

Air Pollution Prevention Through Urban Heat Island Mitigation: An Update on the Urban Heat Island Pilot Project

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ABSTRACT

Urban heat islands increase the demand for cooling energy and accelerate the formation of smog. They are created when natural vegetation is replaced by heat-absorbing surfaces such as building roofs and walls, parking lots, and streets. Through the implementation of measures designed to mitigate the urban heat island, communities can decrease their demand for energy and effectively "cool" the metropolitan landscape. In addition to the economic benefits, using less energy leads to reductions in emissions of CO₂ - a greenhouse gas - as well as ozone (smog) precursors such as NO_x and VOCs. Because ozone is created when NO_x and VOCs photochemically combine with heat and solar radiation, actions taken to lower ambient air temperature can significantly reduce ozone concentrations in certain areas. Measures to reverse the urban heat island include afforestation and the widespread use of highly reflective surfaces. To demonstrate the potential benefits of implementing these measures, EPA has teamed up with NASA and LBNL to initiate a pilot project with three U.S. cities. As part of the pilot, NASA will use remotely-sensed data to quantify surface temperature, albedo, the thermal response number and NDVI vegetation of each city. This information will be used by scientists at Lawrence Berkeley National Laboratory (LBNL) along with other data as inputs to model various scenarios that will help quantify the potential benefits of urban heat island mitigation measures in terms of reduced energy use and pollution. This paper will briefly describe this pilot project and provide an update on the progress to date.

Introduction

One of the fundamental components that sets a city apart from its rural surroundings is the climate that prevails over urban environments. In urban areas, buildings and paved surfaces have gradually replaced preexisting natural landscapes. As a result, solar energy is absorbed into roads and rooftops, causing the surface temperature of urban structures to become 50 - 70 ° F higher than the ambient air temperatures. (Taha, Akbari & Sailor 1992). As surfaces throughout an entire community or city become hotter, overall ambient air temperature increases. This phenomenon, known as an "urban heat island," can raise air temperature in a city by 2 - 8 ° F. (Oke 1987 and World Meteorological Organization 1984).

The resulting higher temperature caused by the urban heat island has the effect of increasing the demand for cooling energy in commercial and residential buildings. Increased demand for energy can cost consumers and municipalities thousands of additional dollars in air conditioning bills in order to maintain comfort levels. In addition, increased electricity generation by power plants leads to higher emissions of sulfur dioxide, carbon monoxide, nitrous oxides, and suspended particulates, as well as carbon dioxide, a greenhouse gas known to contribute to global warming and climate change. Finally, summer heat islands often accelerate the formation of harmful smog, as ozone precursors such as nitrous oxides (NO_x) and

volatile organic compounds (VOCs) combine photochemically to produce ground level ozone. (SOS 1995).

On a larger scale, modification of the landscape through urbanization alters the natural channeling of energy through the atmospheric, land and water systems. Although large-scale atmospheric and climatic phenomena are global in scope, urban areas cannot be viewed in isolation because the local environment modifies the conditions in the thin air stratum above the ground, generally referred to as the atmospheric boundary layer. As humans alter the character of the natural landscape in the city-building process, the local energy exchanges that take place within the boundary layer are affected. Therefore, modification of the landscape influences the local (microscale), mesoscale, and even the macroscale climate.

Urban Heat Island Mitigation Measures

Researchers and policy makers have long understood the primary causes of urban heat islands, but have only recently begun to investigate various strategies to effectively reverse or mitigate them. Scientists at Lawrence Berkeley National Laboratory (LBNL) are among those who have studied both the causes and effects of urban heat islands and have recently begun to identify measures that can effectively cool the metropolitan landscape. These measures include increasing the albedo¹ of surfaces such as roofs and pavement, and urban afforestation to both directly reduce cooling energy use in buildings and to lower ambient air temperature through evapotranspiration. Increasing the albedo of roofs and paved surfaces directly reduces cooling energy demand for individual buildings. Large-scale albedo modifications (such as an entire neighborhood or community), have the effect of reducing overall ambient air temperature, causing further reductions in demand for energy by individual buildings. Trees shade buildings to directly reduce cooling energy demand by blocking the sun's radiation. Indirectly, trees use solar energy to release moisture into the atmosphere in the form of water vapor, which has an additional cooling effect. In addition, trees sequester carbon and reduce soil erosion and water pollution, as well as provide habitat for wildlife and recreation for urban dwellers.

Increasing surface albedo or vegetative cover may prevent a significant rise in surface temperatures which, in turn, will keep the air relatively cooler in the modified areas and downwind of them. The implications of lower ambient temperatures include 1) a decrease in some photochemical reaction rates; 2) a decrease in temperature-dependent biogenic hydrocarbon emissions; 3) a decrease in evaporative losses of organic compounds from mobile and stationary sources; and 4) a decreased need for cooling energy, generating capacity, and, thus, emissions from power plants. All of these have generally positive effects on air quality.

However, decreasing the near-surface temperatures can also affect the atmospheric boundary layer. Such changes can decrease the depth of the mixed air layer at some locations in the cities and airsheds, potentially resulting in higher pollutant concentrations in certain areas. It may also change the air flow pattern (e.g., sea breeze) and affect air quality. Due to these interacting and non-linear effects, an estimation of meteorological and air quality impacts of urban heat island mitigation strategies cannot be done well without the use of advanced computer models. For this reason, advanced computer modeling (described in greater detail below) is an integral part of the Urban Heat Island Pilot Project.

¹Albedo is defined here as solar reflectivity. The albedo range of reflectivity is from 0 to 1, with 0 having no reflectivity and 1 being 100% reflective.

The Urban Heat Island Mitigation Initiative (UHIMI)

Recognizing the beneficial effect that urban heat island mitigation can have on the local and global environment, EPA launched the Urban Heat Island Mitigation Initiative (UHIMI) in the fall of 1997. The primary goal of the UHIMI is to encourage ozone nonattainment areas to pursue urban heat island mitigation measures as a cost-effective, long-term strategy way to improve local air quality and mitigate climate change. Barriers that have been identified which prevent the widespread adoption of urban heat island mitigation measures include a general lack of information, no product differentiation for surfaces, limited product availability (e.g. roofs) and various institutional and political issues which often stem from the first barrier - lack of information. To address the institutional and information barriers, EPA teamed up with DOE, NASA, and LBNL to demonstrate the potential benefits of urban heat island mitigation by undertaking the following activities:

- Conduct detailed analyses to quantify the potential air quality benefits from strategically-planted vegetation and reflective surfaces;
- Identify the most effective means to implement measures aimed at reducing the urban heat island effect;
- Develop "lessons learned" that will serve as guidelines for other cities interested in initiating similar types of programs and policies; and
- Conduct outreach and educational activities to encourage other cities to implement measures intended to reverse the urban heat island effect.

As part of the UHIMI, the Urban Heat Island Pilot Project (UHIPP) seeks to accomplish these objectives by analyzing the "urban fabric" of three U.S. cities and the contribution of various surfaces (roofs, pavement and vegetation) on current energy use and air quality. As the next step, UHIPP seeks to determine what the potential is for each of the cities to reduce air temperature and related air pollution through the widespread implementation of mitigation measures. If successful, EPA will work to incorporate the measures into State Implementation Plans (SIPs) for Clean Air Act compliance for the three designated pilot cities and use the results to develop a methodology that other nonattainment areas can use to similarly reduce compliance costs and accelerate the achievement of the National Ambient Air Quality Standards (NAAQS).

The Urban Heat Island Pilot Project (UHIPP)

Although the urban heat island effect is prevalent in many cities, intensities vary from community to community according to such variables as climate, topography and the degree and pattern of urbanization in a given geographical area. Not surprisingly, the potential benefits that can be gained from urban heat island mitigation also depend on local conditions. In an attempt to better understand the extent to which mitigation strategies will be effective in reducing energy use and preventing pollution in a particular area, EPA is working with NASA and LBNL as part of the UHIPP. The goal of the UHIPP is to use the results from the NASA/LBNL analysis (described below), combined with knowledge gained through working with various organizations within each pilot city to identify the most effective means of

implementing strategies designed to mitigate the urban heat island. These "lessons learned" will be made available and used by cities across the U.S. to assist policy makers and others within various communities to analyze their own urban heat islands and determine which, if any, measures can be taken to help save energy and money, and to prevent pollution.

Year One of the UHIPP (beginning October 1997 through September 1998) will focus on 1) creating a viable partnership between three U.S. pilot cities and EPA; 2) working with representatives in each pilot city to set up "Pilot City Teams;" comprised of air quality officials, policy makers, technical experts, NGOs, private industry, and others to work on the UHIPP; 3) obtaining the necessary data (including satellite and high spatial resolution calibrated aircraft data to be supplied by NASA) to use as inputs into the modeling process to be undertaken by LBNL; 4) gathering baseline information about the city (i.e. land use, tree cover, etc.) to begin to identify areas of maximum potential; and 5) begin developing a methodology which outlines how urban heat island measures can be included in SIPs to reduce the overall cost of compliance with the NAAQS.

During Year Two (beginning October 1998 through September 1999), EPA will continue to work with the Pilot City Teams to develop an "Action Plan" based on both the results of the NASA/LBNL analysis as well as additional information gathered by the Pilot City Teams during the first year of the project. Although specific to each pilot city, the Action Plans will 1) categorize land use across the city; 2) estimate the areas of maximum potential for reflective surfaces and urban afforestation; 3) identify which organizations within the city or a given community would be appropriate in helping to implement the mitigation measures; and 4) outline and prioritize policy levers and potential programs that offer the largest cooling potential at the least cost. If successful, the Action Plans will form the basis for implementation of measures identified by each of the Pilot City Teams. At present, teams have been established in Salt Lake City, UT, Sacramento, CA, and Baton Rouge, LA, and data collection and analysis is now underway. The remaining sections of this paper will describe the type of data collection and analyses to be conducted by NASA and LBNL, and give an update on progress to date.

NASA: High Spatial Resolution Visible and Thermal Infrared Data

NASA's Mission to Planet Earth (MTPE) program seeks to better understand how the coupled land-ocean-atmosphere systems operate and how these systems both affect, and are affected by, human actions. One of the five key MTPE research priorities is to document and understand the trends and patterns of change in local to regional land cover, biodiversity, and global primary production as a function of climate variability and human interactions. Urbanization exists along with deforestation and agriculture, as the most profound example of human alteration of the Earth's surface. Changes that result from urbanization also impact biophysical, hydrologic, and climatic processes, which in turn, affect adjacent natural ecosystems. For the UHIPP, NASA will use remotely-sensed data to measure and map urban surface thermal energy responses in each of the three pilot cities. To complement the meteorological and air quality modeling performed by LBNL, NASA will obtain high spatial resolution surface characteristics data from aircraft as a way to identify more specifically which areas in the particular pilot city will serve as the best candidates for alternations.

Remote Sensing Data (AVHRR or GOES)

For the UHIPP, NASA will obtain visible and thermal infrared data from either the NOAA Advanced Very High Resolution Radiometer (AVHRR) or the NOAA Geostationary Orbiting

Environmental Satellite (GOES) to measure and map urban surface thermal energy responses (or "heat") upwelling into the atmosphere for 10 different cities across the United States. Data from either of these satellites can be used to evaluate urban surface heating and cooling conditions. Use of these satellite data to analyze the thermal energy properties of the three pilot cities, as well as an additional seven U.S. cities, will allow for a broad scale comparison between these cities. Satellite data will be collected, processed and transferred to LBNL as an input into their meteorological model. These data include corrected and georeferenced, gridded albedo (~4 km) and gridded NDVI² (~1 km).

Advanced Thermal and Land Applications Sensor Data (ATLAS)

Although satellite data are very useful for analysis of the urban heat island effect at a coarse scale, they do not lend themselves to developing a better understanding of which surfaces across the city contribute to or drive the development of the urban heat island effect. Analysis of thermal energy responses for specific or discrete surfaces typical of the urban landscape (e.g., asphalt, building rooftops, vegetation) requires measurements at a very fine spatial scale (i.e., < 15m) to adequately resolve these surfaces and their attendant thermal energy regimes. Additionally, very fine scale spatial resolution thermal infrared data, such as that obtained from aircraft, are very useful for demonstrating to planning officials, policy makers, and the general populace how urban afforestation and reflective surfaces help to mitigate the urban heat island effect, while simultaneously making cities more aesthetically pleasing and generally more habitable environments. (Lo et al., 1997). To pursue these efforts, more information is needed about specific characteristics of several different cities.

NASA will use the Advanced Thermal and Land Applications Sensor (ATLAS) to obtain high spatial resolution (10 m pixel resolution) over each of the three pilot cities. Data from the ATLAS will be collected via aircraft flights over the metropolitan areas once within a 24 hour period during clear weather in late spring and early summer. Data will be collected at low level (10 m pixel size) scale around solar noon to measure thermal responses when incident solar irradiance is at its maxima. These low-level data will be obtained along a flight path that encompasses a sampling of "typical" urban surfaces (e.g., residential, industrial, urban fringe) within the metropolitan areas. The data will also be collected along the same flight line at 30 minute intervals to permit the measurement of short-term thermal responses from various surfaces for modeling energy flux relationships, such as evapotranspiration from vegetated surfaces, in concert with observation of upwelling surface heat as a contributor to the urban heat island effect. (Luvall and Holbo, 1989).

As with the satellite data, a portion of the ATLAS data will be transferred to LBNL, including corrected and georeferenced gridded albedo (~10 m) and gridded NDVI (~10 m) for each city, corrected and georeferenced data that LBNL will use in the "urban fabric" analysis, and land-use classification data. In addition to the data that will be collected and processed for use in the models, NASA will work directly with each of the pilot cities to ensure that the data collected during the overflights are transmitted to the user community in each pilot city. An Urban Environmental Planner has been assigned by NASA to ensure that the scientific results derived from the ATLAS data are effectively communicated to policy makers and the general public in each of the pilot cities by helping the Teams develop data products that are specific to their particular situations. As an example, Salt Lake City is proposing to compare the ATLAS data collected by NASA with similar NASA data collected in 1985 to measure changes in land use/land cover

²NDVI = Normalized Difference Vegetative Index and is an indication of the amount of vegetative cover in a particular region.

(LULC) compositions over time. (Quattrochi and Ridd, 1994). This will allow policy makers in Salt Lake City to better understand the effect that population growth along the Wasatch Front has had on the overall environmental health of this area and what may be expected in the future so that appropriate planning can be done with regards to future growth.

LBNL: Meteorological and Air Quality Modeling

The output from meteorological and air quality models carries a wealth of information that can be very useful in designing local ordinances and/or programs to improve the environment and minimize the use of energy. These models can provide an estimate of the response of the climate and related air quality attributes to changes in surface properties (e.g., urban heat island mitigation scenarios). This is useful when attempting to understand the impact of urbanization as well as the effects of implementation of urban heat island mitigation strategies on a particular community.

For the UHIPP, LBNL will build upon the tools and modeling expertise that LBNL's Heat Island Project (HIP) has developed and used over the years to study the feasibility and potential environmental benefits of implementing urban heat island mitigation strategies in Baton Rouge, Sacramento, and Salt Lake City. The surface albedo and vegetative characterization component of the input to the LBNL modeling will be provided by NASA based on the remotely-sensed data described above. This modeling study will provide policy makers in each city with a set of guidelines they can follow to implement urban heat island mitigation strategies, along with estimated energy and air quality benefits from implementation.

Meteorological Modeling

Over the years, LBNL has developed, obtained, updated, and used several advanced computer models and tools to simulate the meteorological and air quality impacts of various surface-change and urbanization scenarios. In recent years, LBNL has modified these models to utilize input from remotely-sensed data, (e.g., satellite or aircraft data) more effectively, in an effort to better differentiate between urban and non-urban land uses and land covers, and improve upon the simulation of changes in surface properties such as urban albedo and afforestation. LBNL has also developed several parameterizations to enhance the simulation of processes of interest to urban heat island mitigation, (e.g., cooling in vegetative canopies). The updated models were used in a variety of applications to simulate meteorological conditions for any region in the U.S. (and the world) and for any particular time or scale. Meteorological models are designed to simulate atmospheric processes of various spatial and temporal scales. The models used in urban heat island mitigation simulations are of mesoscale extent, on the order of 300 x 300 km, with increased differentiation around areas of interest, e.g., urban areas or regions where surface modifications are assumed to occur.

Typical input to meteorological models includes a description of the initial weather conditions, related boundary conditions as the weather system evolves, and a detailed description of the surface. The latter includes topography, water surfaces, vegetation, albedo, roughness, and other thermophysical properties such as density, specific heat, thermal diffusivity, and so on. The surface albedo and vegetation fraction are best characterized through the use of remotely-sensed data. For the UHIPP, LBNL uses AVHRR or Landsat Thematic Mapper (TM) and Multispectral Scanner (MSS) satellite data to develop gridded input fields of albedo and vegetation cover to the mesoscale meteorological models. Part of this data will be obtained and transferred to LBNL by NASA (as described above). In addition, LBNL relies on land-use/land-cover (LULC) data to further characterize the surface and develop urban heat island

mitigation schemes for albedo and vegetative cover. Observational data from regional meteorological-stations networks are used to drive the models and test the validity of the results to establish the model's performance.

Typical output from meteorological models includes four-dimensional (space and time) fields of prognostic variables such as air temperature, moisture, wind speed, wind direction, boundary-layer heights, and so on. For the purpose of urban heat island mitigation modeling, the most important output variable to examine is air temperature. This variable is critical in identifying urban heat islands (if any) and assessing the energy-use and air-quality benefits of urban heat island mitigation strategies (e.g., through effects of reduced air temperature).

Air Quality Modeling

In contrast to meteorological models, air quality models are designed to simulate the transport, reaction, emission, and deposition of air pollutants. The scale of models used in LBNL's urban heat island mitigation work is similar to that of mesoscale meteorological models. These are used off-line with the meteorological models to assess the air quality benefits of the mitigation strategies.

Typical input to air quality models consists of meteorological conditions (which is the output of meteorological models in this study) and emission inventories that provide information on the spatial distribution and rates of emissions of pollutants from power plants, point sources, area sources, mobile sources, and vegetation. Other inputs relate to surface characteristics such as vegetative refraction and roughness.

Typical output from air quality models includes the four-dimensional distribution of pollutant concentrations such as those of ozone, nitrogen dioxide, carbon monoxide and dioxide, and others. In past modeling efforts, LBNL has found that the meteorological and air quality models, although not entirely free of errors, predict reasonably well the observed states. However, the data suggest that further model improvements and input modification may be needed to enhance the prediction capability of these models.

In the past, LBNL has used these capabilities to simulate the Los Angeles Basin and assess the potential benefits of urban heat island mitigation strategies in that area. These simulations of a late-August episode suggest that implementing heat island mitigation strategies in the Los Angeles Basin would have a net effect of reducing ozone concentrations. (Rosenfeld et al.). With increases in albedo or reforestation, peak ozone concentrations at 3 p.m. decrease by up to 7% (from 220 ppb down to 205 ppb) while the total ozone mass in the mixed layer decreases by up to 640 metric tons (a decrease of 4.7%). With respect to the NAAQS, domain-wide population-weighted exceedance exposure to ozone decreases by up to 16% during peak afternoon hours and by up to 10% during the daytime. These effects are comparable to those expected from significant control on mobile-source emissions. For the UHIPP, LBNL will develop the same types of simulations that were done for the Los Angeles Basin; however, by working directly with the Pilot City Teams, it will be possible to develop and input more realistic assumptions of the degree to which albedo alterations and afforestation is possible over a given geographical area and time period.

Progress to Date

As of June 1998, the following activities under the UHIPP have taken place or are planned:

- Pilot City Teams have been formed in Salt Lake City, Sacramento, and Baton Rouge. Although the Teams vary from city to city, members generally include representatives from the city and/or county

government, State air quality and energy offices, local NGOs (e.g. urban forestry organizations), utilities, urban planners, engineers, and researchers. Teams in each of the pilot cities have been meeting on a regular basis and are in the process of developing the first draft of their Action Plan.

- ATLAS data (10 m resolution) were acquired by NASA over Baton Rouge LA. on May 11, 1998 between 11:00 a.m. and 3:00 p.m. local. Measurements of atmospheric visibility and radiosonde moisture profiles were taken in order to correct the data for atmospheric interference. Initial uncalibrated estimates of surface temperatures ranged from 22-25 ° C for vegetated surfaces up to about 65 ° C for roof tops. (Figure 1.1 in the Appendix). ATLAS data will be acquired for Sacramento on or around June 29 and for Salt Lake City on or around July 13.
- LBNL has performed the baseline meteorological and air quality simulations for Salt Lake City and Sacramento and is working with each of the cities to make sure the information (input data and output that is being produced by LBNL) is accurate. An important aspect of the UHIPP is that the meteorological and urban airshed models are continually improved during the process, allowing for more accurate end results.

Conclusion

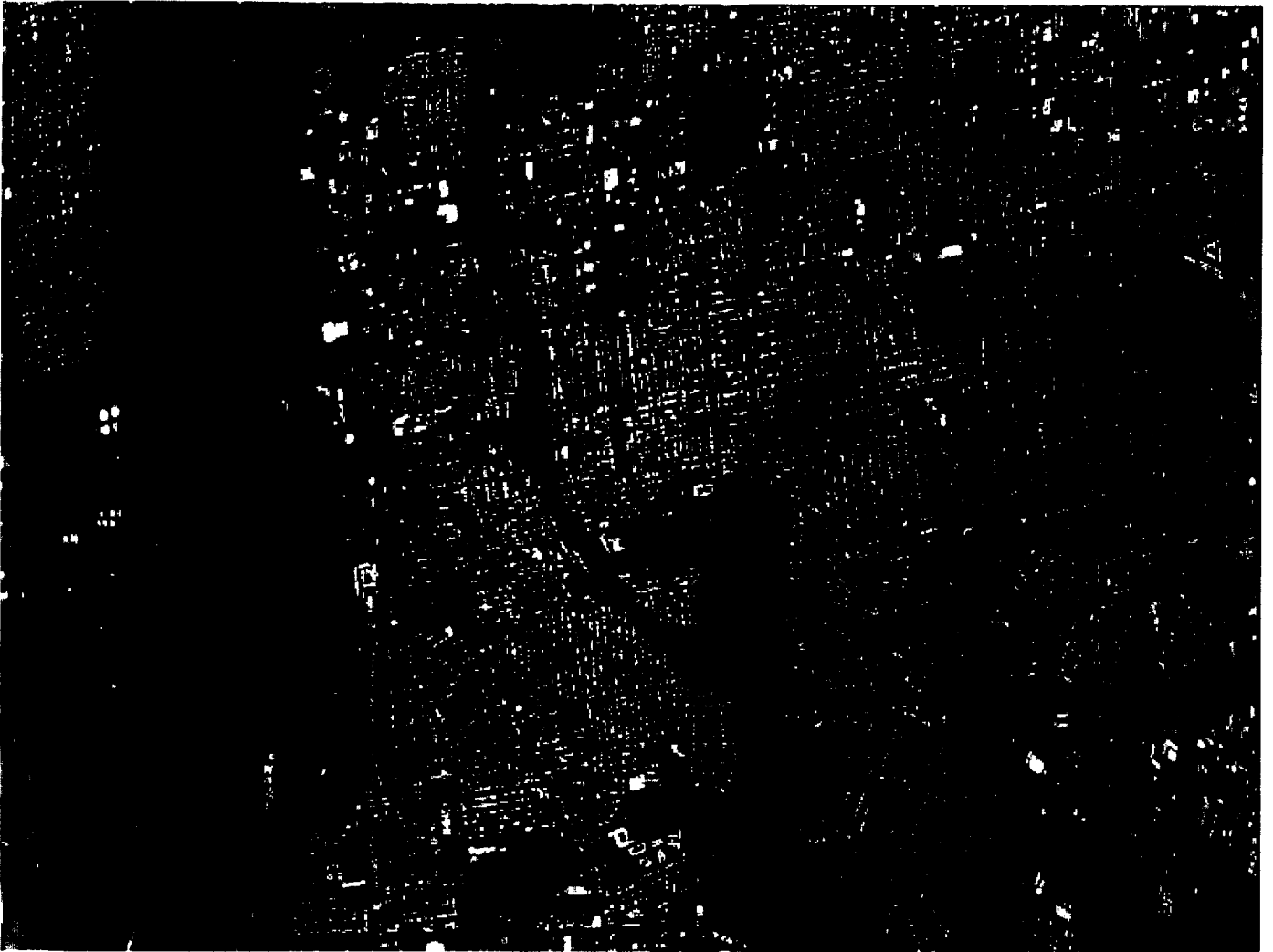
Ongoing research and field studies have shown how strategically planting shade trees and increasing the reflectivity of building and pavement surfaces can greatly reduce energy use for cooling, and prevent the formation of smog. What is less obvious is the effect that these strategies can have on particular cities, given the numerous variables particular to different regions such as climate, topography, and population growth patterns. Results from the UHIPP will determine the extent of the urban heat island in three pilot cities, and illustrate the potential benefits to energy use and air quality through the widespread use of mitigation strategies. During the second year of the project, EPA will work with the pilot cities to use the analysis from this project for developing programs and policies that encourage albedo modifications and shade trees. Such policies will likely include efforts to specify the use of light-colored materials in roads, buildings and renovations, zoning for light-colored building materials in commercial areas, strengthen the ability of roads and parks departments to plant new trees and maintain existing ones, and continue to foster community efforts in these areas through voluntary programs.

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Appendix

Figure 1



Thermal image of downtown Baton Rouge taken about 1:00 p.m. local time on Monday, May 11 1998 from the NASA Learjet's ATLAS scanner. This is a black & white image with white representing warmer surface temperatures and black representing cooler surface temperatures. An estimated temperature range for the surface is about 65 °C (mostly roof tops) to around 25 °C for the vegetation.