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**Urban Climates and Heat Islands:  
Albedo, Evapotranspiration, and  
Anthropogenic Heat**

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Urban Climates and Heat Islands:  
Albedo, Evapotranspiration, and Anthropogenic Heat

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*Abstract*

As an introduction to this special issue of *Energy and Buildings*, this paper reviews some of the characteristics of urban climates and the causes and effects of urban heat islands. In particular, the impacts of surface albedo, evapotranspiration, and anthropogenic heating on the near-surface climate are discussed. Numerical simulations and field measurements indicate that increasing albedo and vegetation cover can be effective in reducing the surface and air temperatures near the ground.

(Keywords: albedo, anthropogenic heating, meteorology, micrometeorology, numerical modeling, simulation, urban climate, vegetation)

## *Introduction*

It is known that urban climates differ from those of rural areas and that the magnitudes of the differences can be quite large at times depending on weather conditions, urban thermophysical and geometrical characteristics, and anthropogenic moisture and heat sources present in the area. For example, northern-hemisphere urban areas annually have an average of 12% less solar radiation, 8% more clouds, 14% more rainfall, 10% more snowfall, and 15% more thunderstorms than their rural counterparts (Changnon 1976,1981). Urban pollutant concentrations can be 10 times higher than those of the "clean" atmosphere and air temperatures can be on the average 2°C higher. The fluxes of heat, moisture, and momentum are significantly altered by the urban landscape and the contrast between the urban and "undisturbed" climates is further enhanced by the input of anthropogenic heat, moisture, and pollutants into the atmosphere.

In most mid- and high-latitude cities, urban air temperatures are generally higher than their corresponding rural values. This phenomenon, the urban heat island, has been recognized since the turn of this century and has been well documented (Chandler 1960; Oke 1987,1988; Karl and Jones 1989). A heat island can occur at a range of scales; it can manifest itself around a single building (Thurow 1983), a small vegetative canopy (Taha et al. 1989,1991), or a large portion of a city. Depending on geographic location and prevailing weather conditions, heat islands may be beneficial or detrimental to the urban dweller and energy user. Generally speaking, low- and mid-latitude heat islands are unwanted because they contribute to cooling loads, thermal discomfort, and air pollution whereas high-latitude heat islands are less of a problem because they can reduce heating energy requirements. This is a generalization however; the actual impacts of urban climates and heat islands depend on the characteristics of local climates. One way of indirectly characterizing these impacts is to examine heating and cooling degree-days data. Table 1 shows that with respect to rural surrounds, urban areas have less heating degree-days (HDD) but more cooling degree-days (CDD). Taha et al. (1994) show that the net effect of HDD and CDD modification by urban areas is an increase in cooling loads.

The causes and effects of urban climates and heat islands are diverse and their interactions complex. In this paper, three parameters of direct relevance to heat islands are examined in very simple terms. These are the surface albedo, evapotranspiration from vegetation, and anthropogenic heating from mobile and stationary sources. They are discussed as factors leading to differences between urban and rural climates. The sensitivity of the temperature field to changes in these parameters is also discussed based on results from numerical simulations. For this purpose, a version of the URBMET model (Bornstein 1975; Taha 1988,1990) was used to simulate typical summer days in a mid-latitude location with warm climate. The Colorado State

University Mesoscale Model (CSUMM), originally developed by Pielke (1974), was also used to simulate the effects of large-scale increases in surface albedo and vegetation cover on regional meteorology.

### *The Surface Energy Balance Equation*

The surface energy balance equation explains quite simply the roles of surface properties and anthropogenic heating in near-surface climates. The general form of this equation for a unit surface area which is flat, horizontal, and homogeneous, is given by:

$$\alpha_s Q + \alpha_d q + \alpha_L L + Q_f = \epsilon \sigma T_o^4 + h_c(T_o - T_a) + k \frac{dT_s}{dz} |_{z=0} + \lambda E \quad (1)$$

where  $\alpha_s$  and  $\alpha_L$  are absorptivities for short- and long-wave radiation, respectively,  $Q$  and  $q$  are the direct and diffuse short-wave radiative fluxes respectively,  $L$  is the incoming long-wave radiative flux,  $Q_f$  is the anthropogenic (man-made) heat flux,  $\epsilon$  is the emissivity of the surface,  $\sigma$  is the Stefan-Boltzmann constant,  $T_o$  and  $T_a$  are respectively the surface and air temperatures,  $h_c$  is a convective heat transfer coefficient,  $k$  is the thermal conductivity of the ground,  $T_s$  is the surface temperature,  $\lambda$  is the latent heat of vaporization, and  $E$  is the evaporation rate.

The first two terms on the left-hand side represent the absorbed solar radiation, the third term is the absorbed longwave radiation, and the fourth term is anthropogenic heat flux at the surface. The first and second terms on the right-hand side represent the radiative and sensible heat fluxes, the third term represents heat conduction into or from the submedium through the surface, and the fourth term is the latent heat flux. Equation (1) can be recast as:

$$(1 - a) R + L^* + Q_f = H + \lambda E + G \quad (2)$$

where  $a$  is the solar albedo,  $R$  is incoming solar radiation,  $L^*$  is net longwave radiation at the surface,  $Q_f$  is anthropogenic heat, and  $H$ ,  $\lambda E$ , and  $G$  are the sensible, latent, and ground heat fluxes, respectively.

In the following sections, three of the terms in equation 2 are discussed, namely: surface albedo ( $a$ ), latent heat flux/evapotranspiration ( $\lambda E$ ), and anthropogenic heating ( $Q_f$ ). Their impacts on the temperature field, which in turn affects the amount of cooling energy needed, are also described.

### *Albedo (a).*

The albedo of a surface is defined as its hemispherically- and wavelength-integrated reflectivity. This definition applies to simple uniform surfaces as well as to heterogeneous and complex ones. Typically, urban albedos are in the range 0.10 to 0.20 but in some cities these values can be exceeded. North African towns are good examples of high-albedo urbanized areas (albedos of 0.30 to 0.45) whereas most U.S. and European cities have lower albedos (0.15 to 0.20). For example, Taha (1993a) performed low-altitude flights over the Los Angeles Basin and found that the highest albedo in that area was 0.20 (near Downtown Los Angeles). He also found that much of the urbanized basin had an albedo between 0.12 and 0.16 and that city-core albedo was higher than that of its surrounds because of more extensive vegetation in the latter.

Table 2 lists values of snow-free urban albedos for several cities. Where available, the difference between urban and rural albedos is given in the third column. The example of Lagos is interesting because the city is built on an intricate mesh of creeks and lagoons that cause albedo to decrease as one gets closer to the suburbs (the albedo of water is lower than that of the light-colored buildings).

Using high-albedo materials reduces the amount of solar radiation absorbed through building envelopes and urban structures and keeps their surfaces cooler. Taha et al. (1992a) measured the albedo and surface temperatures of a variety of surfaces in the field. They found, for example, that white elastomeric coatings (with an albedo of 0.72) were 45°C cooler than black coatings (with an albedo of 0.08) in the early afternoon of a clear day in summer. A white surface with an albedo of 0.61 was only 5°C warmer than ambient air whereas conventional gravel with an albedo of 0.09 was 30°C warmer than air.

The reduction in surface temperature also reduces the intensity of longwave radiation. Local and downwind ambient air temperatures would be lower because of smaller convective heat fluxes from cooler surfaces. Such temperature reductions can have significant impacts on cooling energy consumption in urban areas, a fact of particular importance in hot-climate cities. Thus, the sensitivity of air temperature to albedo change has been of interest to those researching the impacts of urban heat islands.

One-dimensional meteorological simulations by Taha et al. (1988) showed that localized afternoon air temperatures on summer days can be lowered by as much as 4 °C by changing the surface albedo from 0.25 to 0.40 in a typical mid-latitude warm climate. Three-dimensional mesoscale simulations of the effects of large-scale albedo increases in the Los Angeles basin showed similar magnitudes of impacts on air temperature in summer; an average decrease of 2°C and up to 4°C may be possible by increasing the albedo by 0.13 points in certain areas of the



basin (Taha 1993b,1995a). Temperature decreases of this magnitude could reduce the electricity load from air-conditioning by 10% (Akbari et al. 1989) and smog (ozone concentrations) by up to 20% during a hot summer day (Taha 1995a).

### *Latent Heat Flux ( $\lambda E$ )*

Evapotranspiration (evaporation and transpiration) from soil-vegetation systems is another effective moderator of near-surface climates, particularly in the warm and dry mid- and low-latitudes. Given the right conditions, evapotranspiration can create "oases" that are 2-8 °C cooler than their surroundings (Oke 1987; Taha et al. 1989,1991). In extreme oasis conditions, the latent heat flux ( $\lambda E$ ) can be so large that the sensible heat flux ( $H$ ) becomes negative, meaning that the air above vegetation and over the dry surroundings must supply sensible heat to the vegetated area and the Bowen ratio (ratio of sensible to latent heat fluxes) becomes negative. For example, Flohn (1971) reported that in the Tunisian deserts, oases could develop with Bowen ratios ( $\beta$ ) of -0.26.

In more average oasis conditions, Bowen ratios in vegetative canopies are within 0.5-2. For example, measured noontime sensible and latent heat flux densities in a Pine forest in England in July were 400 and 200  $W m^{-2}$  ( $\beta=2$ ), respectively (Gay and Stewart 1974). In a Douglas fir stand in British Columbia, the corresponding values were 200 and 300  $W m^{-2}$  ( $\beta=0.66$ ) (McNaughton and Black 1973). In comparison,  $\beta$  in urban areas is typically around 5, in a desert it is in the neighborhood of 10, and over tropical oceans, it is about 0.1.

Urban areas, with extensive impervious surfaces, have generally more runoff than their rural counterparts. The runoff water drains quickly and, in the long run, less surface water remains available for evapotranspiration, thus affecting the urban surface energy balance (Grimmond and Oke 1991). The lower evapotranspiration rate in urban areas is a major factor in increasing daytime temperatures. In Tokyo for example, vegetated zones in summer are on the average 1.6 °C cooler than non-vegetated spots (Oka 1980, Gao et al. 1994), and in Montreal, urban parks can be 2.5°C cooler than surrounding built areas (Oke 1977). In a vegetative canopy (orchard) in Davis CA, Taha et al. (1989,1991) measured typical summer daytime oases 2 °C cooler than surrounding open fields of bare soil. On one hot and clear day, the oasis grew as large as 6 °C. Robinette (1972) reported summer afternoon temperatures 8 °C lower at 50-cm height over grass than over bare soil.

In numerical simulations, Taha (1988) incorporated a bulk vegetative canopy parametrization in the one-dimensional URBMET PBL model (Bornstein 1975). The sensitivity of air temperature to vegetation cover change was simulated with this modified version of URBMET

using initial conditions from micrometeorological field-measurements in Davis CA (Taha et al. 1989,1991). The vegetation canopy produced daytime temperature depressions (oases) and nighttime excesses (heat islands) compared to the bare surrounds. The factors behind the first are evaporative cooling and shading of the ground, whereas the second is a result of reduced sky view factor within the canopy. The simulations indicate that a vegetative cover of 30% could produce a noontime oasis of up to 6°C, in favorable conditions, and a nighttime heat island of 2°C. In other modeling studies, Gao (1993) found that green areas decrease maximum and average air temperatures by 2°C. Also, Gao et al. (1995) found that vegetation can decrease maximum air temperatures in streets by 2°C. Regional-scale, three-dimensional simulations showed that large-scale urban forestation in the Los Angeles basin can be as effective in reducing air temperature as the use of high-albedo materials (Taha 1993b,1995b).

#### *Anthropogenic Heating ( $Q_f$ )*

Anthropogenic heating in urban areas can affect the near-surface air temperature and potentially play a role in creating urban heat islands. Although the magnitude of  $Q_f$  depends on various factors such as the intensity of energy use, power generation, and transportation systems, the largest  $Q_f$  values are typically found in cold-climate urban centers in winter because of the intensive heating load during that season. In most major U.S. cities,  $Q_f$  ranges between 20 and 40  $W m^{-2}$  in summer and between 70 and 210  $W m^{-2}$  in winter (Hosler and Landsberg 1977). These values are for city centers and the last one is an uncommon extreme. By comparison, solar radiation at the surface on a typical clear or partly cloudy day at noon ranges from about 700 to 1000  $W m^{-2}$ . In Table 3, the annual average anthropogenic heating for selected city cores is given along with a representative local annual average net all-wave horizontal radiation ( $Q^*$ ) where available. In residential and sub-urban areas,  $Q_f$  is negligible.

Taha et al. (1992b) examined energy use patterns in buildings and motor vehicles and developed a diurnal anthropogenic heating profile based on estimated heat rejection from these sources. The profile was then used to parameterize time-dependent anthropogenic heating in prognostic meteorological models to estimate the impact of  $Q_f$  on air temperatures. These meteorological simulations show that  $Q_f$  in a large city core can create a heat island of up to 2-3°C both during the day and at night. This kind of temperature increase, however, is not expected to occur in a suburban residential neighborhood. Also, the simulations indicate that the low  $Q_f$  in residential areas has a negligible impact on air temperature. Yet, combining the effects of anthropogenic heating in city centers with those of other factors, such as low vegetation cover and dark surfaces, can enhance the heat island effect.

### *Conclusion*

Some of the aspects of the causes and effects of heat islands were examined. Field-monitoring data and meteorological simulations indicate that changes in surface albedo and vegetation cover can be effective in modifying the near-surface climate. The effects of anthropogenic heating, on the other hand, seem to be relatively small. The simulations indicate that the impact of anthropogenic heating may be important in urban centers but negligible in residential and commercial areas.

Results from meteorological simulations suggest that cities can feasibly reverse heat islands and offset their impacts on energy use simply by increasing the albedo of roofing and paving materials and reforesting urban areas. The simulations suggest that reasonable increases in urban albedo can achieve a decrease of up to 2°C in air temperature. With extreme increases in albedo, localized decreases in air temperature can reach 4°C under some circumstances. Increases in vegetation in urban areas can result in some 2°C decrease in air temperatures. Under some circumstances, e.g., potentially evaporating soil-vegetation systems and favorable meteorological conditions, the localized decrease in air temperature can reach 4°C.

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## References

- Aida, M. (1982) On the urban surface albedo. 1981 *Japanese Progress in Climatology*, Vol. 4-5.
- Akbari, H., Rosenfeld, A., and Taha, H. 1989. "Recent developments in heat island studies: Technical and policy", Proceedings of the workshop on Saving Energy and Reducing Atmospheric Pollution by Controlling Summer Heat Islands", Berkeley, CA, February 23-24, pp. 14-20.
- Bach, W. (1970) An urban circulation model. *Arch. Meteorol. Geophys. Bioclimatol. Ser. B*, Vol. 18, 155-168.
- Bornstein, Robert D. (1975) The two-dimensional URBMET urban boundary layer model. *Journal of Applied Meteorology*, Vol. 14, No. 8, 1459-1477.
- Bowling, S.A. and Benson, C.S. (1978) Study of the subarctic heat island at Fairbanks, Alaska. *Environmental Monitor Report No. EPA-600/4-78-027*, US EPA Research, Triangle Park, North Carolina.
- Brest, C.L. (1987) Seasonal albedo of an urban/rural landscape from satellite observations. *Journal of Applied Meteorology*, Vol. 26, 1169-1187.
- Chandler, T.J. (1960) Wind as a factor of urban temperatures: A survey in North-East London. *Weather*, Vol. 15, No. 6, 204-213.
- Changnon, S.A. Jr. (1976) Inadvertent weather modifications. *Water Resources Bulletin*, vol. 12, 695-718.
- Changnon, S.A. Jr. (1981) METROMEX: A review and summary. *Meteorological Monographs*, Vol. 18, No. 40. American Meteorological Society.
- Coppin, P., Forgan, B., Penney, C., and Schwerdtfeger, P. (1978) Zonal characteristics of urban albedos. *Urban Ecology*, Vol. 3, 365-369.
- Dabberdt, W.F. and Davis, P.A. (1978) Determination of energetic characteristics of urban-rural surfaces in the Greater St. Louis area. *Boundary-Layer Meteorology*, Vol. 14, 105-121.
- Flohn, H. (1971) Saharization: Natural causes or management?, *WMO Special Environmental Report*, No. 2, WMO No. 312, Geneva, 101-106.
- Gao, W. 1993. "Thermal effects of open space with a green area on urban environment, Part I: A theoretical analysis and its application", *J. of Archit. Plann. Environ. Engng.*, AIJ, No. 448.
- Gao, W., Miura, S., and Ojima, T. 1994. "Site survey on formation of cool island due to park and inner river in Koto-ku, Tokyo", *J. of Archit. Plann. Environ. Engng.*, AIJ, No. 456.
- Gao, W., Sugiyama, H., and Ojima, T. 1995. "Field study of effect of street and its trees on thermal environment of sidewalks", *J. of Archit. Plann. Environ. Engng.*, AIJ, No. 469.
- Gay, L.W. and Stewart, J.B. (1974) Energy balance studies in coniferous forests. *Report No. 23, Instit. Hydrol., Natural Environ. Res. Council*, Wallingford, Berks.
- Grimmond, S. and Oke, T. 1991. "An evapotranspiration-interception model for urban areas", *Water Resources Research*, Vol. 27, No. 7, pp. 1739-1755.
- Hosler, C.L. and Landsberg, H.E. (1977) The effect of localized man-made heat and moisture sources in mesoscale weather modification. In *Energy and Climate*, National Academy of Sciences, Washington, D.C.
- Huang, J., Akbari, H., Taha, H. and Rosenfeld, A. (1987) The potential of vegetation in reducing summer cooling loads in residential buildings. *Journal of Climate and Applied Meteorology*, Vol. 26, No. 9, 1103-1116.
- Kalma, J.D., Aston, A.R., and Millington, R.J. (1973) Energy use in the Sydney area. *Proc. Ecol. Soc. Australia*, Vol. 7, 125-142.
- Kalma, J.D. and Newcombe, K.J. (1976) Energy use in two large cities: a comparison of Hong Kong and Sydney, Australia. *Environmental Studies*, Vol. 9, 53-64.
- Kalma, J.D. and Byrne, G.F. (1975) Energy use and the urban environment: Some implications for planning. *Proceeding of the Symposium on Meteorology Related to Urban, Regional Land- Use Planning*, Asheville, NC. World

Meteorological Organization, Geneva, Switzerland.

- Karl, T., and Jones, P. (1989) Urban biases in area-averaged surface air temperature trends. *Bulletin of the American Meteorological Society*, Vol. 70, No. 3, 265-270.
- Kung, E.C., Bryson, R.A., and Lenschow, D.H. (1964) Study of a continental surface albedo on the basis of flight measurements and structure of the earth's surface cover over North America. *Monthly Weather Review*, Vol. 92, 543-564.
- Landsberg, H. (1981) *The Urban Climate*, Academic Press, New York.
- Lemon, E.R., Glaser, A.H., and Satterwhite, L.E. (1957) Some aspects of the relationship of soil, plant, and meteorological factors to evapotranspiration. *Proc. Soil Sci. Soc. Amer.*, Vol. 21, 464-468.
- McNaughton, K. and Black, T.A. (1973) A Study of evapotranspiration from a douglas forest using the energy balance approach. *Water Resources Res.*, Vol. 9, 1579-1990.
- Mayer, H. and Noack, E.M. (1980) Einfluss der schneedecke auf die strahlungsbilanz im grossraum Munchen. *Meteorologische Rundschau*, Vol. 33, 65-74.
- Oguntoyinbo, J.S. (1986) Some aspects of the urban climates of tropical Africa. *Proceedings of the Conference on Urban Climatology and its Application With Special Regards to Tropical Areas*. WMO, Geneva, Switzerland.
- Oguntoyinbo, J.S. (1970) Reflection coefficient of natural vegetation, crops, and urban surfaces in Nigeria. *Quarterly Journal of the Royal Meteorological Society*, Vol. 96, 430-441.
- Ojima, T. and Moriyama, M. (1983) Earth surface heat balance changes caused by urbanization. *Energy and Buildings*, Vol. 4, 99-114.
- Oka, Tatsou. (1980) Thermal environment in urban areas. *Report D7:1980*, Swedish Council for Building Research, Stockholm, Sweden.
- Oke, T.R. (1977) The significance of the atmosphere in planning human settlements. *Ecological Land Classification in Urban Areas*, in E.B. Wilkin and G. Ironside (eds.), *Ecological Land Classification Series*, No. 3, Ottawa, Ontario.
- Oke, T.R. (1987) *Boundary Layer Climates*, Second Edition, Methuen, London.
- Oke, T.R. (1988) The urban energy balance. *Progress in Physical Geography*, Vol. 12, No. 4, 471-508.
- Pielke, R. 1974. "A three-dimensional numerical model of the sea breeze over South Florida", *Monthly Weather Review*, 102:115-139.
- Robinette, G.O. (1972) Plants, people, and environmental quality. In *Landscape Planning for Energy Conservation*, Robinette, G.O. and McClennon, C. (editors), Van Nostrand Reinhold Company. New York.
- Rouse, W.R. and Bello, R.L. (1979) Shortwave radiation balance in an urban aerosol layer. *Atmosphere-Ocean*, Vol. 17, 157-168.
- SMIC (1971) *Inadvertent Climate Modification*, MIT Press, Cambridge.
- Steyn, D.G. and Oke, T.R. (1980) Effects of a scrub fire on the surface radiation budget. *Weather*, Vol. 35, 212-215.
- Taha, H. 1995a. "Modeling the impacts of large-scale albedo changes on ozone air quality in the South Coast Air Basin", submitted to *Atmospheric Environment*.
- Taha, H. 1995b. "Modeling the impacts of increased urban vegetation on the ozone air quality in the South Coast Air Basin", submitted to *Atmospheric Environment*.
- Taha, H., Akbari, H., and Sailor, D. 1994. "On the simulation of urban climates: Sensitivity to surface parameters and anthropogenic heating", Internal Report, Lawrence Berkeley Laboratory.
- Taha, H. (1993a) Aircraft-based albedo measurements over the South Coast Air Basin. A chapter in a report on *Energy Efficiency and Air Quality in the SoCAB*, LBL Draft Report.
- Taha, H. (1993b) Meteorological and photochemical simulations of the South Coast Air Basin. A chapter in a report on *Energy Efficiency and Air Quality in the SoCAB*, LBL Draft Report.

- Taha, H., Sailor, D., and Akbari, H. 1992a. "High-albedo materials for reducing cooling energy use", Lawrence Berkeley Laboratory Report No. 31721 UC-350, January 1992.
- Taha, H., Akbari, H., Sailor, D., and Ritschard, R. 1992b. "Causes and Effects of Heat Islands: Sensitivity to Surface Parameters and Anthropogenic Heating", Lawrence Berkeley Laboratory Report No. 29864.
- Taha, H., Akbari, H., Rosenfeld, A. (1991) Heat island and oasis effects of vegetative canopies: Micro-meteorological field measurements. *Theoretical and Applied Climatology*, Vol. 44, 123-138.
- Taha, H. (1990) An urban microclimate model for site-specific building energy simulation: Boundary layers, urban canyon, and building conditions, Ph.D. Dissertation, University of California at Berkeley. *LBL Report No. 29630, Berkeley, California.*
- Taha, H., Akbari, H., and Rosenfeld, A. (1989) Vegetation micro-climate measurements: the Davis project. *Lawrence Berkeley Laboratory Report No. 24593.*
- Taha, H., Akbari, H. and Rosenfeld, A. (1988) Residential cooling loads and the urban heat island: The effects of albedo. *Building and Environment*, Vol. 23, No. 4, 271-283.
- Taha, H. (1988) Site-specific heat island simulations: Model development and application to microclimate conditions. *LBL Report No. 26105.* Masters of Geography Thesis, University of California at Berkeley.
- Thurow, Charles (1983) Improving street climate through urban design. *American Planning Association.*
- Vukovich, F.M. (1983) An analysis of the ground temperature and reflectivity pattern about St. Louis, Missouri, using HCMM satellite data. *Journal of Applied Meteorology*, Vol. 22, 560-71.

Table 1. Reduction in heating degree-days and increase in cooling degree-days (base 18.3 °C) due to urbanization and heat island effects. Selected locations' averages for the period 1941-1970. Modified after Landsberg (1981).

Location	Heating DD			Cooling DD		
	Urban	Airport	Δ%	Urban	Airport	Δ%
Los Angeles	384	562	-32	368	191	+92
Washington DC	1300	1370	-6	440	361	+21
St. Louis	1384	1466	-6	510	459	+11
New York	1496	1600	-7	333	268	+24
Baltimore	1266	1459	-14	464	344	+35
Seattle	2493	2881	-13	111	72	+54
Detroit	3460	3556	-3	416	366	+14
Denver	3058	3342	-8	416	350	+19
Chicago	3371	3609	-7	463	372	+24

Table 2. Selected urban albedo values.

Urban area	Albedo	$\Delta$ (urban-rural)	Author
Los Angeles (city core)	0.20	0.09	Taha 1993a†
Madison, WI (urban)	0.15-0.18	0.02	Kung et al. 1964
St. Louis, MI (urban)	0.12-0.14	-	Dabberdt and Davis 1978
St. Louis, MI (center)	0.19-0.16	0.03	Vukovich 1983†
Hartford, CT (urban)	0.09-0.14	-	Brest 1987
Adelaide, AUS (commercial)	0.27 (mean)	0.09	Coppin et al. 1978
Hamilton, Ontario	0.12-0.13	-	Rouse and Bello 1979
Munich, West Germany	0.16 (mean)	-0.08	Mayer and Noack 1980
Vancouver, B.C.	0.13-0.15	-	Steyn and Oke 1980
Tokyo	0.10 (mean)	-0.02	Aida 1982
Ibadan, Nigeria	0.12 (mean)	0.03	Oguntoyinbo 1970
Lagos, Nigeria	0.45	0.25	Oguntoyinbo 1986

‡Measured from low-altitude aircraft flights (<200m above ground level) in summer 1993.

†Limited shortwave sensitivity of sensors



Table 3. Anthropogenic heating ( $Q_f$ ) and net all-wave radiation ( $Q^*$ ) in selected cities. These are annual average values within the urbanized limits of the cities. The data does not include suburban or rural surrounds (Bach 1970; Kalma et al. 1973; Kalma and Byrne 1975; Kalma and Newcombe 1976; Bowling and Benson 1978; Ojima and Moriyama 1983; SMIC 1971; Oke 1987).

City	$Q_f$ ( $W m^{-2}$ )	$Q^*$ ( $W m^{-2}$ )
Chicago	53	-
Cincinnati	26	-
Los Angeles	21	108
Fairbanks	19	18
St. Louis	16	-
Manhattan, NY City	117-159	93
Moscow	127	-
Montreal	99	52
Budapest	43	46
Osaka	26	-
Vancouver	19	-
West Berlin	21	57

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