader is referred to the Landsberg book for a more complete treatment of the topic.

As cities developed so did the realization that the environment in and around cities was different (generally more oppressive) than the rural countryside. Nearly 2000 years ago – about the time of Emperor Tiberius – Lucius Seneca made this observation about Rome:

“As soon as I had left the heavy air of Rome with its stench from smoky chimneys which when stoked, will belch their enclosed pestilential vapor and soot, I felt a change in mood.” – Lucius Seneca.

The observed difference between Rome and the countryside here centers around pollutant emissions associated with space heating and cooking demands and was likely more of an issue in winter months than in summer. As the extent and density of urbanization patterns intensified over the ensuing centuries oppressive urban air became more common. In particular, with the onset of the industrial revolution came more frequent writings about the polluted urban environment. London has long been plagued by pollution problems dating back to the late middle ages when burning of coal in the city limits sparked much public debate. At the dawn of the industrial revolution, London’s existing population and pollution problems combined with a swell in energy consumption (and waste heat/pollutant emissions) to produce an even more oppressive urban environment. Luke Howard, a chemist and amateur meteorologist is generally credited as one of the earliest urban climate researchers. In the early 19th century he wrote extensively about the pollution and climate of London.

“London was this day involved, for several hours, in palpable darkness... Such is, occasionally, the effect of the accumulation of smoke between opposite gentle currents, or by means of a misty calm... were it not for the extreme mobility of the atmosphere, this volcano of a thousand mouths would, in winter be scarcely habitable.” – Luke Howard, 1812.

London was not unique among growing cities of the industrial revolution. Around the middle of the 19th century Renou made similar observations about the polluted environment of Paris.

“The respiration of humans and animals, above all the fumes of innumerable chimneys, maintain above Paris a rust-colored haze which blocks the sun... it is impossible that (Paris) should not have a notably higher temperature than the surrounding country.” – Emilien Renou, 1855.

In 1868 he followed these initial comments with a comparison of temperatures at a number of sites inside and outside of Paris. Specifically, he used simple thermometer (or thermoscope) measurements to show that the city of Paris was in fact about 1 °C warmer than the countryside. While early writings focused on elevated pollution levels in cities, Renou was among the first to quantitatively document the elevation of air temperatures in cities - a concept referred to today as the Urban Heat Island Effect.

Meteorological Characteristics of the Urban Environment

Methods of measuring the urban characteristics and the urban heat island effect have evolved over the centuries. The range of measurements techniques for studies of the urban environment are as varied as the applications for which they are used. The most useful parameters for heat island research include the basic meteorological parameters (temperatures, humidity, winds, etc), land use characteristics (urban morphology, land use, surface thermophysical characteristics, etc), and anthropogenic/biogenic emissions profiles (primary/secondary pollutants, heat emissions, etc).

The primary parameter used in discussing and quantifying the urban heat island is temperature. As defined by (Geer 1996) the urban heat island can be thought of as:

“an area of higher temperatures in an urban setting compared to the temperatures of the suburban and rural surroundings. It appears as an ‘island’ in the pattern of isotherms on a surface map.”

It should be noted, however, that the definition of the urban heat island itself depends on the application of interest and the measurement technique. The development of early handheld instruments from the 16th to 18th century (by Santorio Santorio, Galileo Galilei, Gabriel Fahrenheit, Anders Celcius and others) allowed scientists to measure differences in air temperature near the earth’s surface. As a result, early discussions of urban heat islands referred to temperature differences in the first few meters above the surface. Today, similar measurements can be made at higher elevations (using towers, tethered balloons, or aircraft) or at/below the ground surface itself. Most remotely-sensed measurements from aircraft and satellites represent an indirect measurement of ground-surface heat islands. Furthermore, when comparing temperatures at an “urban” and “rural” setting, one can report differences in daily maxima and minima, or present maximum and minimum differences for specific hours. The wide range of possibilities for how/where heat island measurements are taken makes it exceedingly important that researchers presenting heat island data clearly document the specifics of their measurement and data reduction techniques.

While temperature is the most common variable used to characterize heat islands, it is not the only important meteorological parameter. Whether one is interested in energy consumption, air quality, heat-related mortality, or other end-point impacts, parameters such as humidity, wind profiles, and mixing heights, are also of great significance. For example, in evaluating how heat island mitigation may impact summertime heat-related mortality in cities such as Philadelphia (Sailor 2002) have found that there is a potential

for mitigation strategies to raise dew point temperatures enough to offset the benefits of the corresponding air temperature reductions.

Causes and Characteristics of the Urban Heat Island

Figure 1 shows a representative heat island profile, with a peak associated with downtown and secondary peaks over residential and commercial areas.

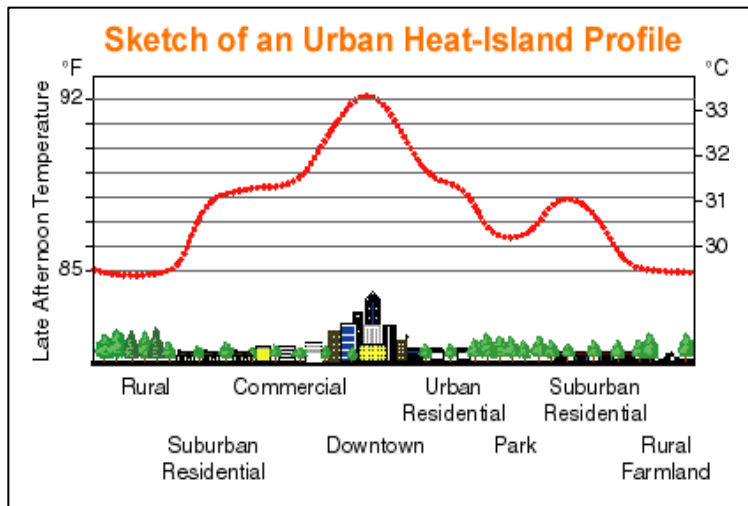


Figure 1. Representative urban heat island profile (source: eetd.lbl.gov/HeatIsland).

Some important complexities of urban heat islands are not evident in this figure or the urban heat island definition introduced above. Specifically:

- The UHI has diurnal and seasonal variability
- The UHI varies spatially (along the surface and vertically)
- Geographic and topographic factors can confound measurement of the UHI
- The UHI causes significant differences in meteorological parameters beyond temperature

It is then instructive to ask – what are the causes of the UHI, and what are the consequences? More importantly, why do we care? To start, consider this simplified analysis of the energy balance in a city shown in Figure 2.

The urban climate is driven by the input of short-wave solar energy. Since urban areas tend to have relatively low reflectivity to solar radiation (albedo) much of the solar energy is absorbed by the urban substrate. The effective urban albedo is further reduced by the “radiative roughness” of the city (Aida 1982; Arnfield 1988; Sailor and Fan 2002). That is, radiation reflected off of one urban surface is often intercepted, and partially absorbed by other urban surfaces. This effect is particularly important in dense and deep urban canyons. Of the energy absorbed at the surface a portion of it is convected away by local winds. This is known as “sensible” heat flux and is proportional to the temperature difference between the surface and the air. Sensible heat flux also depends in a complex manner on the wind profile and vertical mixing characteristics above the urban surface. As surfaces heat up they also lose energy through long-wave radiation. This long wave

emission is proportional to a surface radiative property known as emissivity (typically between 0.90 and 0.98, although often much lower for metallic surfaces). Likewise, the surroundings and atmosphere emit long wave radiation that is in turn intercepted by the urban surface. This, long wave radiative exchange helps to cool the city further.

In contrast to the natural landscape cities tend to have very little vegetation and due to a large fractional cover of impervious surfaces there tends to be less surface moisture in urban areas. What moisture is available, helps to cool the city through evaporation – or “latent” heat flux. In areas of naturally high humidity the role of latent heat flux is diminished since this flux depends upon the ability of the air to carry additional moisture.

A final unique component to the urban energy balance is the presence of waste heat that is emitted from a range of human activities. This comes from automobiles, air conditioning equipment, industrial equipment, and a variety of other sources, including human metabolism.

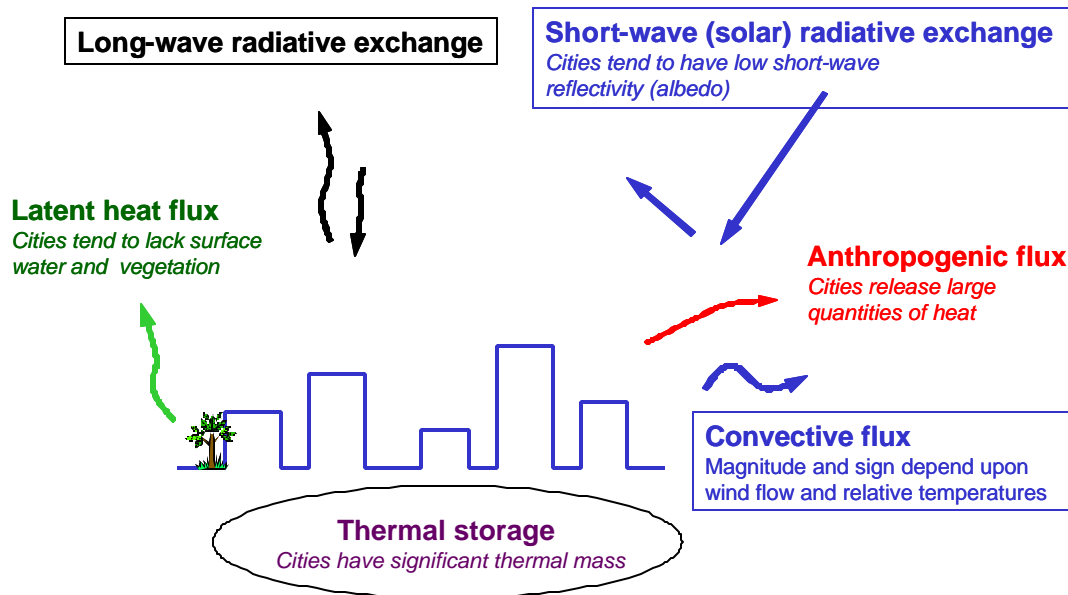


Figure 2. Urban energy balance illustrating some of the causes of the urban heat island.

Effects of the Urban Heat Island

Having established the existence of and causes for the urban heat island the next obvious question is why do we care? There are, in fact, many ways in which the urban heat island can impact the urban inhabitants. While these impacts are generally undesirable, the urban heat island can result in benefits that partially offset the negative aspects of heat islands.

The role of peak urban air temperatures in air quality is well documented (Walcek and Yuan 1995; Greene, Kalkstein et al. 1999). The frequency of ozone exceedances is strongly correlated with daily maximum temperature as shown by the sample plot from a monitoring station in Atlanta (Figure 3). This correlation is a result of a number of factors related to the urban heat island. Specifically, emissions (biogenic and anthropogenic)

increase with temperature. Likewise, rate constants for many important precursor reactions also increase with temperature. Mixing heights can actually be increased by the urban heat island effect with a beneficial dilution of pollutants. And finally, the complexities of urban geometry combined with heat-island induced ventilation result in complex wind patterns and convective transport of pollutants.

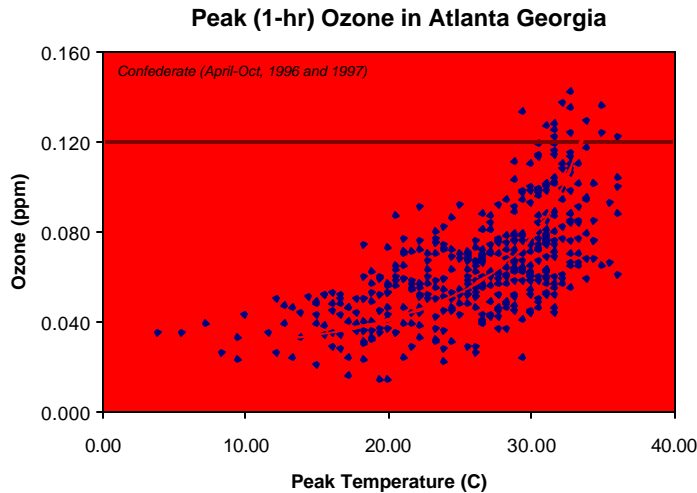


Figure 3. Peak 1-hour ozone concentrations for a single monitoring station in Atlanta during April-October, 1996 and 1997.

Urban heat islands also play an important role in affecting the demand for energy, particularly with respect to space conditioning. In summer, the urban heat island further exacerbates the summertime air conditioning loads, which in many cases dictate the required electricity generation capacity. In winter months, the urban heat island is beneficial from an energy standpoint as it reduces the need for heating energy consumption. It also can have significant implications for air quality and particulate matter pollution, in particular, as it may significantly reduce the use of wood-burning furnaces and fireplaces. Figure 4 demonstrates the role of temperatures in affecting electricity consumption for a sample of a year of peak electric load data from New Orleans.

While the ozone and particulate matter implications of urban heat islands are important health concerns it is also important to note that each year hundreds of people die in the United States as a result of heat-related causes. This has led to a significant level of interest by utilities and city governments in developing and implementing heat health watch systems. Some studies have quantitatively linked urban air temperatures to the likelihood of excess mortality (above typical/average rates). Synoptic climatologists have shown that certain weather patterns put populations at increased risk (Greene and Kalkstein 1996; Kalkstein, Nichols et al. 1996; Kalkstein, Sheridan et al. 1998). In particular, most instances of significant heat-related deaths in cities correspond to heat waves with elevated temperatures and humidity.

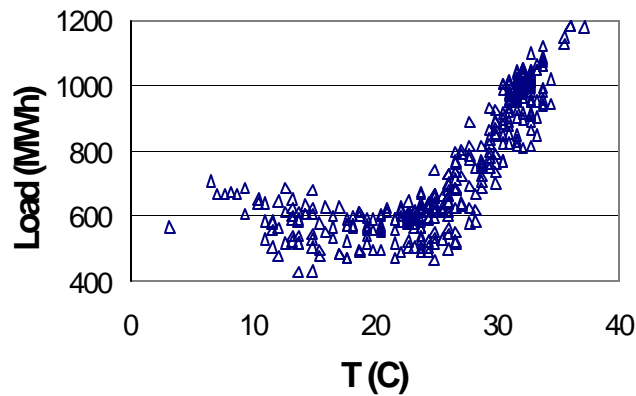


Figure 4. Electricity consumption as a function of peak air temperatures. Sample data from New Orleans in 1995.

While current heat island intensities can be large and the impacts substantial, there are a number of environmental stressors that are likely to lead to even more intense heat island effects in the future. Specifically, there is a global trend toward increasing urban population densities (e.g. (United Nations 1999). This, combined with the potential for global warming (IPCC 1995) may dramatically increase the severity of urban heat island-related impacts.

Opportunities for Urban Heat Island Mitigation

As outlined earlier, the causes of the heat island are known. Hence it is possible to suggest methods of mitigating the heat island. Specifically, end use energy efficiency and demand side management of electric loads can help to reduce waste heat during the hours of peak temperature. Cities can also decrease their solar load by increasing reflectivity of rooftops and paved surfaces. They can also increase latent heat flux by increasing moisture availability. This can be done by decreasing the fraction of impervious surfaces, and increasing vegetative cover.

Of course, large-scale implementation of UHI mitigation measures requires overcoming market barriers, increasing the knowledge base, and educating public officials and consumers. Some of the key challenges for implementing high-albedo surfaces revolve around aesthetics and weathering. For high-albedo surface implementation the key issues are:

- Aesthetics
- Weathering
- Quantifying benefits (direct & indirect)

Vegetation-based heat island mitigation strategies typically face a different set of implementation issues:

- Initial cost
- Maintenance
- Biogenic Emissions

- Damage resulting from growth and storms
- Quantifying Life-Cycle Costs/Benefits

Fortunately there are a number of researchers and agencies who are working hard to address these issues. Researchers at Lawrence Berkeley National Laboratory's Urban Heat Island Program (<http://eetd.lbl.gov/HeatIsland/>) have been studying urban heat island mitigation for more than 15 years now. They have conducted modeling and monitoring studies of both high-albedo and urban vegetation mitigation strategies and have published widely on the topic (Martien, Akbari et al. 1989; Bretz and Akbari 1997; Bretz, Akbari et al. 1998). Researchers at the Center for Urban Forest Research (www.cufr.davis.edu) have been working on life-cycle cost/benefit analysis of urban forestry programs (Dwyer, McPherson et al. 1992; McPherson, Simpson et al. 1999). Other recent efforts addressing heat island mitigation include (Estes 2000; Quattrochi, Laymon et al. 2000; Sailor 2002).

In addition to these and other research efforts there is a growing interest in the general field of urban climate. This swell in interest has given rise to the development of informal and formal newsgroups as well as the International Association for Urban Climate (IAUC, www.iauc.org).

Our understanding of the urban heat island phenomenon is becoming increasingly sophisticated. Nevertheless, public perceptions of some of the negative aspects of mitigation measures have a factual basis and must be overcome with solid evidence of benefits that far outweigh any costs or risks. But how do we estimate the potential benefits of various mitigation strategies?

Mitigation of heat islands can have two types of impacts that must be quantified in assessing total benefits of a mitigation strategy. These are **direct** effects and **indirect** effects. When a particular building is given a high-reflectivity roof or shade trees its energy consumption is directly reduced. Such energy savings are easily measured (Akbari, Bretz et al. 1992), and can also be modeled using sophisticated building energy models (Akbari and Taha 1992). But an individual high-reflectivity roof or shade tree also cools the air that is in contact with it. Widespread implementation of a mitigation strategy can therefore cool the air throughout the city and impact regional climate. This in turn can have feedback to energy consumption and air quality. Indirect effects of widespread mitigation measures are not easy to quantify, and are typically estimated through modeling studies (Sailor 1995; Taha, Konopacki et al. 1999). Such modeling is usually conducted by linking an atmospheric model (such as the MM5 or RAMS) to a model that can estimate the impact on a particular sector or process. For example, in air quality studies of heat island mitigation the atmospheric model is used to estimate the meteorological impacts of surface modification. These meteorological perturbations are then fed into a photochemistry model such as UAM-V or CAMx to provide projections of impacts on ground-level ozone (Taha and Sailor 1997). Likewise, in energy modeling applications the meteorological model is linked to a building energy simulation model such as Energy-Plus or DOE-2 (Akbari and Taha 1992). In studies of heat related mortality the meteorological model is linked to a model relating synoptic climatology to excess mortality (Sailor 2002).

So, a key component of evaluating indirect effects of UHI mitigation is the atmospheric or meteorological model. Such models, however, suffer from a number of

limitations with respect to their ability to capture the complex dynamics of the urban climate. The demand for improved modeling capability for heat island studies has resulted in a dramatic increase in related research activity over the past decade. This activity has focused on the following key limitations of existing atmospheric models:

- Poor representation of radiative exchange in complex urban canyon geometries
- Lack of detail with respect to land use differentiation
- Lack of representation of heat sources in urban domains (anthropogenic heat flux)
- Under-representation of thermal storage in urban areas

Some of the published research efforts in this area include: (Grimmond, Cleugh et al. 1991; Grimmond and Oke 1991; Hanna and Chang 1992; Mills 1997; Arnfield, Herbert et al. 1998; Grimmond and Oke 1999; Taha 1999; Macdonald 2000; Voogt and Grimmond 2000; Sailor and Fan 2002; Vu, Ashie et al. 2002). It should be noted, however, that there is currently a great deal of ongoing work and interest in this topic. The present paper is not intended as a thorough review of this literature, but rather as a brief overview of the key concepts related to urban heat island mitigation.

Conclusions

We know a lot about why our cities are hot, why they are polluted, and the resulting impacts on air quality, energy use, and human health. We also have a growing arsenal of mitigation strategies at our disposal for improving the quality of urban life, and are rapidly improving our understanding of the benefits, costs, and implementation issues associated with mitigation strategies. In many cases heat island mitigation boils down to simple choices made at the level of city governments, businesses, and individual consumers. It is up to us as a research community to provide the necessary technology and information to help decision makers make choices that will ultimately reduce the severity of urban heat islands and benefit the cities within which we live.

References

- Aida, M. (1982). "Urban albedo as a function of the urban structure- A model experiment." Boundary-Layer Meteorology **23**: 405-413.
- Akbari, H., S. Bretz, et al. (1992). Monitoring Peak Power and Cooling Energy Savings of Shade Trees and White Surfaces in the Sacramento Municipal Utility District (SMUD) Service Area: Project Design and Preliminary Results, Lawrence Berkeley Laboratory, University of California.
- Akbari, H. and H. Taha (1992). "The Impact of Trees and White Surfaces on Residential Heating and Cooling Energy Use in Four Canadian Cities." Energy-The International Journal **17**(2): 141-149.
- Arnfield, A. J. (1988). "Validation of an estimation model for urban surface albedo." Physical Geography **9**(4): 361-372.
- Arnfield, J., J. M. Herbert, et al. (1998). A numerical simulation of Urban Canyon Energy Budget Variations. 2nd Urban Environment Symposium,, Albuquerque, AMS.
- Bretz, S., H. Akbari, et al. (1998). "Practical issues for using solar-reflective materials to mitigate urban heat islands." Atmospheric Environment **32**(1): 95-101.

- Bretz, S. E. and H. Akbari (1997). "Long-term performance of high-albedo roof coatings." Energy and Buildings **25**(2): 159-167.
- Dwyer, J. F., E. G. McPherson, et al. (1992). "Assessing The Benefits and Costs of the Urban Forest." Journal of Arboriculture **18**(5): 227-234.
- Estes, M. G., Jr. (2000). "Urban heat island mitigation strategies." Planning Advisory Service Memo(May): 1-4.
- Geer, I., Ed. (1996). Glossary of Weather and Climate, with Related Oceanic and Hydrologic Terms. Boston, American Meteorological Society.
- Greene, J. S. and L. S. Kalkstein (1996). "Quantitative analysis of summer air masses in the eastern United States and an application to human mortality." Climate Research **7**(1): 43-53.
- Greene, J. S., L. S. Kalkstein, et al. (1999). "Relationships between synoptic climatology and atmospheric pollution at 4 US cities." Theoretical and Applied Climatology **62**(3-4): 163-174.
- Grimmond, C. S. B., H. A. Cleugh, et al. (1991). "An objective urban heat storage model and its comparison with other schemes." Atmospheric Environment, Part B **25**(3): 311-326.
- Grimmond, C. S. B. and T. R. Oke (1991). "An Evapotranspiration-Interception Model for Urban Areas." Water Resources Research **27**(7): 1739-1755.
- Grimmond, C. S. B. and T. R. Oke (1999). "Heat storage in urban areas: Local-scale observations and evaluation of a simple model." Journal of Applied Meteorology **38**(7): 922-940.
- Hanna, S. R. and J. C. Chang (1992). "Boundary-layer parameterizations for applied dispersion modeling over urban areas." Boundary-Layer Meteorology **58**(3): 229-259.
- IPCC (1995). Greenhouse Gas Inventory Reference Manual. Paris, France, Intergovernmental Panel on Climate Change.
- Kalkstein, L. S., M. C. Nichols, et al. (1996). "A new spatial synoptic classification: application to air-mass analysis." International Journal of Climatology **16**(9): 983-1004.
- Kalkstein, L. S., S. C. Sheridan, et al. (1998). "A determination of character and frequency changes in air masses using a spatial synoptic classification." International Journal of Climatology **18**(11): 1223-1236.
- Landsberg, H. E. (1981). The Urban Climate, Academic Press.
- Macdonald, R. W. (2000). "Modelling the mean velocity profile in the urban canopy layer." Boundary-Layer Meteorology **97**(1): 25-45.
- Martien, P., H. Akbari, et al. (1989). Light-Colored Surfaces to Reduce Summertime Urban Temperatures: Benefits, Costs, and Implementation Issues. Miami International Congress on Energy and Environment, Miami, Florida.
- McPherson, E. G., J. R. Simpson, et al. (1999). "Benefit-cost analysis of Modesto's municipal urban forest." Journal of Arboriculture **25**(5): 235-248.
- Mills, G. (1997). "An urban canopy-layer climate model." Theoretical and Applied Climatology **57**(3-4): 229-244.
- Quattrochi, D. A., C. A. Laymon, et al. (2000). "A decision support information system for urban landscape management using thermal infrared data." Photogrammetric Engineering and Remote Sensing **66**(10): 1195-1207.

- Sailor, D. J. (1995). "Simulated Urban Climate Response to Modifications in Surface Albedo and Vegetative Cover." Journal of Applied Meteorology **34**(7): 1694-1704.
- Sailor, D. J. and H. Fan (2002). "Modeling the diurnal variability of effective albedo for cities." Atmospheric Environment **36**(4): 713-725.
- Sailor, D. J., L.S. Kalkstein, and E. Wong (2002). The Potential of Urban Heat Island Mitigation to Alleviate Heat-Related Mortality - Methodological Overview and Preliminary Modeling Results for Philadelphia. 4th Symposium on the Urban Environment, Norfolk VA, American Meteorological Society.
- Taha, H. (1999). "Modifying a mesoscale meteorological model to better incorporate urban heat storage: A bulk-parameterization approach." Journal of Applied Meteorology **38**(4): 466-473.
- Taha, H., S. Konopacki, et al. (1999). "Impacts of large-scale surface modifications on meteorological conditions and energy use: A 10-region modeling study." Theoretical and Applied Climatology **62**(3-4): 175-185.
- Taha, H. and D. J. Sailor (1997). "Modeling the impacts of large-scale albedo changes on ozone air quality in the south coast air basin
Simulations of annual degree day impacts of urban vegetative augmentation." Atmospheric Environment **31**(11): 1667-1676.
- United Nations, P. D. (1999).
www.un.org/esa/population/publications/wup1999/urbanization.pdf
- Voogt, J. A. and C. S. B. Grimmond (2000). "Modeling surface sensible heat flux using surface radiative temperatures in a simple urban area." Journal of Applied Meteorology **39**(10): 1679-1699.
- Vu, T. C., Y. Ashie, et al. (2002). "A k - e turbulence closure model for the atmospheric boundary layer including urban canopy." Boundary-Layer Meteorology **102**(3): 459-490.
- Walcek, C. J. and H.-H. Yuan (1995). "Calculated Influence of Temperature-Related Factors on Ozone Formation Rates in the Lower Troposphere." Journal of Applied Meteorology **34**: 1056-1069.