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Proceedings of the Workshop on Saving Energy and Reducing Atmospheric Pollution by Controlling Summer Heat Islands

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Authors

Garbesi, K.
Akbari, H.
Martien, P.

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Berkeley, California
February 23-24, 1989

Energy Analysis Program
Applied Science Division
Lawrence Berkeley Laboratory
University of California

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Berkeley, CA

Editors: Karina Garbesi, Hashem Akbari, Phil Martien

Energy Analysis Program
Applied Science Division
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720

ACKNOWLEDGMENTS

Workshop Organizers:

Hashem Akbari
Linda DeLaCroix
Joe Huang
Phil Martien
Arthur Rosenfeld
Haider Taha

Technical Reviewers:

Hashem Akbari
Joe Huang
Karina Garbesi
Phil Martien
Arthur Rosenfeld
Rowan Rowntree
Haider Taha

Conference Staff:

Debbie Giallombardo
Ralph McLaughlin
Charlotte Standish

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Proceedings of the Workshop on Saving Energy and Reducing Atmospheric Pollution by Controlling Summer Heat Islands

ABSTRACT

A workshop was held at the University of California at Berkeley on the energy and pollution implications of summertime urban heat islands and the potential to control them. The presentations, papers, and discussions fell into four broad categories: (1) the potential to conserve energy, reduce atmospheric pollution, and slow global warming by reducing summer heat islands; (2) the use of computer models to understand and simulate the heat island phenomenon; (3) measurements of heat islands; and (4) the design and implementation of heat island mitigation strategies. On the afternoon of the second day of the workshop, the participants divided into three workgroups. Group 1 discussed research needs to better quantify the effect of heat island mitigation on energy use. Group 2 discussed future research on the characterization and modeling of heat islands. And Group 3 discussed the development of a manual that would present to policy makers our current knowledge of techniques to mitigate heat islands and thereby save energy.

This Proceedings documents the presentations and outcome of the Workshop. The Foreword outlines the goals and accomplishments of the Workshop and the recommendations of each of the workgroups. The five chapters in the body of the Proceedings are composed as follows: Chapter 1 introduces the phenomenon of the urban heat island, its causes and characteristics; Chapter 2 discusses the potential to control heat islands, and thereby conserve energy and reduce power plant emissions; Chapter 3 describes and discusses the strengths and shortcomings of urban climate models used to simulate heat islands; Chapter 4 describes measurements of, and techniques for measuring heat islands and related characteristics of the urban surface and urban climate; and Chapter 5 discusses issues related to policy design and implementation of heat island mitigation measures. An editors' summary introduces each chapter, highlighting important issues raised by the authors and areas requiring further research.

KEYWORDS: air-conditioning, albedo, atmospheric attenuation, atmospheric pollution, black body radiation, buildings, building energy, planetary boundary layer, canopy layer, city planning, cooling, cooling energy, cooling peak power, electricity conservation, energy forecast, energy simulation, evapotranspiration, global warming, heat islands, land use, landscape ordinance, landscape values, landscaping, measurements, microclimate, numerical modeling, parking lots, publicity, reflectance, remote sensing, residential, rural trees, satellite, shading, smog, surface temperature, temperature trends, transpiration, tree maintenance, tree planting, tree values, trees, urban climate, urban design, urban ecology, urban emissivity, urban environment, urban forest, urban forestry, urban trees, urban planning, urban pollution, urban vegetation, urban ventilation, utilities, volunteers, water conservation, water use, wind shielding, wind simulations, wind tunnel simulation, white surfaces.

TABLE OF CONTENTS

Foreword ix
Workshop Agenda xiii
Summary and Recommendations of Discussion Group 1 xvii
Summary and Recommendations of Discussion Group 2 xix
Summary and Recommendations of Discussion Group 3 xxi

CHAPTER 1--Characterizing the Urban Heat Island
Editors' Introduction to the Urban Heat Island 2

Characterization of Urban Heat Islands*
T. R. Oke 7

CHAPTER 2--Mitigation of Urban Heat Islands: The Potential to Conserve Energy, Reduce Air Pollution, and Slow Global Warming
Editors' Summary 10

Recent Developments in Heat Island Studies: Technical and Policy
H. Akbari, A. Rosenfeld, H. Taha 14

Saving Energy and Reducing Atmospheric Pollution by Controlling Summer Heat Islands
H. Akbari, J. Huang, P. Martien, L. Rainer, A. Rosenfeld, H. Taha 31

The Impact of Vegetation on Air Conditioning Consumption
J. H. Parker 45

Vegetation to Conserve Water and Mitigate Urban Heat Islands
E. G. McPherson 53

The Role of Landscape Vegetation in Urban Heat Island Amelioration: Results of a Scale Model Study*
J. R. Simpson and E. G. McPherson 70

Global Warming and Space Conditioning Use in California: Effects and Mitigation
L. W. Baxter, R. Herrera M. Miller, G. Sharp 72

Unit Costs of Carbon Savings From Urban Trees, Rural Trees, and Electricity Conservation: A Utility Cost Perspective
F. Krause and J. Koomey 92

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* Abstract only, no paper submitted to Proceedings.

CHAPTER 3--Modeling the Urban Climate

Editors' Summary 122

Nature, Limitations, and Applications of Urban Climate Models
R. D. Bornstein 124

Approaches to Using Models of Urban Climate in Building-Energy Simulation
P. Martien, H. Akbari, A. Rosenfeld, J. Duchesne 150

Evapotranspiration from Urban Systems*
T. R. Oke 174

Evapotranspiration from Vegetation*
K. T. Paw U 175

Use of Mesoscale Meteorological Modeling as an Assessment of Summer Urban Heat Islands
R. A. Pielke and R. Avissar 176

Thermal and Reflectance Properties of Asphalts, Aggregates, and Their Combinations*
C. L. Monismith 185

CHAPTER 4--Measurements of Heat Islands and Characteristics of the Urban Surface and Urban Climate

Editors' Summary 188

Satellite Observation of Surface Temperature
T. Schmugge 191

Air Surface Temperature Correlations
I. R. Imamura 197

The Shanghai Urban Heat Island and its Formative Factors
S. D. Chow 204

Measurement of Summer Residential Microclimates in Sacramento California*
L. Rainer, P. Martien, H. Taha 217

Remote Sensing of Urban Terrain Zones for Urban Planning Purposes
R. Ellefsen 218

Seasonal Albedo of an Urban/Rural Landscape from Satellite Observations
C. L. Brest 238

Mean Windspeed Below Building Height in Residential Neighborhoods
G. M. Heisler 256

Urban Wind Profile as a Factor Affecting Urban Ventilation and Vehicular Air Pollution Concentration at Street Level
B. Givoni 273

CHAPTER 5--Policy Design and Implementation of Heat Island Mitigation Measures

Editors' Summary 286

The Environmental Function of Urban Trees: *Liquidambar Styraciflua L.* in Seattle, WA
J. R. Clark, R. Kjelgren, and D. Wang 290

Tree Values and Value Measurements
G. A. Moll 306

Taking it to the Streets: Inspiring Public Action
A. Lipkis and K. Lipkis 312

Greenstreets or Meanstreets: Challenges to Planting Urban Trees
A. E. Acosta 325

Planting Guidelines for Heat Island Mitigation and Energy Conservation
R. A. Beatty 333

HEAT ISLAND WORKSHOP REGISTRANTS 345

WORKSHOP ON
SAVING ENERGY AND REDUCING ATMOSPHERIC POLLUTION BY CONTROLLING SUMMER HEAT ISLANDS

Foreword

Urban climatologists and energy researchers have observed that developed urban areas create summer "heat islands". The intensity of the heat-island is usually highest in the evening hours and lowest shortly after sunrise. A typical daily afternoon intensity is 2-5 ° C. In high-latitude cities with cooler weather, heat islands can be an asset in reducing heating loads, but in mid- and low-latitude cities, heat islands contribute to the urban dweller's summer discomfort and significantly increase air conditioning loads. For example, the Los Angeles basin uses 5 gigawatts of air conditioning, an amount which represents $10 billion in power plants and another $5-10 billion for heating, ventilation, and air-conditioning (HVAC) equipment. Ironically, there are indications that much of this need for cooling energy is because of the man-made heat island brought on by urbanization.

Summer heat islands may increase air conditioning demands by as much as 50%. This additional load has a great detrimental impact on summer peaking electric utility companies. The reduction of summer heat islands can save cooling energy, and reduce peak demand, which in turn, like other conservation technologies, can reduce CO_2 emissions from electric power plants. Two potentially cost-effective measures are planting trees and increasing the albedo of buildings, streets, and parking lots.

The Department of Energy (DoE) asked Lawrence Berkeley Laboratory to organize a workshop with invited participation from universities and a variety of governmental, state, local, and research institutions to study issues related to summer heat islands and to address the energy savings potentials and research needs for a nation-wide program. Because of the joint interest and concerns of the U.S. Environmental Protection Agency (EPA), the Electric Power Research Institute (EPRI), and the University-wide Energy Research Group (UERG) of University of California, these institutions co-sponsored the workshop.

Although the workshop was originally intended for one day with 20-30 participants, the overwhelming response to the limited invitations and solicitations for papers resulted in a two-day workshop, with 28 speakers and over 90 participants.

The objective of the workshop was to coordinate a nation-wide effort to study the energy and environmental implications of summer heat islands, with the ultimate goal of identifying and evaluating mitigating strategies and developing policy recommendations to promote energy efficient site design for existing and planned urban areas. The immediate purpose of the workshop was to

- present and discuss recent research concerning causes and characteristics of summer heat islands, their energy and environmental implications, and means of controlling them,
- discuss future research directions, and
- identify existing and potential data sources, and related research activities.

Authors were invited to submit papers in the following areas:

1. **Impacts of Microclimate Changes on Building Energy:** microclimate measurement and simulation, energy conserving site designs.
2. **Characterization of Heat Islands:** data availability for heat islands and micro- or meso-climates, remote sensing techniques, satellite data, correlation between air and surface temperatures, simulation techniques, etc.
3. **Heat Island Mitigation Strategies:** energy conserving urban designs, urban forestry, evapotranspiration rates of trees and urban vegetation, light (reflective) surfaces -- walls, roofs, asphalt.
4. **Global Climate and the Reduction of Atmospheric Emissions:** the potential of summer heat island mitigation measures to reduce CO_2, NO_x, and SO_x and other pollutants, and the implications for global climate.
5. **Policy Issues Related to Heat Island Mitigation Strategies:** financial impacts on building owners and utilities, water issues, implementation tradeoffs and conflicts, and implementation guidelines.

In addition to presentations, the workshop participants attended three study groups to discuss:

1. Microclimate modifications for cooling energy savings, CO_2 reduction, and global warming mitigation;
2. Heat island characterization and modeling; and
3. An outline for a manual for heat island reduction strategies.

The recommendations of the study groups are presented in the proceedings.

The editors have made only minor changes to the Workshop papers submitted for this Proceedings, but each paper was checked for relevance and consistency by at least two technical reviewers. The Proceedings is organized in five chapters discussing:

I. Characteristics and causes of heat islands;

II. Potentials to control heat islands, reduce energy use, and improve environmental quality;

III. Climate models and simulating heat islands, their strengths and shortcomings;

IV. Techniques for measuring heat islands and related characteristics of urban surfaces and urban climate; and

V. Issues related to policy design and implementation of heat island mitigation measures.

Each chapter is preceded by editorial comments summarizing the enclosed papers, discussing their relevance to the subject topic, and highlighting areas requiring further research.

An integral objective of the workshop was to identify needs for future research and development and to prepare detailed research plans for the DoE, EPA, and EPRI. Based on the outcome of the workshop, LBL has prepared a multi-year research plan submitted to the workshop sponsors. On behalf of the DoE, EPA, EPRI, UERG and LBL, the workshop organizing committee would like to thank the authors and participants for their contributions and their active and stimulating participation in the workshop.

Most papers presented in the workshop focused on issued related to urban forestry programs. Although, the energy saving potentials of white surfaces are potentially as impressive as urban trees, the number of papers in this area was very limited, reflecting the fact that there is a greater constituency for urban trees than white surfaces. Some participants suggested a follow-up workshop with a focus on white surfaces.

As the reader will find, in some important areas the workshop raised more questions than it answered. This by itself is a clear indication of lack of knowledge in these areas. We hope that the contents of these Proceedings will constitute a common basis for the development of further research plans on heat island mitigation, modeling, and the assessment of energy conservation, peak power reduction, and the potential for air quality improvement in metropolitan areas.

Hashem Akbari
Workshop Chairman

WORKSHOP AGENDA
DAY 1 THURSDAY, FEBRUARY 23, 1989

Clark Kerr Campus
2601 Warring St., Berkeley, California

MORNING PRESENTATIONS

First Session in Rm 102

Speaker	Organization	Topic
9:00 Akbari	LBL	Summary of Workshop Ideas
9:25 Rosenfeld	LBL	Recent Developments: Technical and Policy
9:50 Oke	Univ. British Columbia	Heat Island Characterization
10:15 BREAK	**In Hall by Room 102**	
CONCURRENT SESSIONS	**Room 102**	**Executive Dinning Room**

Speaker/Topic	Organization	Speaker/Topic	Organization
10:30 Rainer Heat Island Measurements for Sacramento	LBL	10:30 Bornstein Modeling the Urban Boundary Layer	San Jose State Univ.
11:00 Kyaw Tha Paw U Transpir-Evaporation from Vegetated Canopies	UC Davis	11:00 Martien Heat Island Modeling for Bldg. Energy Studies	LBL, UC Berkeley
11:30 Ellefsen/Imamura Remote Sensing of Urban Terrain	San Jose State Univ.	11:30 Pielke Effects of Vegetation on the Urban Boundary Layer	Colorado State Univ.

12:00 LUNCH BREAK	**Dinning Hall**	

WORKSHOP AGENDA
DAY 1 THURSDAY, FEBRUARY 23, 1989

Clark Kerr Campus
2601 Warring St., Berkeley, California

AFTERNOON PRESENTATIONS

CONCURRENT SESSIONS **Room 102** **Executive Dinning Room**

Speaker/Topic	Organization	Speaker/Topic	Organization
1:30 Schmugge Surface Properties and Remote Sensing	USDA Hydrology Lab	1:30 Oke Evapotranspiration from Urban Systems	Univ. British Columbia
2:00 Brest Urban/Rural Albedo from Satellite Observations	NASA	2:00 Imamura Air-Surface Temperature Correlation	San Jose State Univ.
2:30 Chow Shu Djen Five Island Effects of Shanghai	E. China Normal Univ.	2:30 Givoni Effect of Urbanization on Surface Winds	UC Los Angeles

3:00
BREAK **In Hall by Room 102**

3:15
DISCUSSION (3 Groups) **Rooms 102, 104, and 204**

5:30
INFORMAL HOUR **Executive Dinning Room**

6:30
DINNER and SPEAKERS **Garden Room**

Arthur Rosenfeld Energy Efficiency: The Immediate Solution to Global Warming
Michael Totten Global Warming Legislation: Bills and Realities

WORKSHOP AGENDA
DAY 2 FRIDAY, FEBRUARY 24, 1989

Clark Kerr Campus
2601 Warring St., Berkeley, California

MORNING PRESENTATIONS
Room 102

Speaker	Organization	Topic
9:00 Simpson	Univ. of Arizona	Landscape Vegetation to Reduce Heat Islands
9:25 McPherson	Univ. of Arizona	Vegetation to Conserve Water and Mitigate Heat Islands
9:50 Heisler	Northeast Forest Expt. Sta.	Landscaping and Energy Savings
10:15 BREAK	**In Hall by Room 102**	
10:30 Parker	Florida Internat. Univ.	The Impact of Vegetation on Air Conditioning
10:55 Lipkis	Tree People, Los Angeles	Urban Tree Planting
11:20 Clark	Univ. of Washington	Growth Success of an Urban Tree in Three Microclimates
11:45 LUNCH BREAK		

WORKSHOP AGENDA
DAY 2 FRIDAY, FEBRUARY 24, 1989

Clark Kerr Campus
2601 Warring St., Berkeley, California

AFTERNOON PRESENTATIONS
Room 102

Speaker	Organization	Topic
1:00 Moll	Amer. Forestry Assoc.	Trees and Property Values
1:25 Acosta	City of Oakland	Challenges to Planting Urban Trees
1:50 Monismith	UC Berkeley	Light Asphalt
2:15 Beatty	UC Berkeley	Planting Guidelines for Heat Island Mitigation
2:40 Krause	LBL	Tree Planting and Global Climate Stabilization
3:05 Baxter	Calif. Energy Comm.	Global Warming and Heat Islands
3:30 BREAK	**In Hall by Room 102**	
3:45 DISCUSSION (3 Groups)	**Rooms 102, 104, and 204**	
4:30 PRESENTATIONS of group recommendations	**Room 102**	

SUMMARY AND RECOMMENDATIONS OF DISCUSSION GROUP 1

Group 1 Chairman: J. Huang. Notes by J. Huang.

Topic: Microclimate Modifications for Cooling-Energy Savings,
CO_2 Reduction, and Global Warming Prevention.

Trees

The majority of Group 1's discussion was focused on the potentials of trees to save cooling energy. There is general agreement that a *great deal of research* is still needed (particularly on the indirect effects of trees), but there is already *a substantial body of knowledge* that can be turned into a useful manual outlining how trees can be used to save energy and specifying research needs. On a technical level, some thought that it was counter-intuitive that the indirect savings of trees could be greater than the direct savings, in other words it appears that the cooling potential of evapotranspiration has been overstated. On a practical level, it was felt that nuts-and-bolts information is needed to help people to plant the right trees in the right places. This includes even very basic information about how to put a tree in the ground, how big a hole to dig, whether to add mulch, etc. Because of the dangers of overselling a project, some felt that it was better to start small and then build on the experienced gained rather than advocating a massive tree planting program across the nation. It was also mentioned that a distinction must be made between public and private trees and that different programs are needed, targeted at homeowners, city governments, and utilities. Lastly, monitoring is needed on all aspects of tree planting programs, including energy savings, costs, problems, and other benefits.

From a utility's point of view, tree planting is only one of many potential strategies, and would be implemented only if it was proven most cost-effective. Concerns were raised about hidden costs to utilities such as tree trimming and increased power outages. Despite the publicity of Mayor Bradley's recent tree-planting press conference, to date, Los Angeles does not have an implementation plan. On the more positive side, some pointed out that economic calculations about trees should include non-energy benefits such as the higher resale value of the home.

There was some discussion on the water consumption of trees. This is a very site-specific criteria. It was pointed out that even in arid Arizona there is a big difference between Phoenix, which has ample water from the Salt River project, and Tucson, which uses expensive ground water. When the cost of water is added in an economic analysis, the choice of tree type is very important.

There was also some discussion on the impact of trees on smog. It was pointed out that some trees (notably conifers) emit terpenes which can exacerbate urban smog. For example, in Atlanta certain types of trees are not allowed. With these two caveats in mind, it was generally agreed that trees in tune with the local ecology should be selected.

There was general agreement that urban trees reduce CO_2 more effectively than forest trees by curbing electrical demand. However, it was also pointed out that saving forests is far less costly than planting new forests, and that there are many ecological benefits to forests beyond sequestering CO_2.

Light surfaces

Compared to trees, there were fewer technical issues about the use of light surfaces in reducing the urban heat island. Some questions were raised about the potential problems with glare, and the increased reflected heat into a building due to lighter albedos of its surroundings. Possible implementation strategies for light surfaces included energy standards or incentives. It was felt that mandated colors on residential houses might be too restrictive to be accepted, but that small commercial buildings with flat roofs would be good candidates for a pilot conservation program. Although light surfaces do not have the aesthetic appeal of trees, they have the advantage of being potentially cost neutral. In other words, if light-colored roofing and surfacing materials are available at the same cost as dark-colored ones, they could be used at roof or surface replacement time at no added cost.

SUMMARY AND RECOMMENDATIONS OF DISCUSSION GROUP 2
Group 2 Chairman: B. Bornstein. Notes by B. Bornstein (with editorial changes by J. Huang and P. Martien).

Topic: Heat Island Characterization and Modeling

Mathematical models have been developed for simulating both the mesoscale climate (climate of the entire city and its surroundings) and the microscale climate (adjacent to individual buildings). (See Chapter 3.) These models may eventually provide the means to predict changes in climate that result from city-wide modifications in vegetation and surface reflectivity. The ability to make such predictions allows us to investigate the effectiveness of various strategies to reduce climate-dependent energy consumption in buildings, and to quantify the relative costs and benefits of such strategies.

However, before researchers can reliably use climate models for this purpose, further testing against measured data is required. The discussions of Group 2 focused primarily on this issue. The group identified the types of measurements required to validate mathematical models of urban climate, particularly urban boundary-layer models (UBLM's), which simulate mesoscale conditions in the bottom one or two kilometers of the urban atmosphere. It was agreed that these models, once validated, could be useful in addressing questions related to heat islands and energy use in urban buildings. The group briefly considered how the UBLM's could be used alone and in conjunction with the smaller scale urban canopy-layer models (UCLM's), which simulate microscale conditions below the urban canopy.

The most important point which came out of the discussions was the need for area-averaged measurements (integrated over relatively homogeneous land-cover areas) of drybulb temperature T*, specific humidity q*, and wind speed U*. These measurements should be made at a height above buildings and canopy cover. For a typical residential neighborhood, a height of ~30 meters is probably appropriate. Above the street-level circulation, one encounters the so-called constant flux layer (CFL) where the turbulent energy fluxes are approximately constant with height and air flow is well mixed so that measurements are representative of large land-cover areas. The height of the base of the CFL has been observed to depend on the horizontal spacing of the surface roughness elements (for example, buildings). Similarity theory can be used to approximate atmospheric conditions in the CFL.

Spatially-averaged measurements made in the CFL are useful in applications related to building-energy research for two reasons: 1) In making predictions of how climate adjacent to buildings responds to large-scale changes in surface characteristics (such as vegetation and surface reflectivity), we must be able to approximate conditions in the urban boundary layer (See Martien et al., Chapter 3). The UBLM's offer a way to do this, but they must first be validated using measured data. Since UBLM's are unable to resolve small-scale features and assume that the flow near the earth's surface is described by analytical equations derived from similarity theory, measurements to validate the UBLM's should be made in the CFL. 2) Whereas "standard" 1.5 meter observations tend to be specific to a particular microclimate, the CLF measurements provide averaged climate information, which is more appropriate for analyzing the effect of various urban land types on energy use. It is not surprising that an averaged measurement is more representative of a given land type since the land type is itself an average of a collection of individual buildings, roads, trees, etc.

It was suggested that measurements of turbulent fluxes of heat and moisture and radiative energy fluxes could be made from aircraft observations to determine conditions in the CFL. While this may be possible in theory, in practice it is probably difficult to obtain permits to fly close enough to the ground to obtain surface boundary-layer measurements above urban areas. Perhaps a more feasible alternative is to use 30-40 meter instrumented towers at several locations within a city.

Once obtained, values of T*, q*, and U* will be

(a) used to validate UBLM's

(b) correlated with "standard" observations of 1.5 meter quantities.

(c) correlated with levels of energy use within the area over which the area-average quantities are obtained.

Observed fluxes (as well as additional sources of data, including wind tunnel observations) will be used to

(a) validate the results of the UBLM's.

(b) develop parameterizations of canopy-layer fluxes to be incorporated into the lower boundary conditions of UBLM's.

The UBLM's, thus validated, can then be used to

(a) Predict the change in T*, q*, and U* that would result from prescribed alterations in the thermal and radiative properties of the canopy layer induced by activities such as tree planting and painting buildings with light colors.

(b) Provide upper boundary conditions for UCLM's, which could then be used to study the relationships between the T*, q*, and U* values from the UBLM and the near-surface (~1.5 meters) values that the UCLM predicts.

The UCLM's can then be used to predict the energy savings associated with a single building due to the microclimate effects of trees or white surfaces. Cost-benefit analyses of these strategies may then be carried out.

SUMMARY AND RECOMMENDATIONS OF DISCUSSION GROUP 3

Group 3 Chairman: A. Rosenfeld. Notes by A. Rosenfeld and M. Totten.

Topic: A Manual on Summer Heat Island Reduction

The participants of Group 3 agreed that a manual on summer heat island reduction should be produced. Its audience would be primarily elected and appointed officials at the national, state, regional, and city level. It would also provide practical information to utility officers and federal and international officials concerned with global warming who are considering funding tree planting to offset CO_2 produced by power plants.

It is proposed that the manual will include a brief description of summer heat islands and their costs and will be a repository for data on major US heat islands. The principal contribution of the manual will be in providing practical information on heat island reduction through tree planting and increased urban albedo (reflectivity). Topics requiring further research will be specified.

The manual will make recommendations for immediate and long-range implementation of heat island mitigation measures. This section will include model ordinances and discussion of community design and planning. A final section will incorporate new ordinances as they are developed and ongoing evaluation of heat island mitigation projects as they occur.

An outline of the proposed manual is presented below.

A. OVERVIEW

A-I. Urban Heat Islands, History and Prospects. [Ken Andrasko, EPA]

Causes: cutting down vegetation and trees, introducing blacktop, etc.

Result: temperature increases already of 5-10 °F, and rising up to 1 °F/decade.

Costs--in the U.S.: peak power demand and capital expense for air conditioning, with total US electricity costs approaching $1M/hour on a hot afternoon. Smog: perhaps one-third of smog incidents are attributable to the 5-10 °F temperature rise. More electricity means even more smog and more acid rain.

Costs--Global: CO_2 and global warming.

Prospects for Reduction: it should be possible to reduce heat islands at low cost, at least fast enough (say 1 °F/decade) to offset the global warming of cities, and perhaps even to turn them into oases of "coolth." The solution is whiter surfaces (particularly asphalt, also roofs and walls, in order to transform heat-absorbing surfaces into heat-reflecting ones) and to plant trees.

These measures are bound to be cost-effective because a house can be painted in a light color for no extra cost when it needs repainting or reroofing anyway, and it can be shaded by planting 1-inch diameter/18-gallon trees for $50 or less, one time only. But ANNUAL air conditioning savings will be around $100 for houses in hot cities. And, if sufficient numbers of trees are planted, these measures will also cool the neighborhood.

Emphasize the difference between summer and winter heat islands. Summer heating occurs because more solar energy is absorbed by urban than rural environments. In winter, when there is less available solar radiation, heating is caused mainly by cars and heat leaking out of buildings and reduced radiation to the night sky. Reducing the summer heat island has little effect in winter when there is less sunlight to be absorbed by asphalt and buildings, and deciduous trees are bare.

A-II. Light-Colored Surfaces. Descriptive. [LBL]

A-III. Tree Planting. [Andy Lipkis, TreePeople]

Benefits: (long list).

Issues: Perhaps suggest no further loss of urban trees. New communities should plan to preserve as much existing forest as possible.

A-IV. Urban vs. Rural Trees. [Roger Sant & Roger Naill, Applied Energy Services; LBL]

Possible net benefits of urban trees include: atmospheric CO_2 reductions by avoided electric power and carbon sequestered directly from environment, air filtering, increased property value, wildlife habitat, etc.

Net benefits of rural trees include: CO_2 sequestering, wildlife habitat, watershed protection, etc. Cost higher in city, but benefits are too.

A-V. Urban Trees and Water. [Karina Garbesi, LBL]

We must distinguish several different regions:
-- Wet (e.g., the Eastern US)--no water problem. Direct shading of homes is valuable, but since the air is moist, evapotranspiration is low, and trees might be less effective relative to white surfaces in reducing heat islands than in dry cities.
-- Semi-Arid (e.g., Los Angeles). Native trees need watering for a few years, but

then their roots find ground water. Eventually, if they shade lawns, they actually reduce demand for city water.
-- Arid environments. Native trees may not give adequate shade. Does it pay in a given community to choose trees which need watering when mature?
-- General. How densely can we plant trees in dry cities before we use up available ground water? Properly planted vegetation could actually increase available ground water by reducing runoff. Where to go for regional information on ground water and evapotranspiration ratio of various trees?

A-VI. Heat Island Data. List and maps of major US heat islands. Include temperatures since 1940 and peak power vs. temperature. [EPRI, LBL]

B. IMMEDIATE STEPS

B-I. Quantitative Outline of Measures to Reduce Heat Islands. [LBL; Rowan Rowntree, US Forest Service; Gordon Heisler, US Forest Service]

Whiter surfaces:
--Information and labels on albedo (reflectivity to sunlight) of paints, roofing tiles, and road surfaces.
--Whiter surfaces and glare.

Trees:
--Species selection. Outline criteria for choosing among species. Considerations include, for example, water consumption, survivability, deciduous/non-deciduous, etc.
--Trees as air polluters (isoprene, alpha-pinene, etc.) and air cleaners; how much do they reduce airborne particulates, particularly respirable particulates?
--Other planning issues.

Each measure to have cost/benefit analysis, including maintenance, savings potential, and impact on real-estate values.

Water costs. Include, for example, the use of waste stream water for trees and urban composting; both make trees more cost-effective.

B-II. Implementation: Private/Commercial/Public. [Neil Sampson, American Forestry Association]

Suitable species: Too big and region-specific for this handbook, but we can point to sources and supply samples. We badly need information on gaseous reactive hydrocarbon production by various species because hydrocarbons feed smog.

Sources of funds (federal, state, agency, corporate, etc.)

Human resources: summer youth, school clubs, scouts, prisoners, etc.

Education and training: Liaison with Arbor Day Foundation, etc.

Information programs and public education.

Master planning for states, counties, cities.

B-III. Demonstration and Evaluation.

1. Cool Schools. [LBL]
2. Tree Survival. [US Forest Service or Coop Extension]
3. Review the results of existing projects, e.g., forests in China, Kibutzim in Israel, Professor Parker's experiments in Florida, McPherson's experiments in Arizona, etc.

B-IV. Model Ordinances for Streets, Parking Lots, and Buildings.

C. LONG-RANGE IMPLEMENTATION

Community Design: new and existing. [Russell Beatty, Landscape Architecture, UC Berkeley; Ed Vine, LBL]

D. EXPERIENCE

This section will keep up with what states, cities, utilities, etc., are doing. It will grow fast, and it should be loose-leaf. [Greg McPherson, Landscape Architecture, U. of Arizona; American Society of Landscape Architects]

Case studies as they develop.

Incentives and model ordinances as they are written.

E. RELATED ISSUES

Not to be covered fully here but briefly discussed, with references to published work and work in progress. [Andy Euston, HUD; Rowan Rowntree, US Forest Service]

Aesthetics, public safety, community support.

International: Spreading the word to Mexico City, etc., foreign visitors to US laboratories and programs.

Conferences and communication.

CHAPTER 1

Characterizing the Urban Heat Island

Chapter 1

EDITORS' INTRODUCTION TO THE URBAN HEAT ISLAND

This note summarizes the characteristics and causes of the urban heat island by briefly reviewing earlier research on heat islands and their implications for energy-use and air quality. The analysis of causes and implications of heat islands suggest two techniques for reducing their intensity: increasing urban tree cover and increasing the overall reflectivity (whitening) of urban surfaces. Research on the potential of these techniques to cool urban areas and reduce energy use is currently under way at Lawrence Berkeley Laboratory.

The urban heat island is a well documented phenomenon (Landsberg 1981; Lowry 1967). It refers to the observation that most cities are warmer than their rural environs, especially in the late afternoon and at night. For example, the summer heat island intensity of St. Louis, Missouri, is about 5 ° C at night and 1 ° C at noon (Vukovich *et al.* 1979). The heat island is defined as the average temperature difference between the urban and the surrounding rural area (historically based on **air**-temperature measurements). However, the term is now used more broadly to include smaller-scale temperature differences and differences based on surface temperature. Heat island intensity differs in different parts of the city, the greatest intensity usually being in the most densely built areas. Increased temperatures due to summertime heat islands increase cooling-energy needs (Akbari *et al.* 1988) and smog formation rates (Kamens *et al.* 1981, Penner *et al.* 1988). The larger the city, the more intense the summer heat island (Oke 1973), and the greater the air conditioning load and the outdoor discomfort.

Researchers have started to look at the causes and implications of the heat island, and have correlated its magnitude to the activities within and the physical characteristics of the city, such as the rate of anthropogenic heat loading (Torrance and Shum 1975), the concentration of pollutants (Bennett and Saab 1982, Vukovich *et al.* 1979), the thermal storage capacity (Myrup 1969, Atwater 1972), and the net albedo (reflectivity) of the urban surface (Taha *et al.* 1988). The amount of vegetation cover is also an important determinant of heat island intensity, because latent heat loss by vegetation decreases the energy available for heating the near-surface air (Oke 1987). The effect of the canyon geometry of city streets on the energy balance of the city has also been considered (Nunez and Oke 1976), and the nocturnal heat island intensity has been related to the sky view factor (Barring and Mattson 1985).

In fact, all of these factors work together to create the urban heat island. Understanding these interactions and isolating the dominant causes, can facilitate the mitigation of heat islands in warm climates or their enhancement in cold. In the past two decades researchers have attempted to simulate heat islands with one, two, and three dimensional models (see Chapter 3 of this Proceedings). For an overview of modeling research on heat islands see Bornstein (1984).

On a qualitative level, traditional and scientific observations indicate that there are simple ways to reduce the heat island effect, at least at the microclimate (neighborhood) level. Traditional urban architects in hot climates have used whitewashed exterior walls and shade trees to reduce solar gain. The effects of these simple techniques, however, have not been quantified, nor do they specifically address the possibility of changing the climate of the city as a whole.

The heat islands research at Lawrence Berkeley Laboratory and the papers in this Proceedings focus primarily on two mitigation strategies that have the potential to alter the urban climate at the mesoscale (city-wide) as well as the micro-scale: increasing urban albedo and increasing tree coverage. The two methods can act at the mesoscale, altering the energy balance of the city as a whole by decreasing absorption of solar radiation at the surface and increasing latent heat loss. Or they can act at the microscale by shading, thereby changing the heat balance of individual buildings. Since the goal is to decrease cooling-energy use in buildings, the interest is in the near-surface climate.

UNDERSTANDING THE URBAN HEAT ISLAND

The best way to understand the heat island phenomenon is to consider the basic energy-balance equation for the urban surface:

$$A + R_S - R_L = A + R_N = LE + H + G,$$

where,

A is the anthropogenic heat flux,
R_S is the total short-wave radiation absorbed at the surface (direct and diffuse),
R_L is the net outgoing longwave radiation at the surface,
R_N ($= R_S - R_L$) is the net shortwave plus longwave radiation at the surface,
LE is the latent heat flux,
H is the sensible heat flux, and
G is the downward ground flux (by heat conduction).

On a cloudless summer day, the average insolation is about 500 W/m^2 (with a maximum of about 800 W/m^2), and is the dominant term in heating the city. Urban air pollution acts to attenuate R_S by about 15-20% (Landsberg 1981), reducing the intensity of direct solar energy at the surface by atmospheric absorption, reflection and scattering. This effect is countered by the fact that urban albedo ($\sim$0.15) tends to be lower than rural values (often $\sim$0.25), resulting in a relative increase in absorption by the urban surface. Anthropogenic heat, A, is usually an order of magnitude lower than the solar gain in the summertime, and its effect is overshadowed by other features of the city that intensify solar gain, such as generally lowered albedo and evapotranspiration (due to reduced vegetation). In contrast, during the winter, in mid- and high-latitude cities, man-made heat constitutes an important contribution to the heat load.

The longwave radiation budget depends on the balance between the radiation entering and leaving the surface. The incoming longwave radiation is about 5% higher in cities than in rural areas (Landsberg 1981). The outgoing radiation is primarily a function of the surface temperature, which in turn is determined by the heat balance equation. Limited vegetation in urban areas can result in higher surface temperatures and, consequently, higher outgoing radiation. This in turn reduces the net absorbed radiation, R_N. By contrast, increased vegetation would result higher net absorbed radiation.

The net absorbed radiation is channeled into three major fluxes: latent heat and sensible heat moving upwards away from the surface, and the ground flux moving downwards during the warming period and upwards during the cooling period. It is the division of the net incoming energy into these fluxes that determines the intensity of the heat island. In areas where evapotranspiration is high (heavily vegetated areas and free water bodies) most of the incoming energy goes into evaporating water. Therefore, less energy is left for sensible heat, resulting in lower daytime temperatures. Under these conditions, at solar noon, usually more than 50% of R_N will go into latent heat flux and the other 50% is about equally divided into sensible and ground fluxes. This is a typical condition of green rural areas (Oke 1987).

In arid areas, sensible heat flux, H, is the dominant element of the energy balance and carries off more than 50% of the R_N. The ground heat flux usually accounts for 30-40% of the heat gain, and the latent heat flux is limited to the remaining 10-20%, or in some cases much lower. This is the case for desert areas where it is extremely hot during the day and cools rapidly after sunset, when R_S goes to zero.

Thermal storage also affects the urban energy balance. Use of heavy construction materials in city streets and buildings results in a higher thermal storage capacity. During the daytime, a substantial amount of energy is stored in building materials. That energy is released slowly during the night. Stored heat can be both beneficial and detrimental to cooling-energy requirements. The process of heat storage delays temperature rise, and thus the time of peak cooling demand during the day. The slow release of the stored heat during the night, however, tends to accentuate the nighttime heat island. It is this slow release of stored energy that causes the maximum heat island to occur during the evening, when the rural areas, with their small heat storage capacity, cool more rapidly.

During the day the lower urban concentration of vegetation and, therefore, low source for evapotranspiration, is generally more important than thermal storage. More energy goes into sensible heat flux and thermal storage (Nunez and Oke 1977), resulting in higher temperatures in the city than in rural areas. In American cities, the daytime peaks are higher only by ~2 °C, but in some Latin American cities with little vegetation, 8-10 °C heat islands have been recorded (Lombardo 1985). In desert cities, urban landscaping may produce more evapotranspiration than the surrounding desert, actually lowering the temperature of the city below that of the surrounding area. This is referred to as the "oasis" effect (Oke 1987).

The focus of this Proceedings is the summertime heat island, the potential for its mitigation, and the resultant potential for cooling-energy savings. A logical objection to such an approach might be that measures to reduce the harmful summer heat island could also reduce the beneficial winter heat island, offsetting the summertime benefits. Fortunately, measures to reduce summer heat islands, in particular whitening surfaces and planting trees, should have a significantly lower effect in winter for a number of reasons. Lower wintertime insolation due to cloud cover and lower sun angle reduces the relative impact of increased albedo in wintertime, and the decrease in wind offered by an increase in vegetation actually reduces heating-energy needs.[*] This argument is in part supported by McPherson (Chapter 4, herein) who modeled the energy/water use over the entire year in a single family home with various landscapes and found that the house with shade trees offered net positive energy savings at the least total energy plus water cost.

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[*] Furthermore, "warm" cities have relatively low heating energy requirements. However, this fact should not be overemphasized since mitigation of summertime heat islands is also beneficial in cities with hot summers and cold winters.

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CHARACTERIZATION OF URBAN HEAT ISLANDS

T.R. Oke
Atmospheric Science Programme, Department of Geography
University of British Columbia

ABSTRACT

The definition and characteristics of urban heat islands are reviewed.

The first part stresses the need to carefully define the type of heat island under study. Lack of methodological rigour lies at the heart of too many investigations in this field. It is suggested that the basis of any definition must include the scale of enquiry, the medium under study and the sensing technique. Arising out of these thoughts a simple classification scheme is forwarded. Failure to adhere to these matters can lead to faulty experimental design of observational and modeling studies which in turn produce misunderstanding and misinterpretation and hamper the intelligent development of urban design strategies.

The second part considers, in a general way, the energetic causes of heat islands and the multiple controls governing their form and magnitude at any given time and place, including land-use, weather, season, city size and macroclimate.

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CHAPTER 2

Mitigation of Urban Heat Islands: The Potential to Conserve Energy, Reduce Air Pollution, and Slow Global Warming

Chapter 2

MITIGATION OF URBAN HEAT ISLANDS: THE POTENTIAL TO CONSERVE-ENERGY, REDUCE AIR POLLUTION, AND SLOW GLOBAL WARMING (Editor's Summary)

The papers in this chapter demonstrate the energy conservation potential of mitigating summer urban heat islands. Two mitigation methods show great promise and are considered here: modification of urban surface albedos (reflectivity) and increase in tree coverage. Much more emphasis is placed on trees than albedo because there has been more study of trees—the effect of trees being an intrinsically more complex problem. Preliminary estimates, however, suggest that the two mitigation techniques are similarly cost effective means of reducing cooling-energy needs in hot cities.

In the first paper by **Akbari** *et al.* the authors provide evidence that heat islands in hot cities have increased energy use and urban smog problems. In a follow-up paper, **Akbari** *et al.* extrapolate from earlier studies to conclude that increasing urban albedos (reflectivity) and tree cover are probably the most cost effective means we know of to reduce energy use and peak power, although trees and light surfaces probably provide less total potential for reducing energy use nation-wide than energy efficient cars. It should be emphasized that these estimates of the nation-wide conservation potential are based on extrapolations from preliminary studies of energy-savings based on modeling the effects of trees and light surfaces on single family houses. As such they provide good order-of-magnitude estimates of the potential for energy and carbon conservation, rather than precise quantitative measures.[1] Despite this fact, the finding that trees and white surfaces could very well be the least expensive ways of reducing energy use, is certainly enticing and justifies the increasing public attention these measures are receiving.

The next three papers (Parker, McPherson, and Simpson and McPherson) consider energy savings from microclimate modifications by planting of trees and shrubs next to buildings. Although planting around a single building does not affect the urban heat island as a whole, the impact on per-dwelling energy use is significant, and these studies indicate the potential for savings at a larger scale. **Parker** summarizes results of measurements made around an uninsulated mobile building in the hot, humid south of Florida. He found that the trees and shrubs planted around the building reduced cooling-energy requirements by up to 55% on warm summer days.

McPherson and **Simpson and McPherson** raise an issue critical for the arid west of the United States—the tradeoff between energy and water if vegetation is used to conserve energy use in buildings. These papers present the results of computer

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[1] Akbari's estimates of per-dwelling savings are supported by measurements and modeling of other researchers. See, for example, McPherson, Parker, and Simpson and McPherson in this Chapter.

modeling and measurements of cooling-energy and landscape-water use for various landscapes around houses in Phoenix and Tucson, Arizona. The authors considered three landscape types: one primarily gravel, one primarily lawn, and one primarily low-water-use plants and shrubs. Both studies found the landscape with low-water use plants and shrubs to minimize the total energy-water cost. More research of this sort for other western cities would be very useful since the cost and availability of both energy and water are likely to be quite volatile in this area in the future.

Baxter *et al.* use preliminary estimates from research at Lawrence Berkeley Laboratory (summarized by Akbari in this Chapter) of potential energy-savings from albedo modifications and tree planting to determine if increases in California's cooling-energy demand from future global warming might be offset. The authors found that full implementation of these mitigation measures "nearly offset" the estimated increase in net annual electricity use by buildings of the worst-case global warming scenario. A predicted increase of about 4950 GWh by the year 2010 was reduced to an increase of only 350 GWh by trees and light surfaces. Again it is emphasized that these results contain a high degree of uncertainty as they are based on large-scale cooling-energy savings extrapolated from a simple models of energy use in single buildings.

The final paper by **Krause and Koomey** compares the cost of net sequestered and conserved carbon from rural tree planting, urban tree planting, and energy efficiency improvements from the perspective of an electric utility. The study found urban trees to be comparable in cost to conservation. But the authors assert that trees are subject to a larger number of constraints than energy-efficiency improvements. While this is certainly true for efficiency improvements which are unrelated to climate, for example, increased gasoline efficiency in automobiles, this might not be the case for many climate related measures such as improved building insolation, more efficient air-conditioning, etc. The issue of which measures are most applicable and can yield the greatest energy savings deserves further study. Krause and Koomey found the planting of rural trees to be the most costly approach for the utility. The paper provides an excellent framework for assessing the economic merits of the various techniques, but has limited applicability since the focus is restricted to costs and benefits to the electric utility. This paper could provide a basis for a broader study that considers the costs and benefits to other sectors of society (such as the home owner, commercial businesses, etc.) and accounts for non-energy related benefits of the various mitigation techniques.

Indeed, when reading these papers one should bear in mind that their focus is generally limited to the benefits derived directly from a reduction in energy use, except in McPherson and Simpson and McPherson, who consider the economic trade-offs between energy and water. However, in general, energy-conservation benefits are a subset of the benefits that might be derived from conservation via mitigation of heat islands. Whereas all conservation techniques provide numerous environmental, social, and political benefits in direct proportion to their reduction of energy use, cooling hot urban environments provides additional benefits such as improved outdoor comfort. If trees are used, a host of secondary benefits may accrue, such as control of storm-water runoff, enhanced groundwater recharge, increased wildlife habitat, direct sequestering of carbon dioxide from the atmosphere by photosynthesis, provision of fruit, and an improved aesthetic environment. Tree planting can also increase property values—an economic incentive to property owners that could have both positive and negative effects on the rest of society. Trees also can have negative effects such as damage to overhead power lines, damage to sidewalks and streets by tree roots, and damage to buildings and cars by falling limbs. These factors have not been considered in the studies in this Proceedings, but should be included in some way if we are to maximize the benefits derived from conservation programs.

There are a number of related issues that merit research. Although there is a lot of evidence that trees and white surfaces can alter the microclimate in their vicinity, there has been less study of the potential for a large-scale implementation program to alter the urban climate as a whole. If hot cities (dry cities in particular) contain enough space to increase tree cover significantly, then the heat balance of the city can be altered, decreasing sensible heat and increasing latent heat loss through transpiration. Similarly, if albedos of cities can be significantly increased, accounting for deposition of particulates and detritus and the geometry of the rough urban surface, net absorption of short-wave radiation could be significantly reduced, lowering the energy available for transformation into sensible heat. The resulting mesoscale cooling of the air above the city could reduce temperature-dependent smog formation and the emissions of smog precursor gases via volitalization as well as reducing cooling-energy use and associated emissions from the burning of fossil fuels. This is a timely area of study because of numerous proposals for large-scale tree planting in cities[1] and the continuing nonattainment status of air quality in many cities.

Any study of the potential to alter urban climate with large-scale tree planting will also require a realistic assessment of the water requirements of trees. In arid cities where the gains due to increased transpiration by trees would be the largest, water availability is generally limited. The question then becomes: Is soil water availability in representative cities large enough to support a significant increase in the urban forest without a large increase in the application of surface water? If low-water-use plants are used, the question then becomes: Will the increase in transpiration be sufficient to change the heat balance of the city? Such questions will need to be answered to estimate the net benefit of planting large numbers of trees in cities, and to understand what approaches will maximize these benefits.

Similarly, research on the potential to reduce urban temperatures by increasing surface albedos must account for changes in urban surfaces after installation. High rates of

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[1] For example, in October of last year Tom Bradley, the Mayor of Los Angeles, announced a program to plant 5 million trees in Los Angeles as part of Global Releaf, the American Forestry Association's nationwide campaign to plant 100 million trees by 1992.

particulate deposition in large cities dull reflective surfaces making them more absorptive, as can detritus from vegetation, people, and animals. Similarly, dark surfaces bleach out in the sun—all surfaces "graying" with time. Despite these problems, it appears that many strategic surfaces (such as roofs) could be lightened, and provide a possibly significant positive feedback working in our favor. Increased albedo cools the urban surface, resulting in reduced burning of fossil fuels for cooling-energy, and consequently reduced particulate loading. This translates into reduced surface graying, which is equivalent to increased surface albedo. This reinforces the original modification and the entire process results in an overall improvement in the urban environment: increased thermal comfort, cleaner surfaces, and cleaner air.

A final word is necessary on the interaction between trees and white surfaces. It must be acknowledged that, to some extent, tree planting and whitening of urban surfaces are competing techniques. Dark colored trees have relatively low albedos, and there is some indication that overly high albedos can cause excessive radiation loads on trees resulting in reduced function. Clearly further thought will be required to optimize the benefits of these two techniques. We could increase the albedo of those surfaces which will tend to remain lighter and which receive the highest radiant loading, such as roofs. Trees could be planted in areas of currently low albedo, which are less likely to remain light anyway, in parking lots, over lawns, along streets, etc. All of these issues will require more thought if we are to optimize the benefits to be derived from the mitigation of urban heat islands.

RECENT DEVELOPMENTS IN HEAT ISLAND STUDIES: TECHNICAL AND POLICY

H. Akbari, A. Rosenfeld, H. Taha
Applied Science Division
Lawrence Berkeley Laboratory

ABSTRACT

This paper summarizes the recent work at Lawrence Berkeley Laboratory (LBL) to quantify the effects of summer heat islands on the utilities' electric load and urban smog, both in the short and long terms. We have started to analyze 100-year temperature trends in several U.S. cities. Since ~1940 there has been a steady overall increase in urban temperatures. Summer monthly averages have increased by 0.25-1 °F per decade (~1 °F for larger cities like Los Angeles and 0.25 °F for smaller ones). There is no evidence that this rise is moderating, and reports suggest global greenhouse warming will add a comparable rise. Typical electric demand of cities increases by 1-2% of the peak for each °F, and most major cities are now ~5 °F warmer than they were in the early 1900's. Hence, we estimate that about 5-10% of the current urban electric demand is spent to cool buildings just to compensate for the heat island effect. For example, Downtown Los Angeles is now 5 °F hotter than in 1940 and so the L.A. Basin demand is up by 1500 MW, worth $ 150,000 per hour on a hot afternoon (the equivalent national bill is ~$1M/hour). Smog is another consequence of higher urban temperatures. In major cities, there are no smog episodes below about 70 °F, but they become unacceptable by 90 °F, so a rise of 10 °F, because of past and future heat island effects, is very significant.

KEYWORDS: electric demand, heat islands, smog, temperature trends, utilities

RECENT DEVELOPMENTS IN HEAT ISLAND STUDIES: TECHNICAL AND POLICY

H. Akbari, R. Rosenfeld, H. Taha
Applied Science Division
Lawrence Berkeley Laboratory

INTRODUCTION

In hot climates, summer urban heat islands significantly increase cooling energy use and peak demand. In the long term, cities are getting warmer than their suburban and rural surroundings [Karl et al. 1988, Kukla et al. 1986], and as we show in this paper, this long term warming is responsible for an increase of 1-2% in cooling loads (with respect to the peak) for each °F raise. As temperature rises, so does the severity of smog and the production of other airborne pollutants.

The objective of this paper is to track the long term temperature trends in major U.S. cities and present snapshots of temperature-dependent loads in some of them. We do so in order to propose some heat island mitigation strategies to reduce smog and the need for cooling energy.

LONG TERM TEMPERATURE TRENDS IN SELECTED CITIES

Temperature data for our analysis were obtained from the Carbon Dioxide Information Analysis Center [CDIAC 1987] and Goodridge [1987,1989]. The data we present have been adjusted for weather station moves (relocation), change of height, time of observation bias, change in type of instruments, and discontinuity in record [Karl et al. 1986,1987]. They have not been corrected for urban growth (population) effects.

We first present **Los Angeles**, a large metropolis with a mild to warm climate. **Figure 1** depicts the annual temperature highs between 1877 and 1984. A polynomial is fitted to the data to highlight the mean trend. It clearly indicates that Downtown Los Angeles was cooling at a rate of 0.05 °F/year up to 1930 and then started a steady warming of 0.13 °F/year (1.3 °F/decade) afterwards. In other words, Downtown Los Angeles's annual high temperatures are now ~6 °F higher than they were in 1940. In **Figure 2** we study the post-40's warming trend in further detail. We can see that the summer months' average temperature slopes are in the range of 0.11 - 0.13 (±0.02) °F/year. The plot of annual averages shows a relatively smaller slope, indicating that winter temperatures are rising more slowly.

Figure 3 depicts the long term trend in annual mean temperatures in **Washington D.C.** between 1871 and 1987. We can see that after 1900, there has been a steady rise of 0.5 °F/decade and that the total rise over 80 years is about 4 °F. Contrary to

Los Angeles, whose temperatures were all urban (**Figures 1 and 2**), Washington D.C.'s urban weather stations moved to airport locations in 1942[1].

Our data indicate that this recent warming trend is typical of most U.S. metropolitan areas. As an example, we discuss some California cities. **Figure 4** [Goodridge 1989] shows that before 1940, the average urban-rural temperature differences for 31 urban and 31 rural stations in California were always negative, i.e., cities were cooler than their surroundings (both annual and 10-year averages show this). We speculate that this was a result of oasis effects in the relatively more vegetated city centers. After 1940, when the built-up areas became larger than the vegetated ones, the urban centers became as warm or warmer than the suburbs, and the trend becomes quite obvious after 1965, with a slope of about 0.7 °F/decade. The heat island effect has thus become dominant in these urban areas.

Figure 5 [Goodridge 1989] shows the spatial distribution of temperature trends in California. Areas near San Diego, Los Angeles, San Francisco, and Sacramento have trends exceeding 0.4 °F/decade, i.e., it will take them less than 25 years to become 1 °F warmer than before. Our data indicate that the August warming trends in San Diego CA and San Bernardino CA are, respectively, 0.8 °F/decade and 0.6 °F/decade. Maximum temperatures in Davis and Pasadena CA, of ~0.8 and ~0.9 °F respectively, also show these trends.

In the near future, we will be studying in more detail the long-term heat island trends in large cities such as New York NY, Atlanta GA, St. Louis MO, Houston TX, Chicago IL, and Miami FL. The success of such a study depends on the availability of long and reliable urban climate records.

COOLING LOADS VERSUS TEMPERATURE: EXAMPLES FOR 1986

We study the correlation between cooling loads and the heat island intensity by examining the dependence of system-wide utility load on dry-bulb temperature in selected locations. In this paper we discuss examples from the Los Angeles Department of Water and Power (LADWP), Southern California Edison System (SCE), and Washington D.C.[2].

Figures 6a,b depict the data for Los Angeles. In **Figure 6a**, 4-pm load is plotted against 4-pm temperature for 365 days in 1986. We can distinguish some weekend

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[1] Up to 1942, the data are for Downtown Washington weather stations, but after 1942, the stations moved to airports. **Figure 3** thus depicts data from different locations. So while we need urban heat island information, the last forty years provide us with airport data (adjusted or unadjusted), which may underestimate the urban effects, because cities warm up faster than the suburbs, where airports are usually located. This is not only the case with Washington D.C., but also with most major cities in the U.S. We are not aware, as of this time, of any continuous **urban** temperature data base for the last 100 years (except for Los Angeles and San Francisco CA), and we believe that monitoring of this kind should be undertaken, if city-wide energy use is to be better understood and mitigation strategies properly applied.

[2] We chose 1986 because weather and load data were already available.

scatter, base load scatter, and temperature-dependent cooling load. The peak demand slopes at ~72 MW/°F (2%/°F). In **Figure 6b**, the same procedure is repeated by plotting peak load (at 4pm) against average daily temperature, for 365 days in 1986. The same overall pattern prevails, but the slope becomes 75 MW/°F, still about 2%/°F of the peak. Recalling that the city of Los Angeles has warmed by ~5 °F since 1940 (**Figure 2**), we can see that we have incurred an increase of 375 MW or 10% of the current peak load.

In **Figure 7**, a similar plot is constructed for the Southern California Edison (SCE) System[3]. The 4-pm loads are plotted against the daily average temperatures for 365 days in 1986. Although temperature data from the Edison system area were available, we plotted the SCE load against the LADWP temperatures, so we can consistently use these reference temperatures[4] and compare them with the long term trend shown in **Figures 1 and 2.**

We can see in **Figure 7** that the peak slopes at 225 MW/°F or about 1.6%/°F. If we add this to the LADWP slope (75 MW/°F), the total reaches 300 MW/°F, and for the 5 °F rise since 1940, that means ~1.5 GW of heat island-dependent load. If peak electricity is worth 10¢ /kWh, then this represents $150,000/°F for each hour.

For Washington D.C. (**Figure 3**), the slope is 100 MW/°F (2%/°F of the 5200 MW peak). So for an increase of 4 °F over the last 80 years, this is an additional 400 MW, and at 10¢ /kWh, this is equivalent to $40,000/hr. There are about 1300 hours of air-conditioning in D.C., resulting in ~$50M every year.

We now discuss the relation between heat islands, which can be controlled, and global warming, which will probably add another 0.5-1 °F/decade before it is brought under control. The pessimistic scenario is that the two effects will add, thus doubling the discomfort and expense in large cities; our more optimistic proposal is to reduce heat islands fast enough to offset global warming. Since we have already seen an hourly cost of $150,000 for the Los Angeles Basin, and $40,000 for Washington D.C., we estimate that the hourly cost of all the heat islands in the U.S. is of order of magnitude $ 1 million. Hence our proposal to offset global warming in these hot cities is very attractive both in terms of human comfort and dollar savings.

In the foregoing figures, we assumed that there was a correlation between ambient temperature (heat island) and cooling load. This is only part of the picture, however, because this correlation does not distinguish between direct and indirect effects. Recall

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[3] The SCE system area surrounds Los Angeles but does not include the city itself, which is served by LADWP.

[4] To study peak load/temperature dependence, an appropriate method is to use 4-pm temperatures over the period of interest, as was the case in Figure 6a. But hourly data are not always available for long term periods, i.e., the last 100 years; only daily or monthly averages can be found. Therefore, the use of the daily average temperatures is justified, and we have shown that in Figure 6b. We saw that there was no major change in the slope, compared to Figure 6a. When the SCE load was plotted against LADWP temperatures (Figure 7), it resulted in a similar pattern. We will be using temperature averages in our analysis of load/temperature data for other locations, as well.

that some buildings are shaded, others are not, some are passively cooled while others rely on HVAC systems, some are in light-colored neighborhoods, others are in darker ones, etc. Thus the figures show only the indirect effects on building energy use, but more savings can be achieved by accounting for (and implementing) direct-effect strategies for energy conservation.

All this indicates that huge savings can be attained by mitigating summer heat islands. With the climate and load data we are now compiling, we shall be able to better estimate the impact of heat island mitigation strategies as energy conservation measures.

SMOG LEVELS VERSUS TEMPERATURE IN SELECTED CITIES

Not only does the heat island increase city-scale cooling loads, but it also increases the amount of smog, brought on by the higher urban temperatures. **Figures 8 and 9** show the daily maxima in ozone (O_3) levels for Los Angeles and Texas[5]. In **Figure 8,** we see that below 74 °F, smog never exceeds the National Atmospheric Air Quality Standard (NAAQS), but by 94 °F, smog levels are too high (~26 pphm). Restated, smog is very sensitive to this 20-°F difference of which, one fourth is already attributable to the heat island effect. **Figure 9** shows similar results for 13 cities throughout Texas [Argento 1988].

MITIGATION POLICY and INITIATIVES

Utility Contributions to Offset CO_2 Emissions

In October 1988, Applied Energy Services (AES), a DC-based vendor of cogeneration plants, announced a policy of planting trees to offset the CO_2 produced by their power plants, most of which burn coal. At the time AES came up with this idea, they were unaware of the Berkeley studies of heat islands and urban trees. They discovered that CARE had a successful aforestation program in Guatemala, and would be able to leverage a $2M AES contribution by a factor of 7 and plant the 200,000 acres necessary to offset 200 MW. The time factors cancel out of the offset because the lifetimes of trees and power plants are comparable. The final cost to plant these trees is about $80/acre (= $80 to offset 1 kW), which corresponds to a cost of about 1 mil per kWh equivalent of sequestered carbon. This of course assumes no land costs, whereas in the U.S. the Conservation Reserve Program is already paying $50/acre-year for land, and the Environmental Defense Fund (EDF) estimates that payments will soon double [Dudek, 88].

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[5] The Texas data represent the maximum hourly average for thirteen locations in the following areas [V. Argento, personal communication]: Houston, South Houston, Dallas, East Dallas, Arlington, Ft. Worth, Waco, Austin, San Antonio, Corpus Cristi, Odessa, and El Paso.

This raises the question of the relative cost of sequestering carbon by forest trees vs. avoiding the combustion of carbon by urban trees. We urge support of both. Urban trees are more lucrative, they actually save money, but as we show in our papers, we can only find about 25 million U.S. homes to shade, and we can only save about half a quadrillion Btu (0.5×10^{15} Btu) of energy per year[6].

On the other hand, there are several million square miles of discretionary land available worldwide for forestation, which could offset the carbon emission of many power plants. We therefore recommend that we start getting experience with both programs. In California, the two ideas of offset contributions and urban trees have now been connected by a cogeneration vendor, and the issue is currently being discussed with the California Energy Commission.

Bond Issues for Heat Island Reduction

There are now at least two bills in the California Legislature for bond issues for trees/light surfaces. One of them is a Transportation Committee bill sponsored by Assemblyman Katz for $100 M to be spent over 5 years. A similar bill has been introduced in the Assembly Committee on Natural Resources by Lloyd Connally and Byron Katz.

The need for a Manual on Reducing Heat Islands

In our opinion such a manual would be the best way to advance intelligent state or local government, or utility programs to start reducing heat islands. We have already applied to UC/UERG (the UC, Universitywide Energy Research Group) for support to start such a manual, and are actively soliciting support from other agencies, institutes, and foundations. **App. 1** reproduces the abstract from our UERG proposal, with 10 chapter headings. This manual could be a productive collaboration of several warm-weather states.

Comparison of Urban and Rural Trees

There is need to compare rural trees, and two sorts of urban trees. We already know that it is very cost effective to plant trees which shade buildings directly. Trees on streets, highways, and parks are less lucrative, although still probably very valuable. We need to compare the economics of all three sorts of trees, in several locations. This issue will particularly interest utilities.

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[6] Half a quad corresponds to 50 BkWh, or the output of about 10 baseload one-GW power plants.

Demonstration and Monitoring

After the Manual, we view the next priority to be to demonstrate the cost effectiveness of shading and painting school buildings in many cities. LADWP has already agreed to help us work with the Los Angeles Unified School District to shade and paint some "bungalow" buildings, and measure the payback times. We even want to experiment with lightening the color of blacktop playgrounds with chalk or some equivalent non-abrasive light colored material. The sooner we can compile a list of such experiments, the faster communities can be convinced to swing into action.

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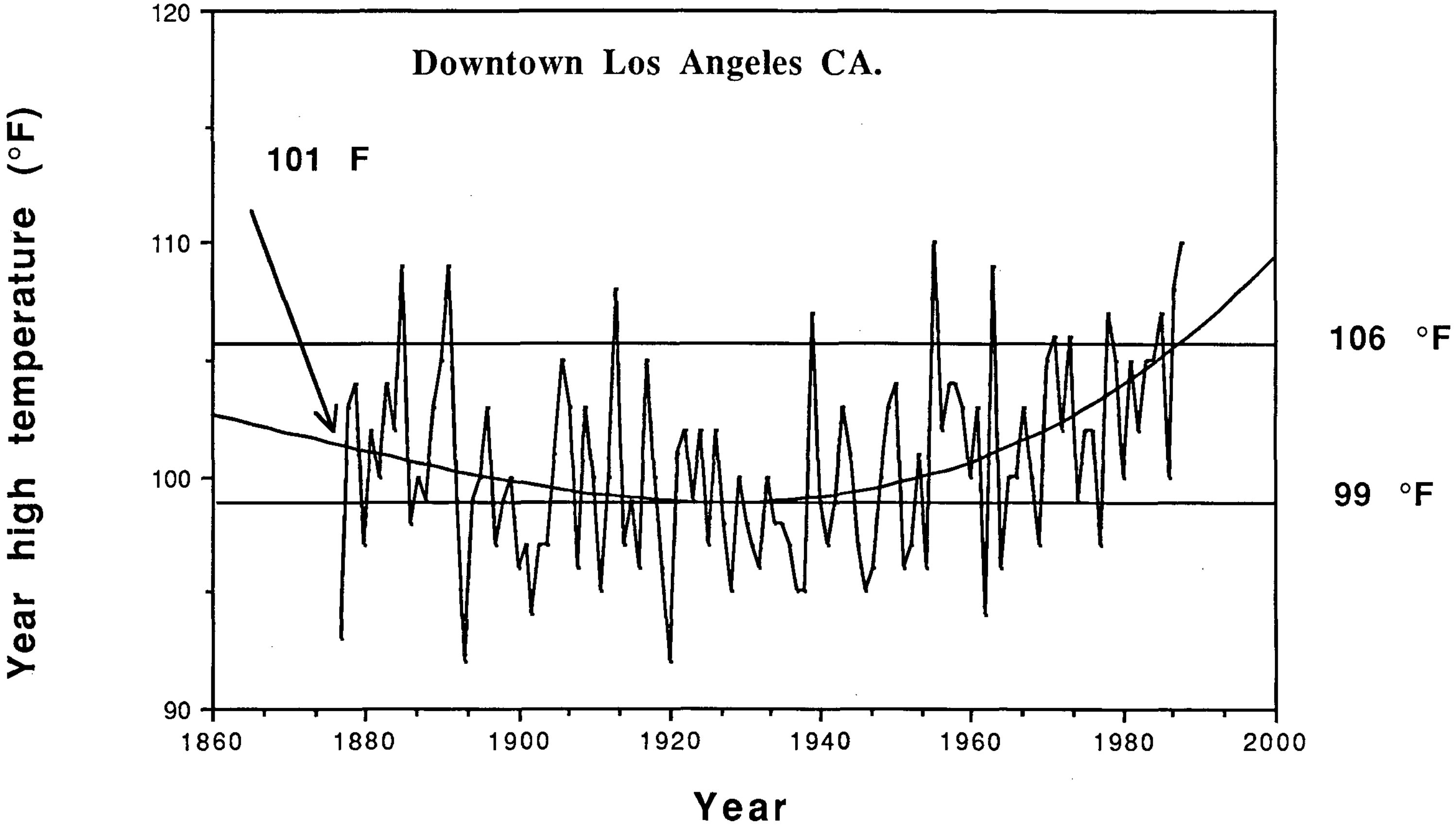


Figure 1. Annual high temperatures for Downtown Los Angeles CA (1877 - 1984).

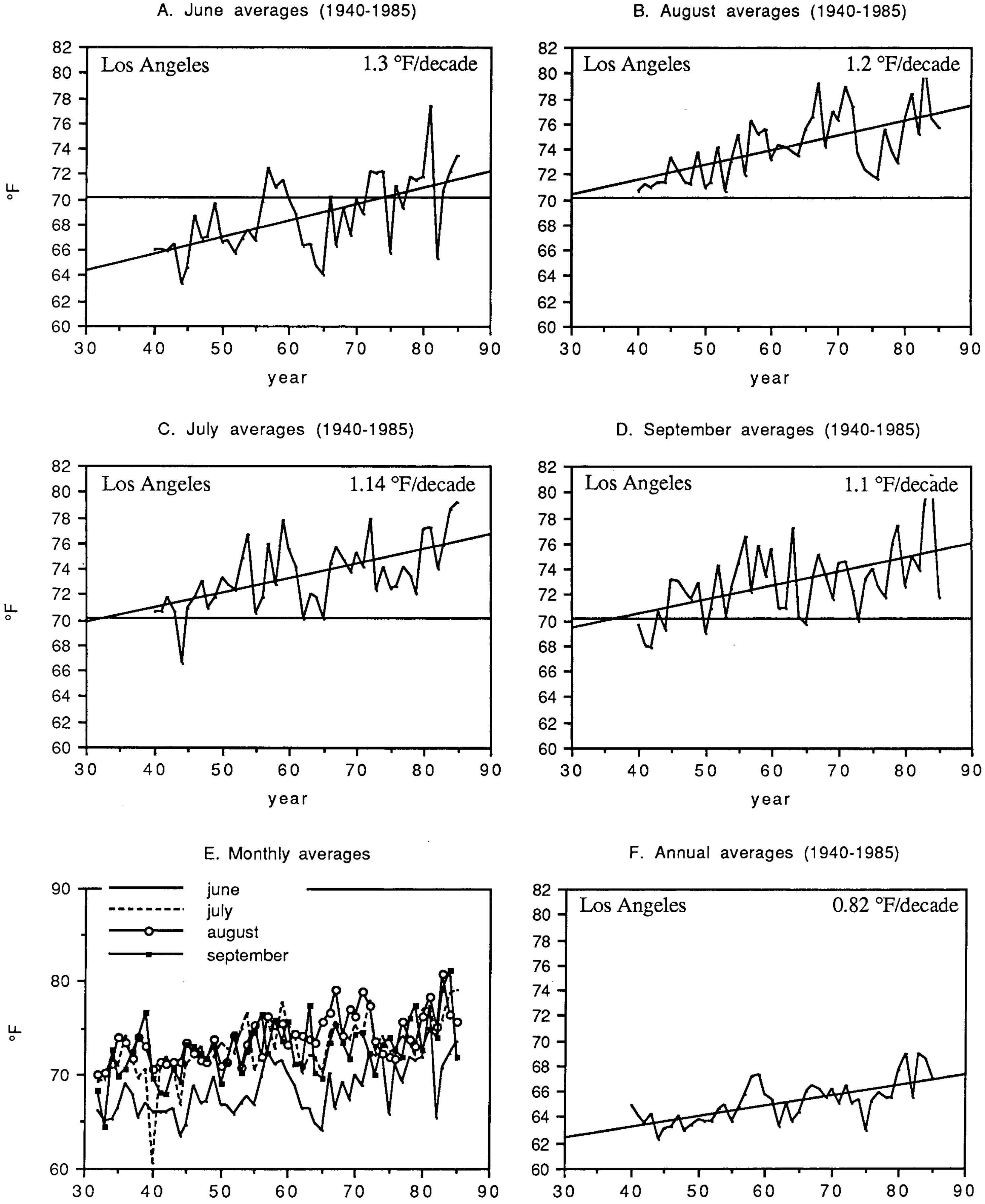


Figure 2. Four summer months of Downtown Los Angeles monthly average temperatures, showing a rise of 5 °F/46 years.

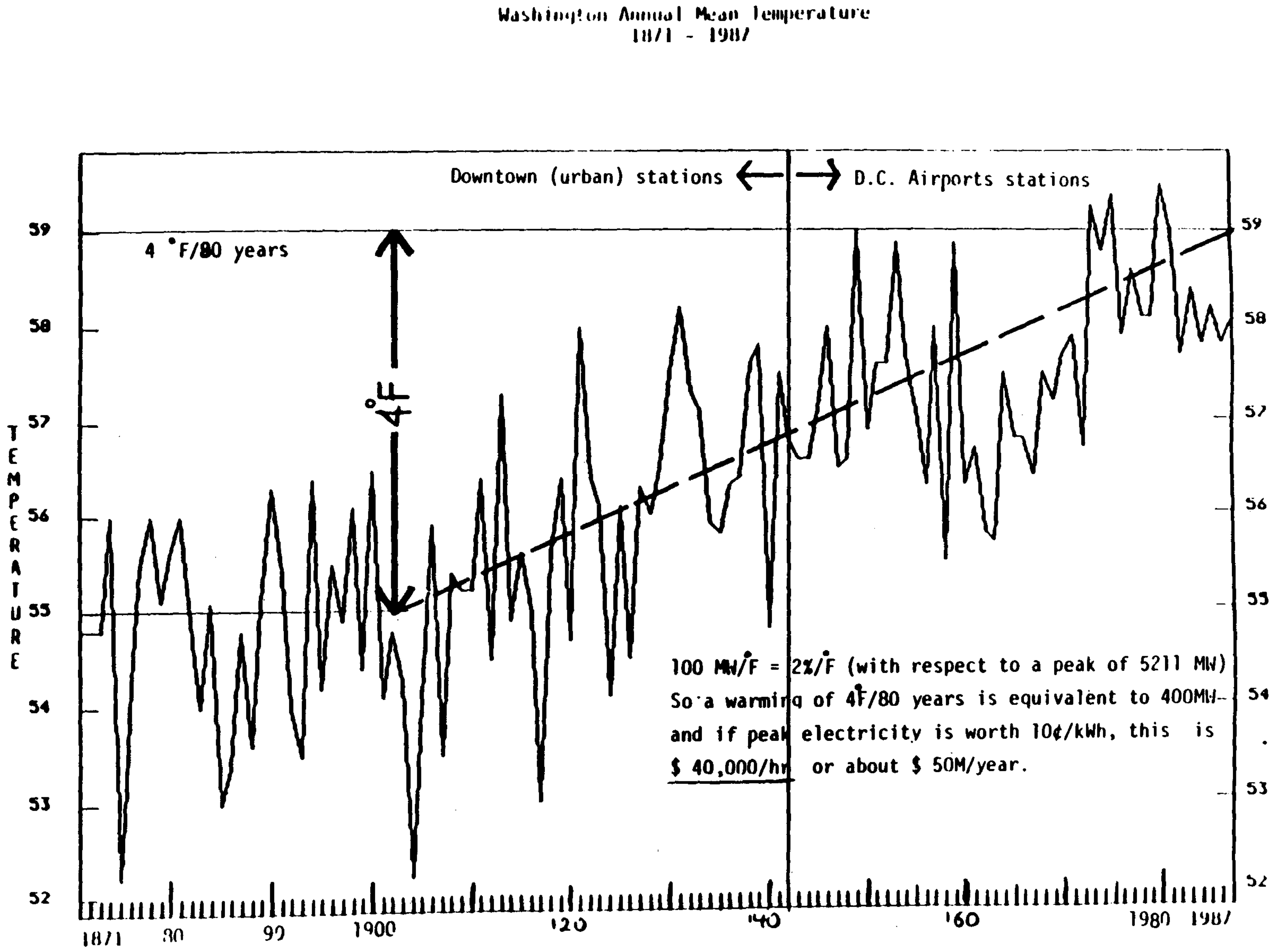


Figure 3. Annual mean temperatures in Washington D.C. (1871-1987).
Source: Mayberry, E. Potomac Electric Power Company. Washington D.C.

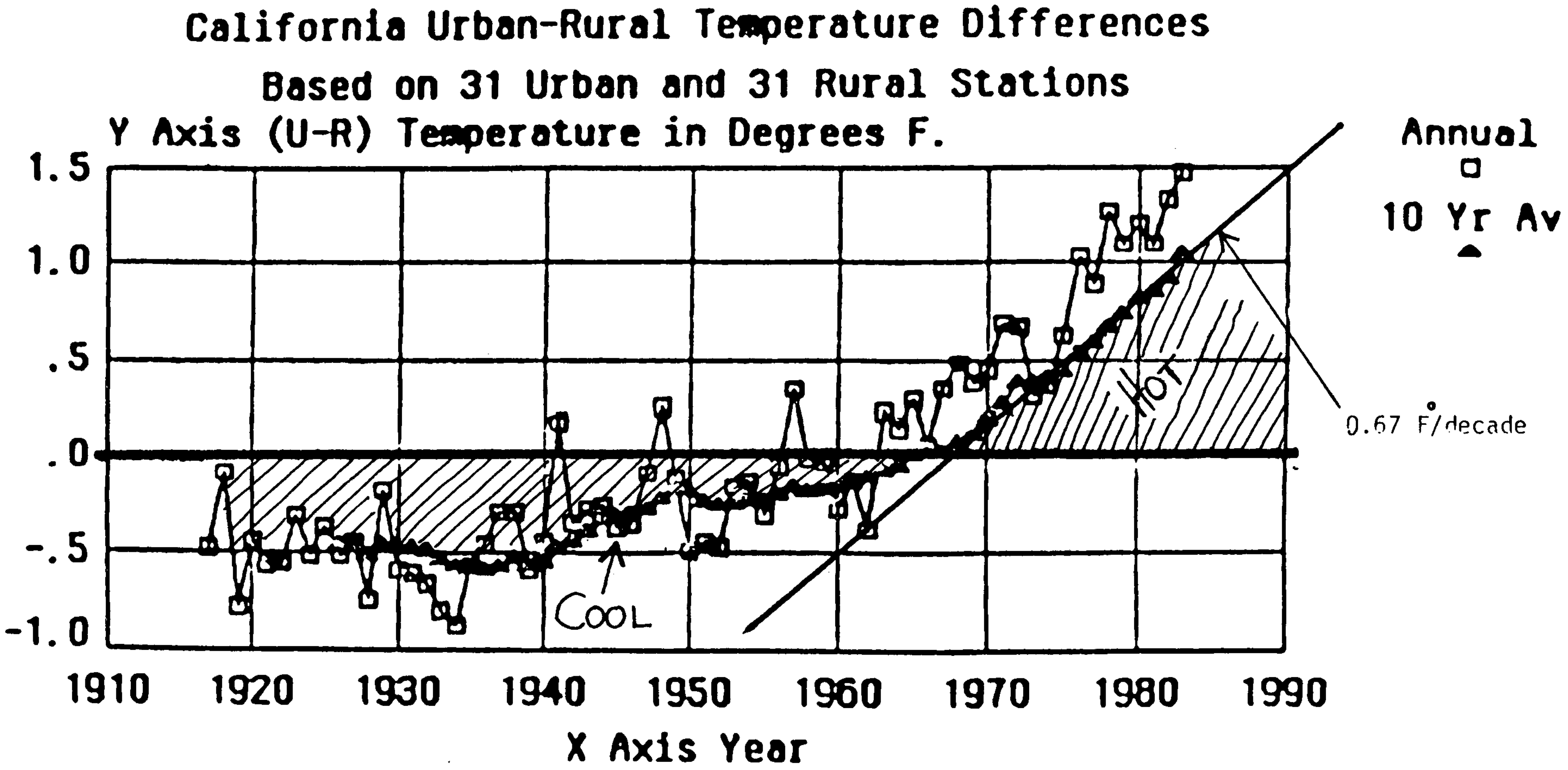


Figure 4. Urban-rural temperature differences in California.

Source: Goodrige, J. 1989.

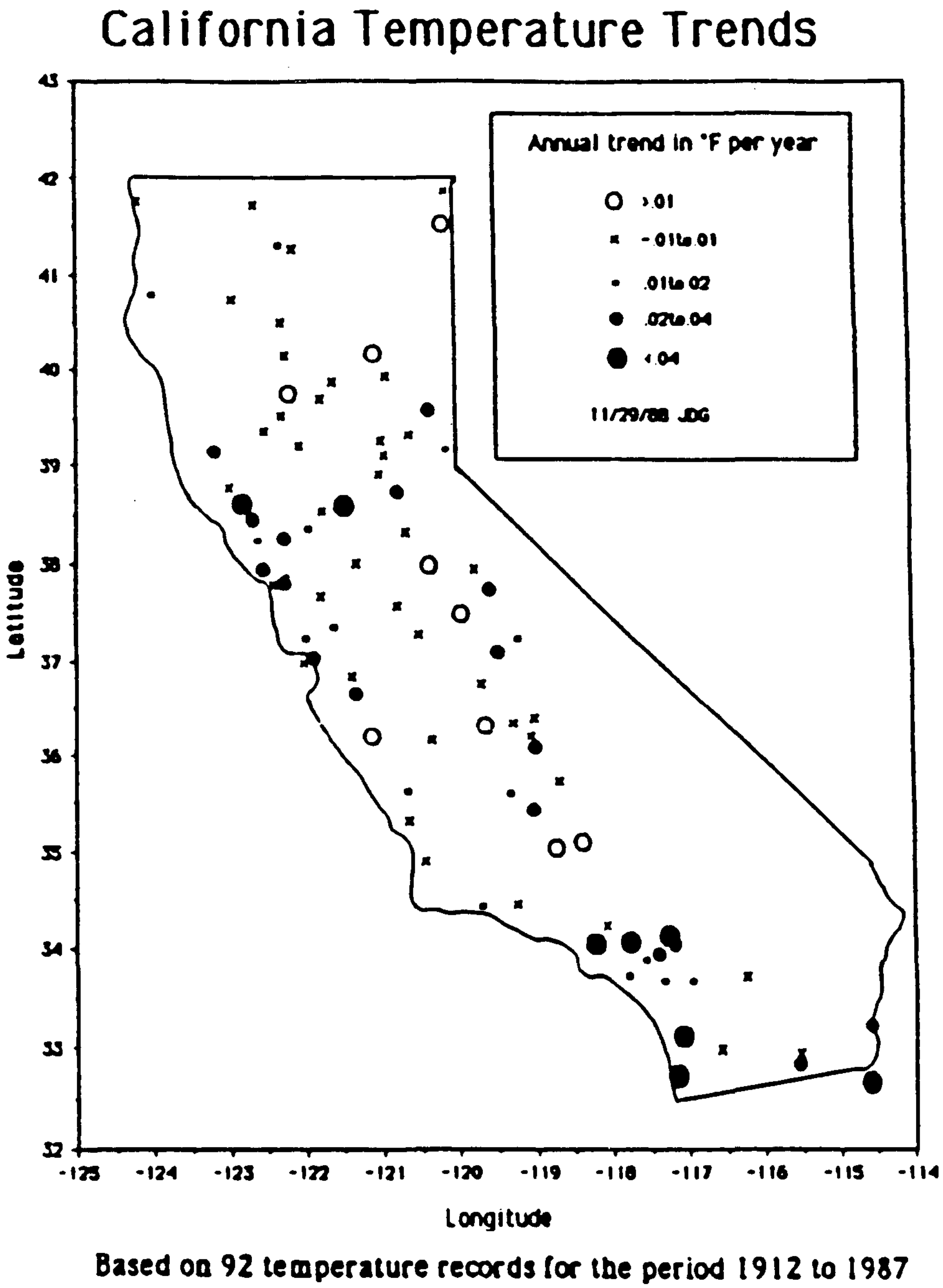
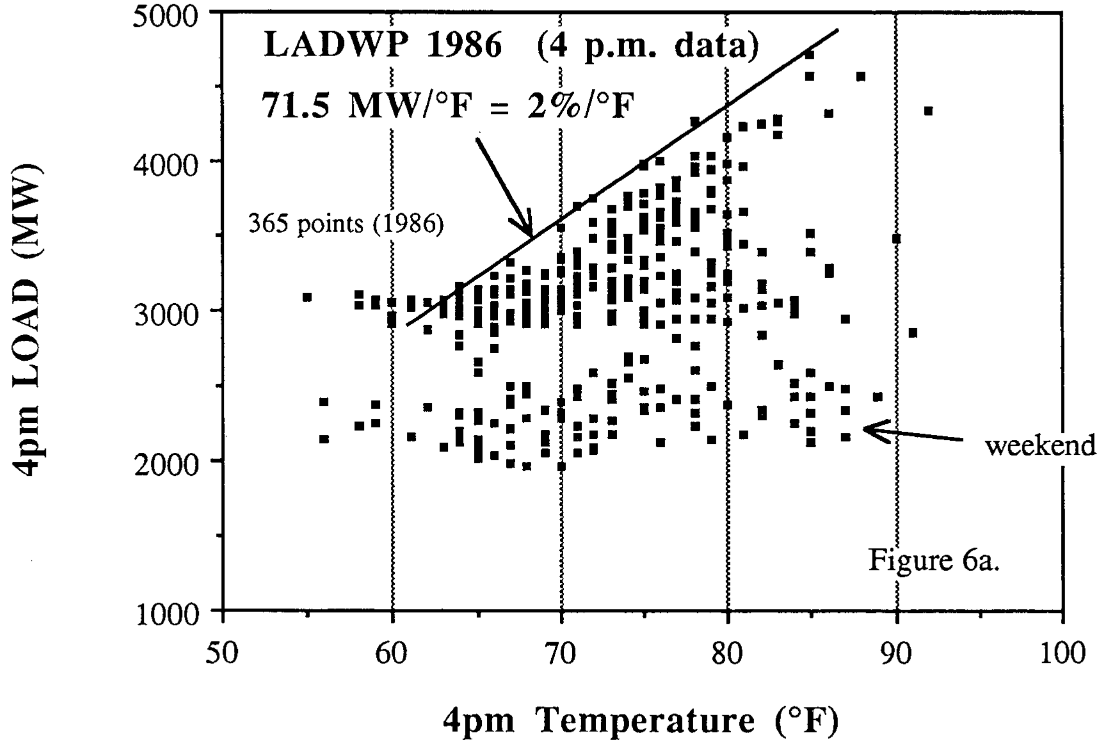


Figure 5. Temperature trends in California. Source: Goodrige, J. 1989.



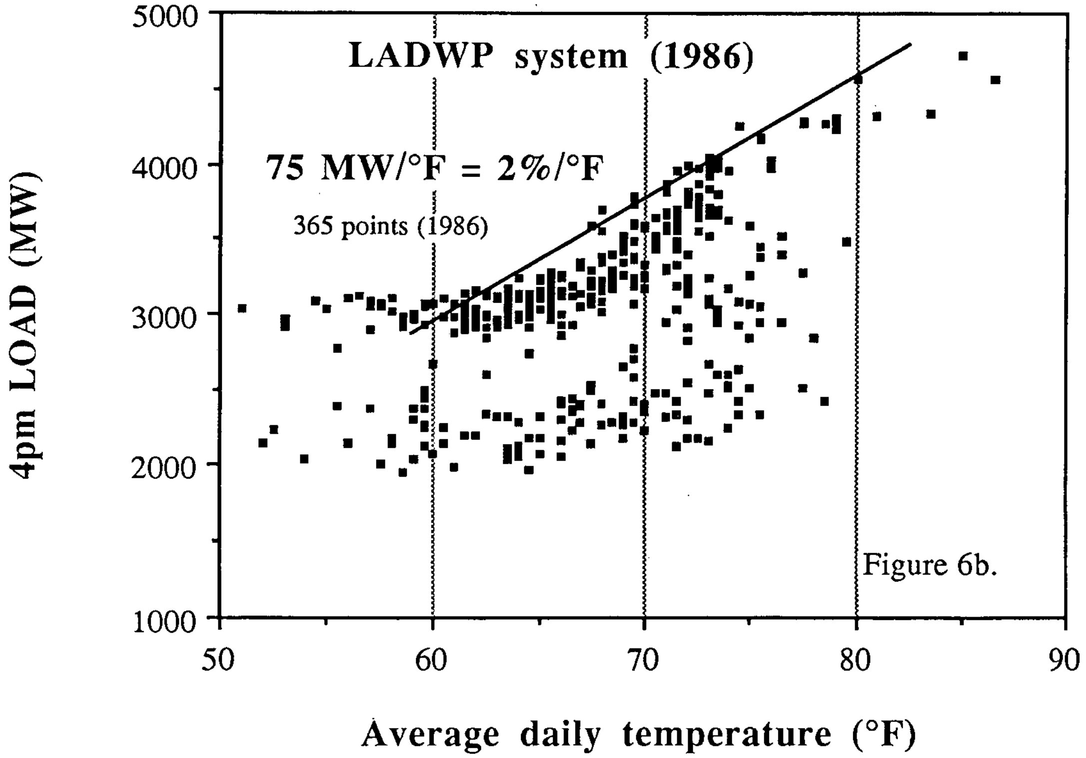
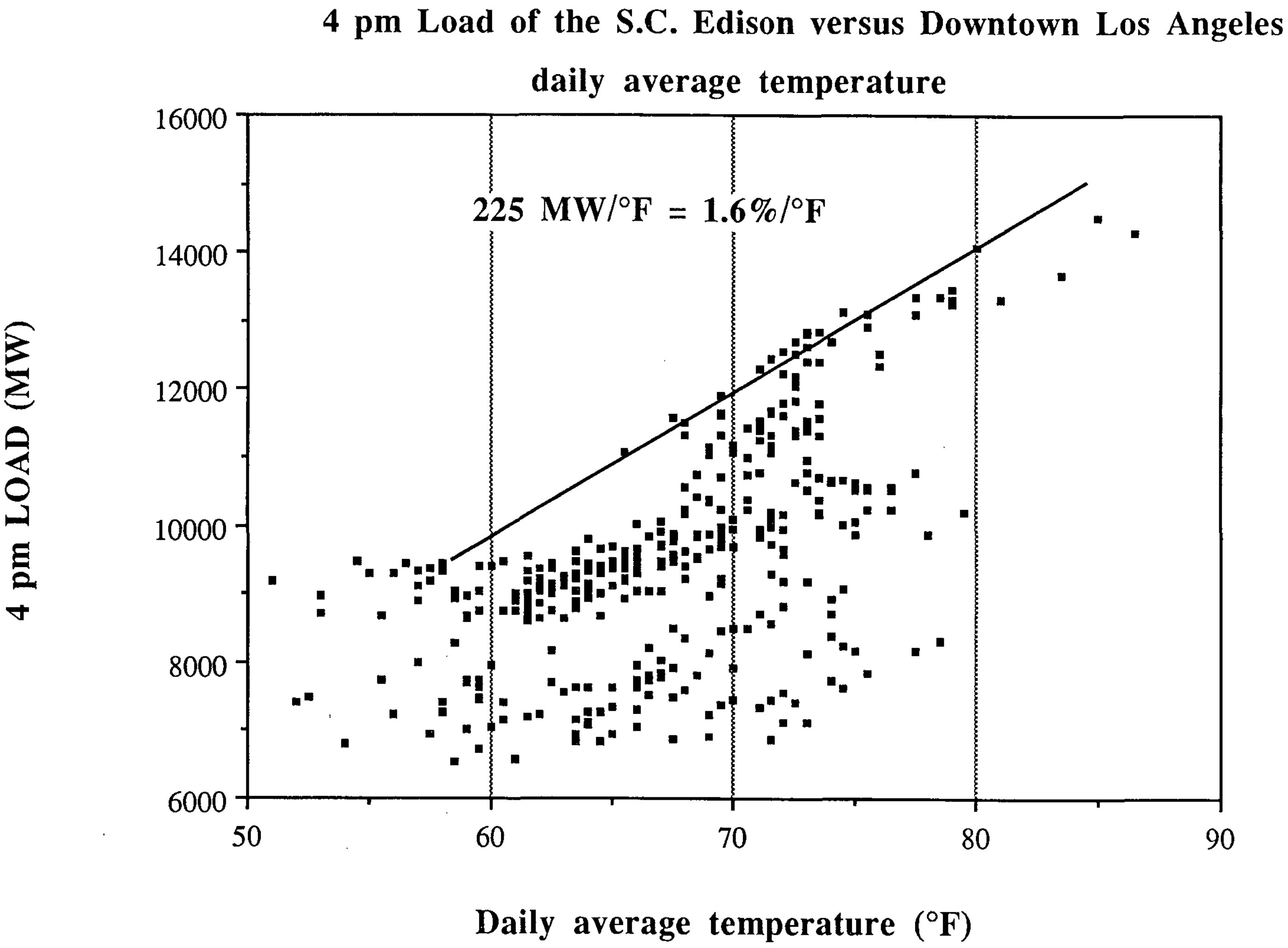


Figure 6. Load versus temperature in Downtown Los Angeles (1986).



Total LA Basin: 75 MW (LADWP) + 225 MW (SCE) = 300 MW

300 MW * 5 °F = 1500 MW, worth ~ $150,000 per hour

Figure 7. Load versus temperature for the SCE system (1986).

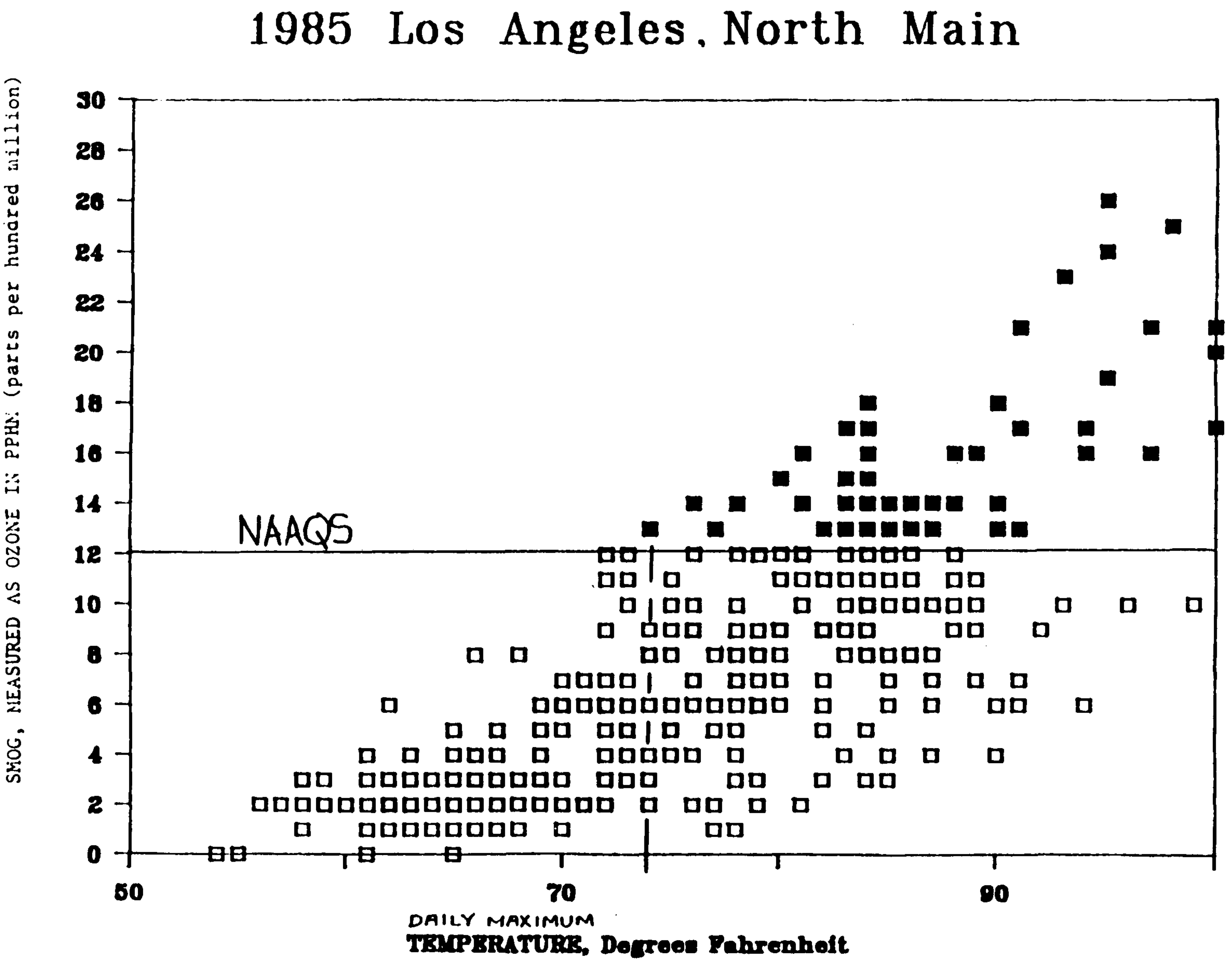


Figure 8. Ozone level versus temperature in Los Angeles CA (1985).

TEXAS

SMOG

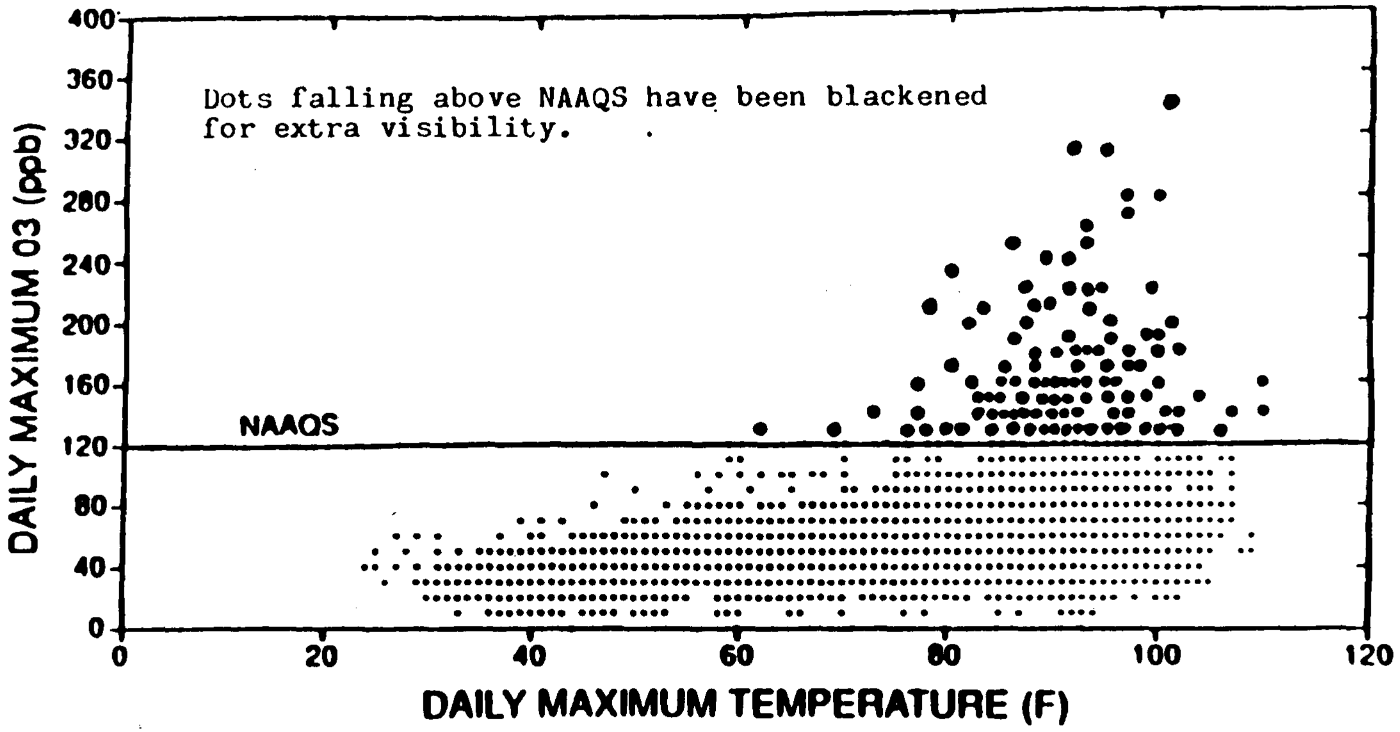


Figure 9. Maximum daily ozone concentration vs. maximum daily temperature.

Figure 9. Ozone levels versus temperature in 13 cities in Texas.

Source: V. Argento, Chemical Engineering Progress, Dec 1988, pp. 50.

This proposal is to prepare a guidebook for control of summer heat islands to include:

- a discussion of direct air conditioning savings of heat island mitigation measures in homes, schools, hospital, and small commercial buildings;
- a discussions of methods to cool the entire city;
- a comparison of heat island mitigation technologies;
- heat island maps of California cities;
- heat island effects on smog and water usage;
- a model ordinance;
- a discussion of policy issues;
- tree selection, cost, and maintenance requirements;
- how to mobilize and pay for summer youth to plant and nurture trees;
- and how California can incorporate heat island control in environmental plans for counties and cities.

Appendix 1.

SAVING ENERGY AND REDUCING ATMOSPHERIC POLLUTION BY CONTROLLING SUMMER HEAT ISLANDS

H. Akbari, J. Huang, P. Martien, L. Rainer,
A. Rosenfeld, and H. Taha
Heat Island Project
Applied Science Division

ABSTRACT

Summer afternoon heat islands increase costly air conditioning demand, leading to greater electrical energy use and increased atmospheric pollution. In individual buildings, the use of strategic landscaping and selection of lighter building surface colors have been demonstrated to greatly reduce electrical energy use. Multiplied on a city-wide scale, the same strategies can produce further energy savings by mitigating the urban heat island, or even changing them into daytime summer oases. In addition to saving cooling energy use and reducing peak electric demand, heat island mitigation, like other conservation strategies, will reduce atmospheric pollution from electric power plants.

This paper summarizes the results of computer simulations and field studies conducted at the Lawrence Berkeley Laboratory to quantify the potential of trees and light surfaces to reduce summer heat islands. We also compare the economics of heat island mitigation technologies with other fuel-saving technologies such as energy efficient refrigerators and cars as strategies for reducing the growth of atmospheric CO_2. Our results indicate that the cost of conserved energy and avoided CO_2 through control of heat islands is less than 1 ¢ /kWh and 2 ¢ /kg of carbon, respectively. This is about half the cost of energy efficient appliances as defined by the National Appliance Energy Conservation Act (NAECA), and 1/10 of the cost of new generation capacity. The paper concludes with outlining an agenda for further research.

KEYWORDS: air-conditioning, atmospheric pollution, cooling energy, electric power, energy conservation, global warming, heat islands, trees, white surfaces

SAVING ENERGY AND REDUCING ATMOSPHERIC POLLUTION BY CONTROLLING SUMMER HEAT ISLANDS

H. Akbari, J. Huang, P. Martien, L. Rainer
A. Rosenfeld, and H. Taha
Applied Science Division
Lawrence Berkeley Laboratory

INTRODUCTION

Before mechanical air conditioning, people cooled their homes by surrounding them with trees and painting the walls and roofs white. The disappearance of such practices today in many urban areas contributes to summer "heat islands" with a typical daily average intensity of 3-5 ° C. However, there are ways to mitigate this negative effect, on both micro- and meso-scales (Landsberg, 1978; Thurow, 1983).

Urban trees and light-colored surfaces are two effective and inexpensive measures to reduce summer heat islands and even create summer oases. Trees can improve the urban climate by shading and evapotranspiration, reducing summer cooling energy use in buildings at about 1% of the capital cost of the avoided power plants and air conditioning equipment. Light colors decrease surface absorption of short wave radiation, thereby reducing surface temperatures and convective heating of near-surface air. External surfaces of buildings can be painted white (or a light color) and streets and parking lots surfaced with white sand when resurfacing is necessary anyway, thereby reducing cooling energy needs at low costs.

In addition to saving energy, urban trees and light-colored surfaces are the most cost-effective ways to slow the growth of atmospheric CO_2. By reducing the need to burn fossil fuels for generating electricity, urban trees are indirectly many times more efficient at limiting atmospheric CO_2 than is rural forestation.

World energy use is the main contributor to atmospheric CO_2. In 1987, the people of the world burned some 300 quadrillion Btus ('quads') of fuel, releasing 5.4 billion tons of carbon into the atmosphere, 2 to 5 times the amount contributed by deforestation (Brown et al., 1988). The increasing use of fossil fuels and deforestation together have raised atmospheric CO_2 concentrations by about 25% over the last 150 years. According to models of global climate and preliminary measurements, these changes in the composition of the atmosphere may already have begun raising the earth's average temperature. If current energy use trends continue, these changes could significantly raise the earth's temperature, with unknown but potentially catastrophic environmental and political consequences. Since the first OPEC embargo in 1973 and the oil price shocks in 1979, increased energy awareness has led to conservation efforts and leveling of energy consumption in the industrialized countries. U.S. energy use remained at 74 quads/year from 1973 to 1986, but is now back in lockstep with GNP. An important byproduct of this curtailed energy use is a lowering of the rate of growth of CO_2 emissions.

Our calculations indicate that heat island mitigation strategies such as urban trees and light-colored surfaces are attractive conservation measures that can save 0.5 quad per year at a cost of less than 1 /kWh, and decrease CO_2 emissions by about 17 million tons of carbon per year.

DIRECT AND INDIRECT EFFECTS OF MODIFYING THE URBAN ENVIRONMENT

The effects of modifying the urban environment, by planting trees and increasing albedos, are best quantified in terms of direct and indirect contributions. The **direct** effect of planting trees around a building or painting the building surfaces a light color is to alter the energy balance and cooling requirements of that particular building. However, when trees are planted and albedos are modified throughout an entire city, the energy balance of the whole city is modified, producing city-wide changes in climate. Phenomena associated with the city-wide changes are referred to as **indirect** effects. The energy use of an individual building is indirectly affected by the changes made throughout the city.

An important reason for making the distinction between direct and indirect effects is that, while direct effects are well-recognized and can be well-accounted for in present models of building energy use, indirect effects have received much less recognition. Methods of accounting for indirect effects have not been as well-developed and remain comparatively much less certain. Understanding these effects and incorporating them into accounts of building use is the focus of our current research. It is worth noting that the phenomenon of summer urban heat islands is itself the consequence of indirect effects of the built environment. We are proposing to use the same principles to cool hot cities.

The issue of direct and indirect effects also enters into our discussions of atmospheric CO_2. Planting trees has the direct effect of reducing atmospheric CO_2 because each individual tree, during its lifetime, directly sequesters carbon from the atmosphere through photosynthesis. However, planting trees in cities also has a secondary (indirect) effect on CO_2. By reducing the demand for cooling energy, urban trees indirectly reduce emission of CO_2 from power plants. As we shall discuss, the amount of CO_2 avoided via the indirect effect is considerably greater than the amount sequestered directly.

URBAN TREES AS AN ENERGY CONSERVATION STRATEGY

Case studies have documented dramatic differences in cooling energy use between houses on landscaped and unlandscaped sites. In particular, researchers at Florida International University (Parker, 1981) measured cooling savings resulting from well-planned landscaping and found that properly located trees and shrubs reduced daily air conditioning electricity use by as much as 50%.

Trees affect energy use in buildings through direct processes such as (1) reducing solar heat gain through windows, walls, and roofs by shading, (2) reducing the radiant heat gain from surroundings by shading, and (3) reducing infiltration by shielding a particular building from wind. Deciduous trees are particularly beneficial because they allow solar gain in buildings during the winter.

The indirect effects include (1) reducing the outside air infiltration rate by increasing surface roughness and decreasing city-wide wind speeds, and (2) reducing the heat gain of buildings by lowering summer ambient temperatures through **evapotranspiration** (the evaporation of water from vegetation). On hot summer days, a tree acts as a natural "evaporative cooler" using up to 100 gallons of water a day and thus lowering the ambient temperature. The effect of evapotranspiration is minimal in winter because of lower ambient temperatures and the absence of leaves on deciduous trees. A significant increase in urban trees, increasing evapotranspiration during the summer, can produce an "oasis effect" and significantly lower urban ambient temperatures. Buildings in this cooler environment will then consume less cooling power and energy.

ALBEDO AS AN ENERGY CONSERVATION STRATEGY

The energy balance of a building or an entire city depends significantly on the net solar radiation reflected from its surface. To describe this dependence, one uses the terminology **albedo**. An albedo of 1.0 corresponds to a surface that completely reflects, while an albedo of 0.0 refers to one that completely absorbs all incident solar radiation. The albedo of an individual building can be modified to achieve direct savings: a lighter building reflects more solar radiation and stays cooler. The albedo of an entire city can be modified to achieve indirect savings by lowering city-wide temperatures.

Most buildings and cities have albedos in the range of 0.20-0.35. Traditional cities of white-washed buildings found in hot climates have albedos in the range of 0.30-0.45 (Taha et al., 1988). Reflective roof membranes and the popular "solar control" glazings of commercial buildings both have albedos of up to 0.8. There is a practical constraint in the maximum achievable urban albedo if this strategy is used in conjunction with increased urban vegetation, since a dense urban tree canopy will cover a large amount of the surface area (the albedo of trees is $\sim$0.25). We have estimated an upper limit of 0.40 for the albedo of a highly-vegetated city with light-colored surfaces.

ENERGY SAVINGS

Table I shows the simulated **direct** savings in cooling energy and peak power resulting from the direct effects of increased urban tree cover and albedo. The results are shown for both the 1973 housing stocks and newer 1980 prototype houses. The 1973 stock is representative of leaky and poorly-insulated housing, while the 1980 homes are tight and well insulated. The 'Base' column in each case represents the base case for a building with normal albedo (30%) and no surrounding trees. The savings are calculated for an increase in tree coverage of 30% (3 trees per house) and an increase in house albedo from 30% to 70%.

Table II shows the simulated **indirect** savings in cooling energy and peak power. For the cities modeled, the effect of an additional 3 trees per building results in approximately 30% savings in annual cooling energy and approximately 15-20% annual savings in peak cooling power. The indirect effects of albedo were quantified for Sacramento, CA for only four days in July. During these days, simulations showed that by increasing the albedo of the surroundings from 0.25 to 0.40, the cooling energy was reduced by 45% and peak power by 21%, suggesting that for a house the potential savings from albedo and vegetation are roughly equivalent.

We have comparatively few simulations of the indirect effects. Since our models of urban climate are still under development, we conservatively interpret these results as maximum effects. When extrapolating to determine national savings (**Table III**), we typically assume smaller effects.

QUANTIFICATION OF NATIONAL ENERGY SAVINGS

Total Cooling Energy Use In the U.S.

Table III shows savings of primary energy use for air conditioning in the U.S. Total residential electricity use for air conditioning (room and central) is about 100 billion kWh or 1.2 quads of primary energy per year (Akbari *et al* 1988). In the U.S. in 1987 commercial buildings used 670 billion kWh of electricity (EIA, 1987), of which, approximately 20% was used for cooling, corresponding to about 130 billion kWh or 1.5 quads of source energy per year. Together, residential and commercial cooling uses 2.7 quads of source energy per year, worth $20-25 billion[1].

Direct Savings

We will assume that tree planting and albedo modification can be applied to 50% of the 51 million air conditioned houses. These measures cannot be applied to all houses with air conditioners since tree density may already be high (especially in older cities).

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[1] Most residential electricity is still sold at an average price of ~7.5 cents/kWh, but air conditioning power is mainly "on-peak" and the cost of new peak power is closer to 10 cents/kWh.

Increase in tree cover and/or albedo modification may also not be acceptable to all municipalities, and some areas may not have a significant cooling load. We will also assume that half of the commercial building stock of 4 million buildings is sized small enough to be directly affected by shading and albedo increase.

Our analysis shows that the direct effect of planting 3 trees per house and changing the building albedo is an average of 20% cooling energy savings (See **Table I**). Applying this to the 25 million available residential houses, using 75 million total trees, would result in an energy savings of 0.12 quad. The corresponding direct savings due to the planting of 30% tree cover around small commercial buildings is about 8% (Akbari et al., 1987). When this is applied to 50% of the 2 million small commercial buildings, using another 25 million trees, this would save an additional 0.03 quad. Conservatively, a direct savings of 0.15 quad would be achieved if 100 million trees were planted.

Indirect Savings (Heat Island Effects)

Our preliminary results (See **Table II**) suggest that the indirect effects alone of tree planting and albedo modification can save at least 20% of the 1.2 quad of residential cooling energy use (thus 0.23 quad). Because small commercial buildings are less sensitive to outdoor temperature than houses, we expect indirect savings only about 12% of the 0.75 quad of small commercial cooling energy use (thus 0.09 quad). By reducing temperatures throughout the city, these measures also decrease cooling energy use in large commercial buildings by increasing system efficiency and economizer operating hours. We estimate this would save 5% or an additional 0.04 quad.

CO_2 Savings

Carbon, produced in the form of CO_2 for each kWh of electricity generated, varies from about 0.5 lb carbon/kWh for natural gas fired power plants to about 1 lb carbon/kWh for coal fired power plants. Because cooling energy is almost always used during peak demand periods (except in the case of thermal storage), the electric utility must meet this demand using a combination of coal, oil, and gas fired power plants. The fraction of each fuel type used varies greatly depending on the region of the country and can vary from all coal in some parts of the East to all oil and gas in Texas. However, the national average is approximately half coal and half oil and gas (DOE, 1988). This results in an average emission of 0.8 lb. carbon/kWh generated for peak power.

About half of the savings from the combination of the direct and indirect effects shown in **Table III** would result from the planting of 100 million urban trees. This savings of 0.25 quads (22 billion kWh) corresponds to a savings of 9 million tons of carbon. A fast-growing forest tree sequesters carbon at the rate of $\sim$13 lb carbon per year. Therefore, 100 million trees could directly sequester 0.65 million tons of carbon, or only one-fifteenth of the energy saved through their reduction in cooling energy use. Another way of looking at this is that to directly sequester the amount of carbon saved by the planting of 100 million urban trees would require planting of 1.5 billion forest trees corresponding to 1.5 million hectares of forest (by comparison, the total area of Connecticut is about 1.3 million hectares).

THE COST OF CONSERVED ENERGY AND CARBON: A NATIONAL PERSPECTIVE

Table IV gives the cost-effectiveness, energy savings, and carbon reduction of urban trees/light surfaces compared to other conservation and generation strategies. All energy conservation measures that reduce fossil fuel use also reduce carbon emissions. For example, the trend to more efficient electric appliances yields a cost of conserved energy (CCE) of about 2¢ /kWh, equivalent to a cost of conserved carbon (CCC) of 2.5¢ /lb carbon. Another conservation strategy is to improve efficiency in automobiles. The cost of conserved carbon in going from an automobile that gets 26 mpg to one that gets 36 mpg is 10¢ /lb carbon. Both these measures are effective and proven, but they are much more expensive than urban trees and light-colored cities.

Urban trees and light surfaces have a CCE of about 0.2 - 1.0¢ /kWh, and a CCC of about 0.3 - 1.3¢ /lb of carbon. This is as much as ten times cheaper than either of the alternative strategies just cited. The point of the comparison is not to discredit the other conservation strategies, which are effective and proven, but to suggest that planting urban trees and modifying urban albedos seems attractive, and definitely worth investigating.

There are still many things left to learn about summer heat islands. A multi-year effort in research, modeling, and data gathering is required to further investigate the energy saving potentials and ways for controlling summer heat islands. **Table V** shows some elements of a multi-year research program including: quantifying the heat island effect, verifying the mitigation savings, developing implementation guidelines, and quantifying the heat island effect on pollution and global warming.

It is the intention of this workshop to take the cause one step further. The workshop is organized around six important topics:

1. **Impacts of Microclimate Changes on Building Energy:** microclimate measurement and simulation, energy-conserving site designs.
2. **Characterization of Heat Islands:** data availability for heat islands and micro- or meso-climates, remote sensing techniques, satellite data, correlation between air and surface temperatures, simulation techniques, etc.
3. **Heat Island Mitigation Strategies:** energy-conserving urban designs, urban forestry, evapotranspiration rates of trees and urban vegetation, light (reflective) surfaces—walls, roofs, asphalt.

4. **Global Climate and the Reduction of Atmospheric Emissions:** the potential of summer heat island mitigation measures to reduce CO_2, NO_x, and SO_x and other pollutants, implications for the global climate.
5. **Policy Issues Related to Heat Island Mitigation Strategies:** financial impacts on building owners and utilities, water issues, implementation tradeoffs and conflicts, and implementation guidelines.
6. **Smog:** Relationship between heat island, smog, and creation of smog feedstocks.

ACKNOWLEDGEMENT

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Table I. **Simulated direct savings in cooling energy and peak power resulting from planting trees and whitewashing buildings.** The tree cover was increased by 30% with respect to the base case, whereas albedo was increased from 30% to 70%. We have used these estimates for calculating the national savings. (Source: Akbari *et al* 1988)

Location	1973 Houses (leaky and low-insulation)		1980 Houses (tight and high-insulation)	
	Base	Savings ($\Delta\%$)	Base	Savings ($\Delta\%$)
Chicago IL	1400 ft^2		2000 ft^2	
Peak kW	3.60	23.6	3.20	29.1
Annual kWh	2584.0	19.9	1888.0	21.6
Miami FL	1400 ft^2		1600 ft^2	
Peak kW	5.42	25.3	3.29	23.4
Annual kWh	13623.0	22.5	8730.0	16.5
Minneapolis MN	1400 ft^2		2000 ft^2	
Peak kW	3.14	27.1	2.65	31.7
Annual kWh	1916.0	20.2	1325.0	22.6
Phoenix AZ	1400 ft^2		1600 ft^2	
Peak kW	7.56	26.2	5.18	31.1
Annual kWh	13117.0	19.8	7789.0	17.3
Pittsburgh PA	1600 ft^2		1600 ft^2	
Peak kW	3.50	24.9	2.36	23.3
Annual kWh	1821.0	23.3	1177.0	20.1
Sacramento CA	1400 ft^2		1600 ft^2	
Peak kW	5.40	25.4	3.85	26.0
Annual kWh	3767.0	28.3	2372.0	23.8
Washington DC	2000 ft^2		2200 ft^2	
Peak kW	5.80	30.3	3.98	29.4
Annual kWh	4358.0	22.7	2790.0	20.0
Average				
Peak kW		**26.3**		**28.0**
Annual kWh		**21.9**		**18.6**

Table II. **Simulated indirect savings in cooling energy use and peak cooling power for single-story 1980-prototype houses.** Canopy savings are annual figures. Albedo savings are for the period from July 9 to July 12 only. (All entries are indirect effects.)

	Urban canopy density increased by 3 trees/house*	Albedo of house and surrounding increased**
Location	Percent energy savings	Percent energy savings
Sacramento CA		
Peak kW	23	21
Annual kWh	37	45†
Phoenix AZ		
Peak kW	12	--
Annual kWh	27	--
Lake Charles LA		
Peak kW	15	--
Annual kWh	31	--

* Data from Huang et al., 1987. Assumes an increase of 3 trees per house.

** Data estimated from Taha et al., 1988. Assumes an increase from 0.25 to 0.40 in the albedo of the surroundings.

† Canopy savings are annual savings. Albedo savings for the period from July 9 to July 12.

Table III. **Yearly savings (by 100 million trees) of primary energy used for air conditioning in the U.S. and consequent reductions in released carbon*.** (Source: Akbari *et al* 1988)

	Residential **			Small Commercial †			Large Commercial ‡			Total	
	Energy		Carbon	Energy		Carbon	Energy		Carbon	Energy	Carbon
	(%)	(10^{15}Btu)	(M Tons)	(%)	(10^{15}Btu)	(M Tons)	(%)	(10^{15}Btu)	(M Tons)	(10^{15}Btu)	(M Tons)
Direct Savings	10	0.12	4	4	0.03	1	0	0.0	0	0.15	5
Indirect Savings	20	0.23	8	12	0.09	3	5	0.04	1	0.36	12
Total	30	0.35	12	16	0.12	4	5	0.03	1	0.51	17

* Production of carbon (as CO_2) from a peak power plant assumes 11,600 Btu/kWh sold, and $\sim$14,500 Btu/lb. of carbon.

** **Residential.** US annual residential cooling electricity use is $\sim$100 BkWh/yr, corresponding to 1.2 quads. We assumed 3 trees (plus light surfaces) for 50% of our 50 million air conditioned homes, so 75 million trees (plus light surfaces).

† **Small Commercial.** US uses 65 BkWh (= 0.75 quad). We assumed 30% coverage by trees (25 million more trees).

‡ **Large Commercial.** US uses 65 BkWh (= 0.75 quad). We assumed no additional trees.

Table IV. **Cost-effectiveness, energy savings, and carbon reduction of urban trees/light surfaces compared to other conservation and generation strategies.** (Source: Akbari *et al* 1988)

Strategy	CCE[1] (¢/kWh)	CCC[1] (¢/lb C)	ΔE (Quad/yr)	ΔC (M Tons/yr)
Conservation				
(Direct + Indirect Effect)				
Urban Trees/ Light Surfaces	0.2-1.0	0.25-1.25	0.5	17
(direct CO_2 sequestered)				(0.65)
Efficient Electric Appliances[2]	2	2.5	0.6	21
Efficient Cars[3]	4.2 (50 ¢/gal)	8.3	2.8	60
New Generation				
Coal Power	8	Base Case	—	Base Case
Nuclear Power	11	4	—	60

1. **CCE** is Cost of Conserved Energy and **CCC** is Cost of Conserved Carbon.
2. Improved standards as defined by National Appliance Energy Conservation Act (NAECA).
3. Improved car efficiency from 26 mpg to 36 mpg.

Table V- **Elements of a multi-year research program for control of summer heat islands.**

(1) **Quantify the heat island effect**
- gather, benchmark, develop, and test heat island simulation models
- collect data and make experimental measurements to validate the models
- evaluate other ways of obtaining heat island data (e.g. satellite and aircraft data)
- integrate all simulated and measured data into a single data base
- develop simplified tools to extract heat island data for major urban areas in the U. S. from the integrated data base

(2) **Verify the mitigation savings**
- model the peak power and energy savings of the heat island mitigation measures
- design and develop wind-tunnel and full-scale experiments to compare and improve simulation results
- perform field monitoring of energy savings to verify estimated savings

(3) **Develop implementation guidelines**
- evaluate the cost-benefits of heat island mitigation measures, and compare savings in energy, equipment, and avoided generation to the costs of implementation
- develop implementation strategies and guidelines

(4) **Quantify the heat island effect on pollution and global warming**
- develop algorithms to correct for heat island contamination of temperature data used to estimate the severity of global warming
- estimate the fossil energy saved by the mitigation measures and hence the delay in global warming
- measure the relation between heat islands, smog, and creation of smog feedstocks

THE IMPACT OF VEGETATION ON AIR CONDITIONING CONSUMPTION

John H. Parker
Chemistry and Environmental Science
Florida International University

ABSTRACT

Recent studies have documented the potential impacts of planetary greenhouse heating due to atmospheric CO_2 levels as well as increases in urban temperatures due to heat island effects. Proposals to mitigate those climatic effects include the planting of large numbers of trees in urban and deforested areas.

This paper evaluates the potential savings in air conditioning energy and peak power as well as in CO_2 emissions due to precision landscaping of buildings in warm, humid climates. Detailed energy measurements show that trees and shrubs planted immediately adjacent to a south Florida building reduced air conditioning requirements by up to 55% during warm summer days. Reductions in summer power demands ranged from 3.3Kw during mornings to 5.0Kw during afternoons. The primary cooling mechanism associated with these savings in air conditioning is the reduction in heat gain through walls and windows. Measured wall temperatures for an air-conditioned building showed that trees and shrubs reduce heat gain through concrete walls by about 60% during peak power periods. The magnitude of these reductions indicates that vegetation cools not only via shading of direct solar radiation but also via evapotranspiration cooling of the microclimate and shading of indirect radiation from the surroundings.

These experimental results can be used to determine landscape designs for buildings in warm, humid climates which optimize energy and peak power savings. For example, trees and shrubs can be positioned to maximize reductions in solar gain during the warmest periods but allow for natural ventilation during milder periods.

Trees and shrubs are effective in the photosynthetic conversion of CO_2 to O_2 as well as in mitigating urban heat island effects. However, this analysis indicates the largest reductions in CO_2 emissions occur when vegetation is strategically positioned around buildings to reduce cooling requirements.

KEYWORDS: cooling energy, cooling peak power, energy savings, evapotranspiration, trees.

THE IMPACT OF VEGETATION ON AIR CONDITIONING CONSUMPTION

John H. Parker
Chemistry and Environmental Science
Florida International University

INTRODUCTION

There is increasing evidence that global warming due to greenhouse gases poses a serious threat to planetary ecological and cultural systems. Although, there are clear options for reducing some greenhouse gas emissions, reductions in CO_2 emissions may be the most difficult. Because of the ability of trees to convert CO_2 to O_2, reforestation in tropical areas has been suggested as a partial solution.

A recent study (Akbari et. al., 1989) of large urban areas in the United States indicates that significant temperature increases are already occurring in many of these cities due to urban heat island effects. This has been attributed primarily to the replacement of vegetation with heat-absorbing pavement and dark roofs. Thus, to offset this, the planting of large numbers of trees in urban areas has been recommended (Akbari et. al., 1988).

In addition to their ability to offset urban heat island effects and to photosynthetically convert CO_2 to O_2, trees can further reduce atmospheric CO_2 levels by reducing the fossil fuels used to heat and cool our buildings (Heisler, 1986, Parker, 1983). This paper summarizes the basic concepts of energy conservation landscaping, as well as, experimental measurements of the impact of vegetation on the energy required for air conditioning buildings in cities in warm, humid climates.

BASICS OF ENERGY CONSERVATION LANDSCAPING

In order to optimize reductions in air conditioning using vegetation, one should position trees and shrubs so that solar radiation is blocked from the building envelope <u>and</u> the adjacent ground. In addition, vegetative evapotranspiration should be used to create a cool microclimate immediately adjacent to the building.

TREES

During the summer months, solar radiation is most pronounced on the east and west sides of a house and roof overhangs offer little protection due to low sun angles during much of the morning and afternoon. In areas where significant air conditioning is used in late August and September, south walls and windows also receive large amounts of solar radiation unless there is a large overhang.

Trees are quite effective in shading east and west-facing walls and windows, particularly if they are planted fairly close to the house. However, it should be noted that if trees are planted too close, roots can disturb the foundation and overhanging limbs can cause damage during storms. (The best way to reduce the very large heat gain via the roof is to use attic insulation and radiant barriers.) Generally, the trees should be planted so that, near maturity, the limbs extend almost to the roof. This proximity planting provides optimal shading patterns and also creates cool microclimates directly adjacent to the house through evapotransportation.

REDUCTIONS IN WALL TEMPERATURES

A primary measure of the effectiveness of vegetation in reducing building cooling requirements is the resultant reductions in wall temperature. Table I compares the measured reductions in surface temperatures of east and west-facing concrete block walls for various types of landscape plants during warm summer days. The first point to be noted is the 24.5 °F reduction in average wall temperature when a tree shades a wall in periods of direct sunlight. Secondly, the data indicate that shrubs planted immediately adjacent to a wall can reduce local wall temperatures as much as trees. A moderate size shrub, five feet tall and four feet wide, reduced the wall temperature from 112 °F to 87.7 °F during periods of direct sunlight. These measurements also reveal the somewhat surprising fact that trees and shrubs cause significant reductions in wall temperatures even when there is no direct sunlight.

Table I also confirms that vines are effective in reducing heat gain through walls, but less so than trees or shrubs. Vines can be particularly useful in providing wall cooling during the first few years of a landscape when trees and shrubs are still small and provide little shading.

SHADING THE AIR CONDITIONER AREA

Perhaps the most effective way to use vegetation to reduce cooling requirements is in the shading of a building's air conditioner and the adjacent areas. Several trees should be planted fairly close to the unit so that after a five-year growth period their canopies will completely shade the air conditioner and the adjacent area during mornings and afternoons of the entire cooling season. Preliminary temperature measurements indicate that the blocking of direct solar radiation, coupled with the evaporative cooling by the vegetation, can reduce the ambient operating temperature of the unit by six or seven degrees Fahrenheit. Thus, this strategic planting can increase the operating efficiency of the air conditioner by as much as 10% during the warmest periods. Clearly, this is an extremely cost-effective energy conservation landscape design idea.

Table I. Average reductions in surface temperatures for east and west facing light-colored walls with various types of landscape plants providing shade and cover. Data was recorded on warm summer days in Miami, Florida.

Landscape Element	Average Temperature Reduction During Daytime Period With No Direct Sunlight (°F)	Average Temperature Reduction During Daytime Period With Direct Sunlight (°F)
Large Tree	6.4	24.5
Moderate-size Shrub	7.6	24.3
Tree/Hedge Combination	10.0	28.0
Moderately Thin Vine	8.0	13.8
Moderately Thick Vine	7.5	16.0

PEAK LOAD LANDSCAPING

In many areas of the United States, the primary component of peak electrical utility demand during the summer months is air conditioning. Thus, it is particularly important to position trees and shrubs to maximize energy reductions during hot summer afternoons, the "peak load" period.

The shading of west-facing windows is of prime importance. However, for a concrete block building, wall-shading priorities are not so obvious. Figure 1 shows the impact of a moderately-large tree on external and internal temperatures of a south-facing wall of an air-conditioned concrete building. The data show a 3 to 4 hour delay between the external solar impact and the resultant increase in interior wall temperature. These experiments show that vegetation is most effective at reducing electrical consumption during peak load periods when positioned to shade east and south-facing walls. The shading of west walls is effective in reducing air conditioning during the late evening, after the peak load period.

It should be noted that reducing interior wall temperatures not only reduces the heat load on the air conditioner, but also lowers the mean radiant temperature inside the room. This can result in increased comfort levels or can result in additional energy savings through a higher thermostat setting.

LANDSCAPING FOR WIND CONTROL

Trees and shrubs can be positioned around a residence so as to significantly influence the movement of air through and around it (White 1954, Parker, 1987). For a residence in which air conditioning will be used only minimally, low branches of trees should be pruned to allow the passage of prevailing summer breezes through the house. In fact, the trees and shrubs should be strategically positioned so as to funnel the breezes into the windows in order to maximize natural cooling.

Designs which channel winds towards an air-conditioned residence can actually increase the energy consumed in air conditioning via warm air infiltration. This design conflict can be alleviated by a careful placement of shrubs and trees so that winds are channeled into the dwelling when the windows are open, but away from it when the windows are closed. For example, in south Florida, the prevailing summer winds are from the southeast. Consequently, air infiltration through the windows can be reduced by locating tall shrubs close to and on the north sides of east facing windows and on the west sides of south facing windows. When the windows are opened during mild periods, these same shrubs will facilitate natural ventilation through the windows.

MEASURED ENERGY SAVINGS

How effective are these design concepts in reducing the energy consumed in a building in a warm, humid climate? In order to answer this, a detailed study was made on a mobile home that is a childcare center at Florida International University in Miami. The double-width mobile home had insulation (R) values of about 8 for the ceiling, floor, and walls—thermal characteristics that are comparable to those of many concrete block single-family residences in Florida. Both patterns and levels of air conditioning consumption by the totally unlandscaped childcare center were monitored during warm summer days. Then an energy conservation landscape plan using trees and shrubs was designed and installed.

Table II shows a brief summary of the air conditioning data obtained before, and two years after the vegetative landscaping. The results are the averages of large numbers of experimental data points gathered during periods of similar climatic conditions. Overall, the energy used in air conditioning during warm summer days was reduced by an average of about 58 percent. These data can be used to estimate that, for an entire cooling season in Florida, landscaping can reduce air conditioning costs by approximately 40 percent. With regard to the electrical peak load period, average power demand during the warmest summer afternoons was about five kilowatts lower for the landscaped condition. The magnitude of these savings suggests that trees and shrubs reduce cooling requirements not only by shading but also by reducing warm air infiltration and creating cool microclimates near the residence.

Table II. The rate of electrical energy consumption for Air-conditioning the Childcare Center during a number of warm summer days, with and without vegetative landscaping

Time Period and Landscape Condition	Average Ambient Temperature	Average Rate of Energy Consumption	Reduction in Air-Conditioning
	°F	**Kilowatt-hr per hour**	**Percent**
Morning (9 a.m.-12 p.m.)			
No landscaping	90.0	5.56	
Landscaping	91.0	2.28	**58.9**
Afternoon (12 p.m.-6 p.m.)			
No landscaping	93.8	8.65	
Landscaping	93.9	3.67	**57.6**

CONCLUSIONS

The analysis presented in this paper indicates that energy conservation landscaping is one of the most effective tools in reducing the energy consumed in residential space cooling, even in hot humid climates. Careful positioning of trees and shrubs can optimize the energy savings, particularly during the crucial peak load periods. Vegetation can increase comfort levels in both air-conditioned and non-air-conditioned buildings during the cooling season.

A recent study which models the impact of planting trees in urban areas (Akbari et. al., 1988) indicates that the largest cooling energy savings is associated with reductions in city-wide temperatures and reduced infiltration rates—called indirect savings. The magnitude of the measured energy savings associated with the planting of vegetation immediately adjacent to a building documented in this paper suggest that direct savings are probably larger.

Perhaps of most importance, trees and shrubs planted to shade buildings offer a three-fold mitigation impact on CO_2 global warming. By offsetting urban heat islands and reducing building cooling requirements, CO_2 emissions due to fossil fuel combustion are reduced while, at the same time, the vegetation photosynthetically converts CO_2 to

O_2. Clearly, the planting of large number of trees near buildings in cities with significant cooling requirements is an attractive alternative.

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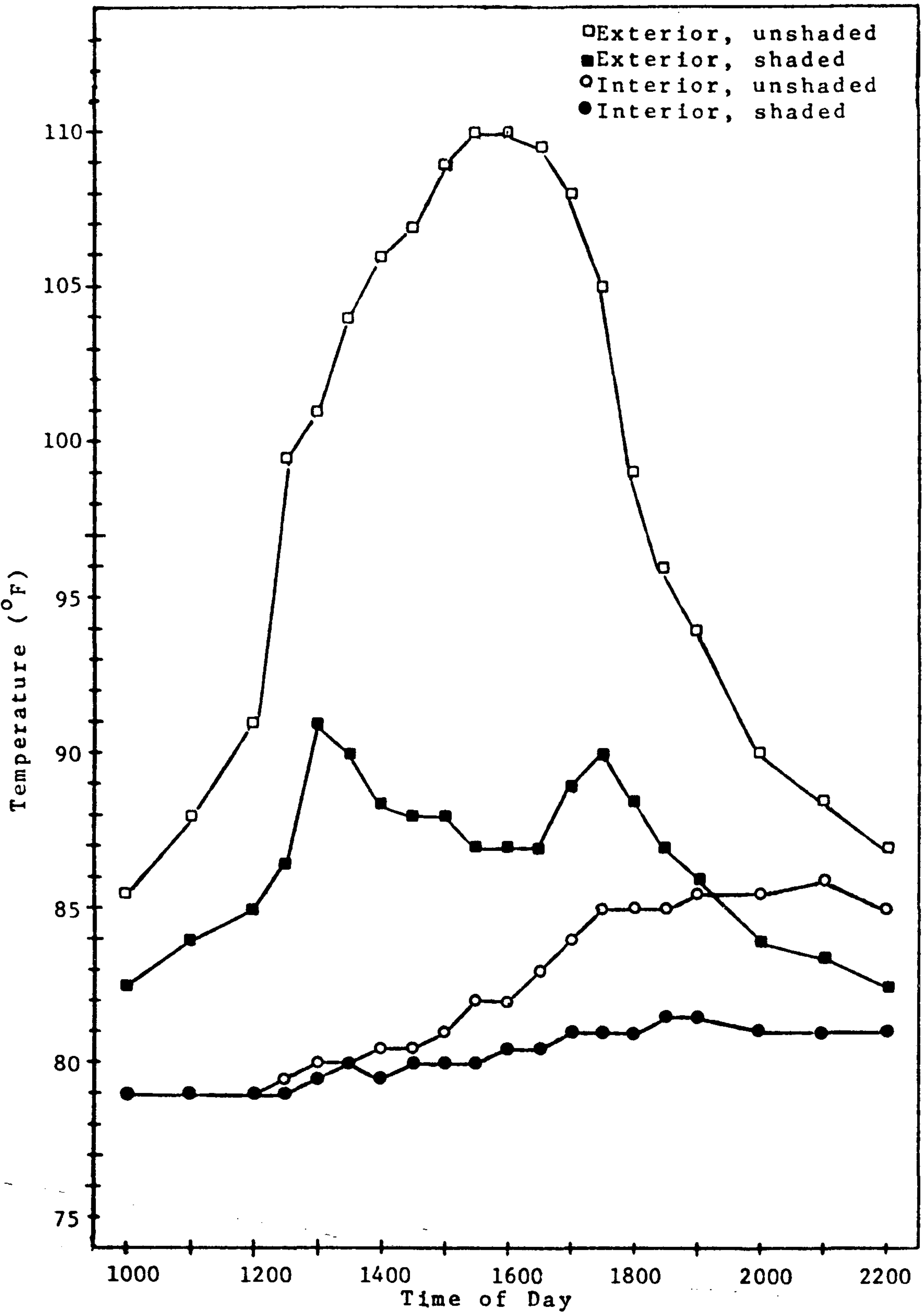

Figure 1. South wall temperature profiles for a clear, warm day in late summer

VEGETATION TO CONSERVE WATER AND MITIGATE URBAN HEAT ISLANDS

E. Gregory McPherson
Landscape Architecture
University of Arizona

ABSTRACT

Summertime temperatures have increased 1 °F and 2 °F per decade in Tucson and Phoenix, Arizona, during the past 40 years. At the same time, vegetation land cover in Tucson has diminished by 9%, as people replace lush landscapes with gravel and few plants to reduce water and maintenance costs. Data derived from computer simulations using three full-sized landscapes around identical buildings in Phoenix and Tucson indicated that these "Zeroscapes" are uneconomical compared to "Xeriscapes", which used low water use plants for shade. Net energy-water savings for the Xeriscapes were $123 (22%) in Phoenix and $55 (15%) in Tucson, compared to the Zeroscapes. "Mesiscapes" in Tucson, which contained large lawns and water-thirsty plants, were more costly than Zeroscapes because of higher water prices. Reduced cooling tower evaporation associated with energy savings from shade resulted in modest water savings (800-993 gals/yr) at off-site power plants for the Xeriscape designs. More dramatic reductions in carbon-dioxide emissions from local power plants were estimated for the Xeriscapes (1465-1779 lbs/yr), largely due to shading effects. The paper concludes with design guidelines for energy and water conserving landscapes, and examples of how Landscape Water Use Efficiency can be used as a tool to evaluate energy and water tradeoffs.

KEYWORDS: energy conservation, landscaping, water conservation, heat islands

VEGETATION TO CONSERVE WATER AND MITIGATE URBAN HEAT ISLANDS

E. Gregory McPherson
Landscape Architecture
University of Arizona

INTRODUCTION

Phoenix and Tucson, Arizona, have experienced relatively large increases in summertime temperatures during the past 40 year period of rapid urbanization (1 to 2°F per decade). Urban warming increases electricity demand for air-conditioning (about 1-2% per degree F) (Akbari et al., 1989) and water demand for landscape irrigation (Woodard & Horn, 1988). Additionally, the increasing duration of smoke/haze events in Phoenix appears to be related to the impact of the growing urban heat island on the structure of local inversion layers (Brazel et al., 1988). When global warming is added to these summer heat islands, the rate of temperature rise will be about doubled (Akbari et al., 1989).

Vegetation can counteract urban warming through shading and evapotranspirational (ET) cooling. Recent research findings (Huang et al., 1987) suggest that direct shading of buildings and ET cooling can reduce average residential cooling use in Phoenix by 25%, and peak power consumption by 18%. An additional benefit is reduced carbon-dioxide emissions from local power plants due to a reduced demand for electricity. It has been shown that an urban tree can reduce 10-20% more carbon-dioxide than a rural tree due to this indirect effect (Akbari et al., 1988). Early results also indicate that the costs of energy and carbon conserved by planting trees and switching to light colored surfaces in cities are substantially less than for energy efficient electric appliances, fuel efficient cars, and new electric supplies (Akbari et al., 1988).

Given these facts it is not surprising that a tree planting revival is underway. The American Forestry Association just began a program called Global Releaf, which includes planting of 100 million trees in U.S. cities (Sampson, 1988). Los Angeles' Mayor Bradley is at the vanguard of this nationwide campaign, pledging that 5 million trees will be planted in L.A. by 1992. In addition, Congresswoman Claudine Schneider (Rep., R.I.) has authored The Global Warming Prevention Act, which includes authorization for $100 million to establish an urban tree planting program to reduce the "summer heat island" effect in communities.

However, questions regarding the cost-effectiveness of urban tree plantings in the desert Southwest should be addressed before massive planting programs are initiated. In examining potential benefits, it should be recognized that many homeowners practice deficit irrigation, which means that the ET cooling effects may be less than predicted. On the other hand, trees provide numerous benefits in addition to climatic amelioration (e.g., reduced stormwater runoff, increased property values, wildlife habitat, etc.). With respect to costs, installation and tree maintenance expenses are greater in the desert Southwest than in other regions with less extreme climates. For instance, it can cost three dollars a week to keep a tree alive during summertime in Tucson. Our high priced water may result in irrigation costs that exceed energy savings for certain species. Planting costs may be greater than the national average as well. For example, it costs more to dig a hole in caliche soil than to buy the tree that will be planted there. Finally, questions remain as to the most effective way to implement an urban tree planting program. Trees require a long term commitment if they are to have long and functional lives. Thus, any "tree planting program" should be part of a comprehensive urban forestry program that identifies program priorities and includes a long range management element (McPherson & Johnson, 1988).

This paper provides an overview of a research program at the University of Arizona that is quantifying the impacts of vegetation on building microclimates and energy-water use. Thus far, we have documented change in Tucson's urban vegetation from pre-settlement to the present, and addressed the question of how one can balance the need for a water-conserving landscape with an energy-efficient home in the dry Southwest. Investigation of other benefits and costs is needed before the cost-effectiveness of large-scale tree planting in southern Arizona can be fully evaluated.

BACKGROUND

Phoenix and Tucson, Arizona are rapidly growing cities in the southwestern desert. Both have experienced more than a tenfold increase in population between 1940 and the present. Currently, about 80% of the State's population live in the Phoenix (2 million) and Tucson (0.6 million) metropolitan areas. Rapid urbanization has been accompanied by increased social and environmental problems. For example, Phoenix had the worst environmental ratings of 192 U.S. cities in a recently completed national survey (Kelly, 1988), and in a similar survey Tucson ranked as the 25th- highest stress city out of 286 cities surveyed (Duarte, 1988). City officials, planners, and concerned citizens are searching for ways to make their city's more livable. Examples of approaches now being studied include: better mass transportation, comprehensive land use planning, stormwater management planning, and downtown revitalization. As yet, no consideration has been given to comprehensive urban forest planning. However, results of urban forestry research in other regions suggest that tree planting could improve the physical environment of desert cities (Hopkins, 1978). Additionally, urban forestry programs can be relatively easy to implement and manage. Many programs have high levels of citizen participation, and this provides political, social, and economic benefits (McPherson & Johnson, 1988).

URBAN HEAT ISLANDS IN PHOENIX AND TUCSON

Rapid urbanization in Phoenix and Tucson have resulted in the conversion of desert and irrigated agricultural fields to urban landscapes, and large increases in atmospheric pollution levels. The resulting impact on urban climate has been well documented. Nighttime summer temperatures at Sky Harbor Airport in Phoenix increased an average of 2 °F every decade from 1948 to 1984 (Balling & Brazel, 1987a). This warming rate is about double the national average for large cities (Akbari et al., 1989). About 5-10% of the current electric demand used to cool buildings in Phoenix is spent just to compensate for the heat island effect. Less dramatic but significant increases in afternoon temperatures have occurred in Tucson (1 °F per decade) (Balling & Brazel, 1987b).

Tucson and Phoenix are becoming drier as well as hotter. Pan evaporation rates have increased gradually due to long-term urbanization. In one case, construction of a regional shopping center and parking lot near the measurement site resulted in a 30% increase in pan evaporation (Balling & Brazel, 1987c).

In a recent study of climate effects on municipal water demand, investigators found that a 1% increase in pan evaporation caused total municipal water demand in Tucson to increase by 0.32% and outdoor demand to increase by 1% (Woodard & Horn, 1988). Also, daily water demand was strongly influenced by maximum temperature. Plant evapotranspiration (ET) rates are an important component of the urban water balance because landscape irrigation accounts for 30-60% of summertime water demand. Hot and arid conditions increase ET rates and landscape water consumption, often during the summertime peak demand period.

LAND COVER CHANGE IN TUCSON

Investigators have linked urban heat islands to land cover change associated with urbanization. The replacement of vegetated areas with artificial surfaces alters the radiation budget by reducing latent heat loss by evaporation, and increasing sensible heat gain. The results of our research on urban vegetation change in Tucson indicate that the amount of vegetation in Tucson has diminished substantially during the past 30 years.

Massive tree planting during the first decade of the 20th century transformed Tucson from a "Desert City" to a "Garden City." The primary reasons for planting trees were to beautify the city and ameliorate the inhospitable desert climate (McPherson & Haip, 1988). Ample water and a growing tourist economy resulted in landscapes that were evocative of a sun-drenched subtropical oasis. However, tree planting diminished after World War II, as developers rushed to construct tract subdivisions to alleviate the housing shortage. This trend was accelerated in the mid-70's, when water prices increased over 20% and water conservation became an accepted ethic. Lush landscapes were converted to desert landscapes, with little lawn and fewer trees and shrubs. One study reported an 18% decrease in residential lawns from 1976-1979 (Mouat & Parton, 1979).

In a current study we have sampled land cover change using aerial photographs from 1953, 1971, and 1983. Preliminary results indicate the following:

1. Vegetation cover decreased from 37% to 31% between 1953 and 1983 in the area of Tucson developed prior to 1953.
2. Vegetation cover decreased from 38% to 27% between 1971 and 1983 in the area of Tucson developed from 1953 to 1971.
3. In 1983 vegetation covered 31% of areas in Tucson developed from 1971 to 1983.

Hence, just as Tucson was transformed from a desert to lush oasis, it is now returning to a more desert-like environment. Water conservation landscaping ordinances in Phoenix and Tucson require use of drought tolerant plants and restrict the amount of turfgrass in certain areas. Communities such as Mesa, Arizona offer landscape rebates as an incentive to convert from lush to water-conserving landscapes. Homeowners can qualify for rebates by replacing all vegetation with decomposed granite mulch, and many do this to reduce water bills and landscape maintenance. Although these "Zeroscapes" are water-conserving, they increase cooling loads, and are biologically sterile, unattractive landscapes.

Results of our research using scale models and reported by Dr. Simpson in this Workshop Proceedings show that shade or turf can reduce cooling energy use by 20-30% compared to the Zeroscape (McPherson et al., 1989). Additionally, it appears that energy savings can be greater than water costs for shade provided by low water use plants. To extend our research to full-sized landscapes I used computer simulations to compare energy and water costs for three prototypical landscapes in Phoenix and Tucson.

SIMULATIONS OF ENERGY AND WATER COSTS FOR FULL-SIZED LANDSCAPES

The purpose of this study was to evaluate the tradeoffs between energy savings from shade and landscape water costs for three typical mature landscapes surrounding identical residential buildings. A brief summary of methods and results follows.

Methods

Three landscapes were designed for a typical single family residential lot (6,500 ft^2) containing 4,130 ft^2 of landscapable area.

Zeroscape. Decomposed granite covered all landscapable area (Figure 1). Three moderate-water-use privet trees and 11 indian hawthorn shrubs were the only plants. These plants provided little shade to the building.

Xeriscape. This landscape was designed to provide good summer shade from low-water-use plants (Figure 2). Eight trees (palo verde, Heritage oak, and mesquite) were located to shade all sides of the building. Deciduous pomegranate shrubs shaded the east and west walls, while other shrubs enclosed the outdoor living areas. The backyard contained a 400 ft^2 lawn area, desert wildflowers, and cacti.

Mesiscape. Lawn (1,500 ft^2) covered most of the landscapable area (Figure 3). Four magnolias south of the building and two ash in the north lawn did not provide much shade. Sixty-eight shrubs enclosed the lot and outdoor living areas, but gave little shade. All woody plants were moderate water users.

Three 1,476 ft^2 one-story ranch homes similar to three construction types commonly found in the Southwest were chosen for study. The buildings were oriented with the longest sides facing east-west. Windows accounted for 14% of the total floor area and 70% of the glassed surfaces faced east-west. Other thermal specifications and HVAC features for the air-conditioned residences are detailed in a related study (McPherson & Dougherty, 1989). Results for one building type are presented in this report.

New masonry construction (Masonry 80) is similar to currently constructed masonry homes. Walls were made of 6-inch reinforced block with hardboard insulation (R-8), fiberglass batt insulated the attic (R-31), and windows were double pane. The air conditioner efficiency was 9.0 SEER and the seasonal energy efficiency (EER) of the furnace was 0.76. Thermostat settings were 70 °F and 78 °F.

The Shadow Pattern Simulator (McPherson et al., 1985) and a building energy analysis program called MICROPAS (ENERCOMP, 1985) were used to estimate effects of irradiance reductions from trees and shrubs on space cooling and heating costs for Phoenix and Tucson sites. Evapotranspirational cooling effects were included in one of two Mesiscape design scenarios. The first scenario (Mesiscape #1) assumed no ET cooling and the second (Mesiscape #2) assumed a 25% reduction in annual cooling costs, based on our scale model results. Energy costs for electricity and natural gas were based on 1988 prices for residential consumers in Phoenix ($0.0994/kWh and $0.57/1000 cf) and Tucson ($0.08/kWh and $0.54/1000 cf). Larger cooling loads were anticipated for Phoenix than Tucson based on MICROPAS heating and cooling degree day data. There were 979 more cooling degree days in Phoenix (3,801 vs. 2,822 CDD) and 248 more heating degree days in Tucson (1,680 vs. 1,432 HDD).

To estimate water costs we used consumption data for study species as listed in Water Conservation for Domestic Users (University of Arizona, 1976) for typical mature crown diameters of plants in Tucson. Consumptive use of landscape water was assumed

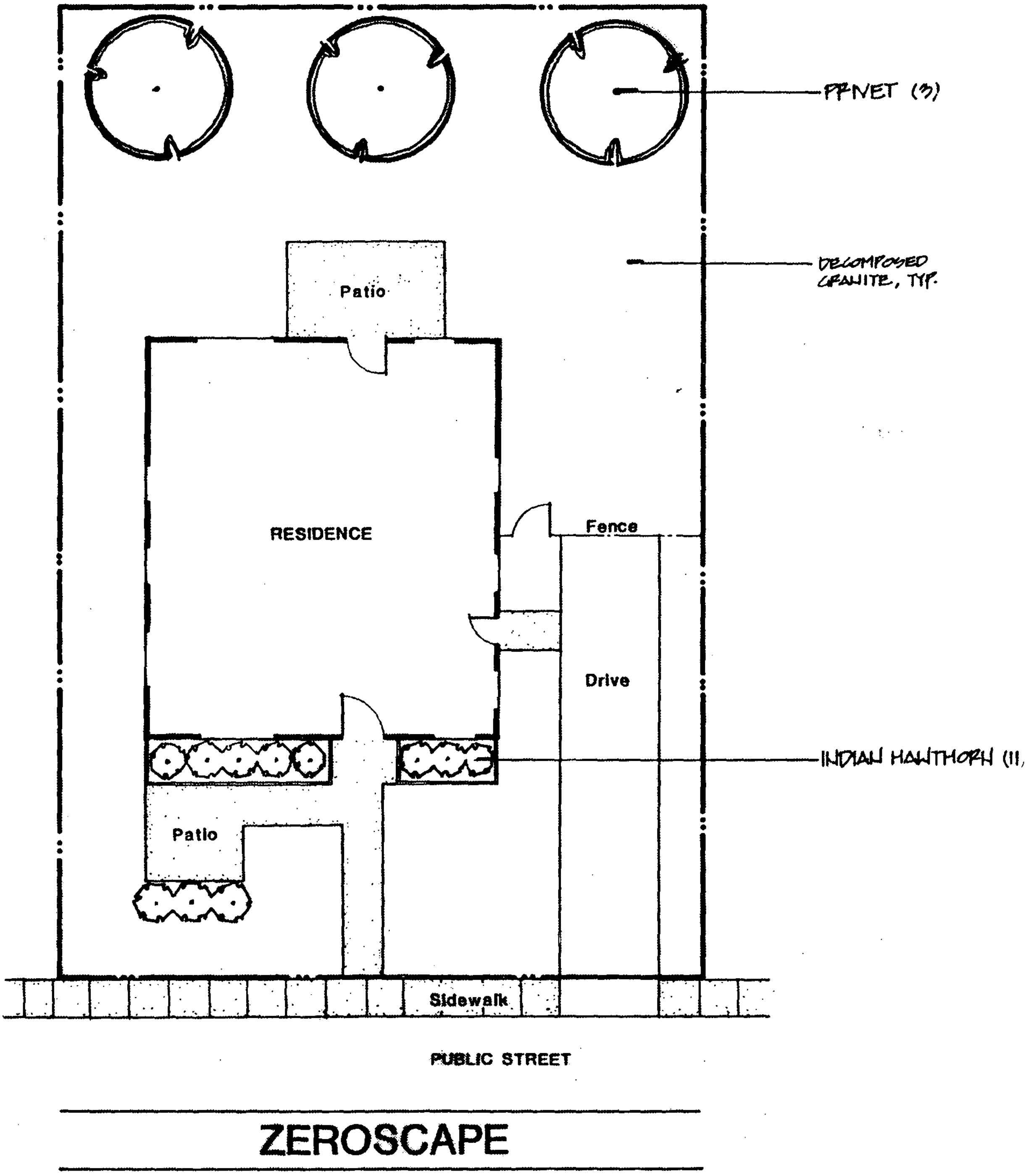

Figure 1. This Zeroscape design is primarily decomposed granite with little vegetation.

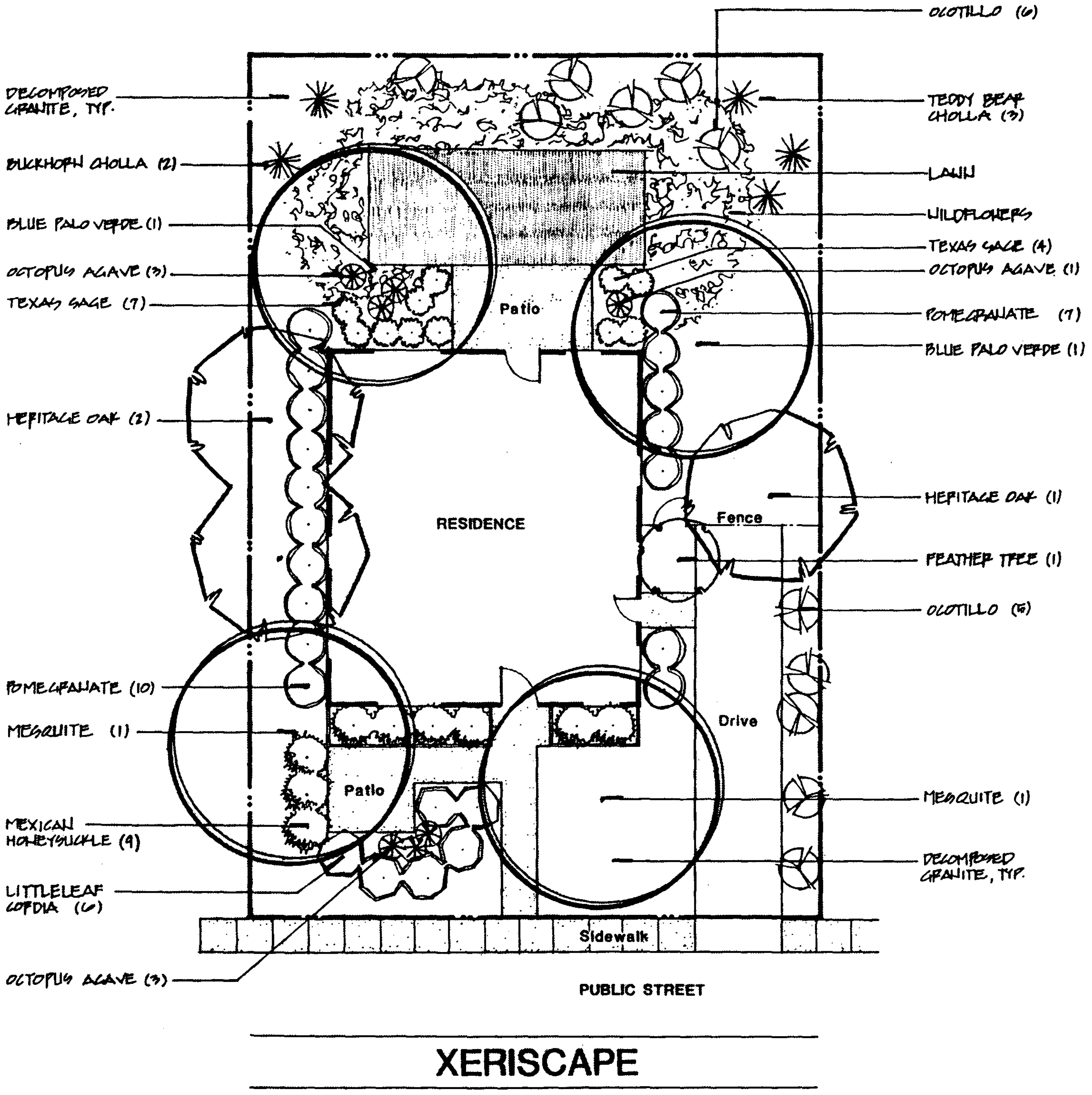

Figure 2. The Xeriscape design uses plants that require little irrigation to shade the building and a small lawn area.

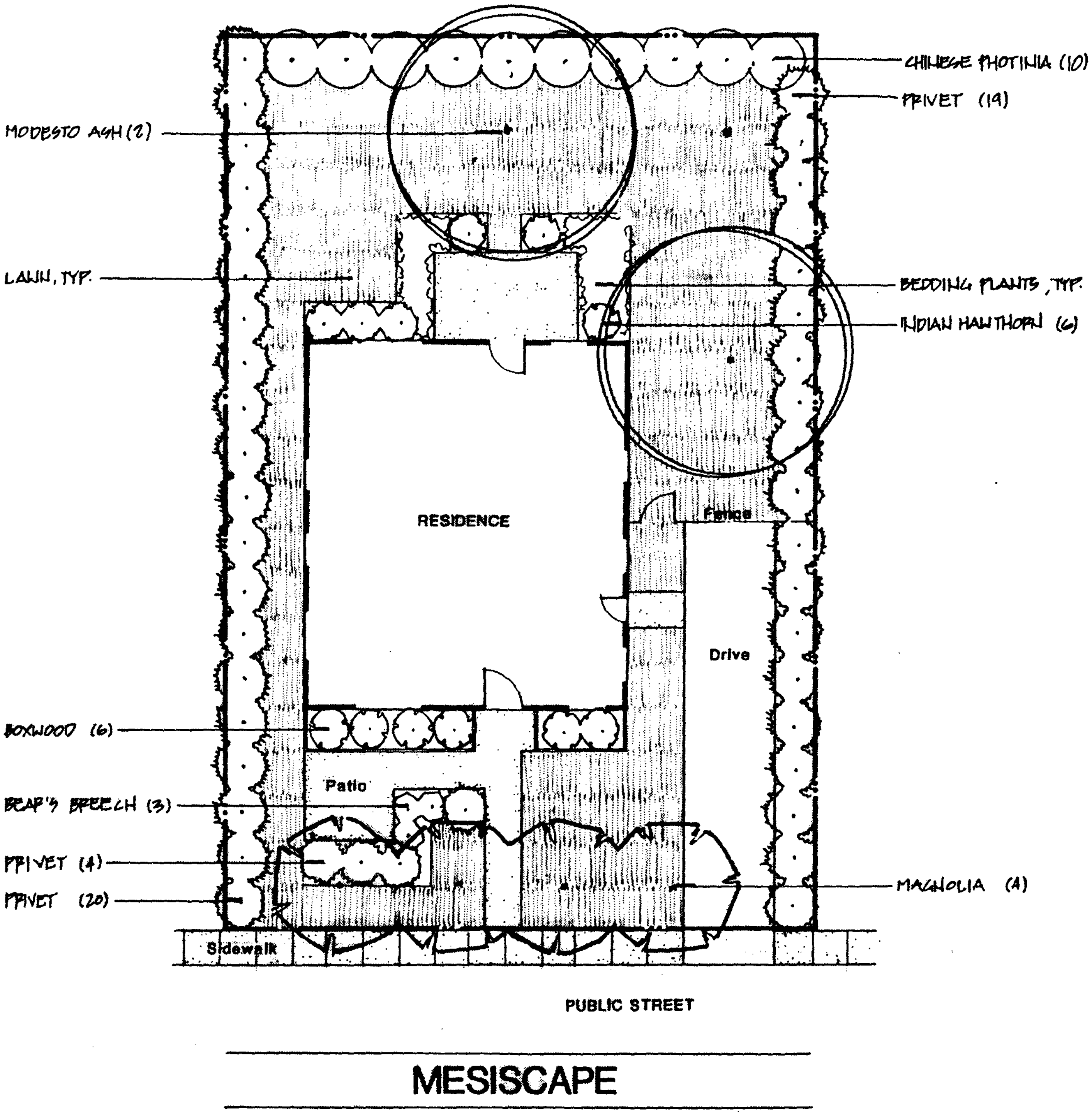

Figure 3. This Mesiscape design contains a large lawn area and water-thirsty trees to the south that block winter irradiance.

to be 10% greater in Phoenix than Tucson. This figure was based on 12-15% greater pan evaporation in Phoenix, and the assumption that ET is usually about 80% of pan evaporation (Dr. Paul Brown, personal communication, Nov. 10, 1988). Water costs were based on 1988-89 summer and winter prices in Phoenix ($1.18 and $0.87/Ccf) and Tucson ($1.72 and $1.28/Ccf).

Landscape irrigation consumption for Tucson designs was as follows. All lawns received 45 in/year. Trees and shrubs in the Zeroscape and Mesiscape #1 designs received 30 in/year but they received only 6 in/year in the Xeriscape. In the Mesiscape #2 scenario trees in lawn areas received no supplemental irrigation.

Results

Xeriscapes in Phoenix and Tucson consumed 26-27% less energy ($87-147 savings) for total space heating and cooling than the unshaded Zeroscapes (Table I). This result is probably conservative because ET cooling is not considered for the Xeriscapes. Vegetation in the Mesiscape designs blocked winter irradiance and provided relatively little summer shade. Total energy costs for the Mesiscape #1 design in Tucson were 2% ($7) greater than for the Zeroscape, indicating the potential deleterious effects of inappropriately located vegetation. In Phoenix, where heating loads are less important, the Mesiscape #1 design provided a modest savings of 3% ($14). Net energy savings of 15-23% ($124-50) resulted for the Mesiscape #2 designs, which assumed 25% cooling reductions from ET.

Landscape water costs ranged from 4-60% of space conditioning costs. Zeroscapes were most water-conserving, reducing water use by 86% ($176-137) compared to the Mesiscape #1 designs. Landscape water use in the Xeriscapes was 70% ($144-113) less than for Mesiscape #1 designs. Elimination of supplemental irrigation for trees in lawn areas in the Mesiscape #2 designs reduced water use by 32% ($69-51) compared to the Mesiscape #1 designs.

Energy savings from shade were 22% and 15% greater than additional water costs for Xeriscapes compared to Zeroscapes in Phoenix and Tucson, respectively. Total net savings were greater in Phoenix ($123) than Tucson ($55), primarily due to larger cooling savings (reflecting higher electricity prices) and lower water prices. The Mesiscape #1 designs proved to be more costly than Zeroscapes at both sites because water costs exceeded cooling savings. Net energy-water costs for the Mesiscape #1 designs were 50% ($183) greater in Tucson and 22% ($123) greater in Phoenix than their respective Zeroscapes. The impact of relatively higher water prices in Tucson is reflected in these results. The Mesiscape #2 design was uneconomical in Tucson (-$57), but provided a 7% ($38) net savings in Phoenix. Because current electricity prices are higher and water prices are lower in Phoenix than Tucson, it may be cost-effective to use turf in Phoenix for ET cooling. However, this strategy could be short-lived if increasing water scarcity and distribution costs cause water prices to rise faster than electricity prices.

Table I. Annual Space Conditioning and Landscape Water Costs for Landscapes Around the Masonry 80 Building

	Heating & Cooling Energy Use				Landscape Water Use				Net Costs		
Design	Total (kBtu)	Total ($)	Saved from Zero ($)	Saved from Zero (%)	Total (Ccf)	Total ($)	Saved from Mesici ($)	Saved from Mesici (%)	Total ($)	Saved from Zero ($)	Saved from Zero (%)
Phoenix											
Zero	52668	546	--	--	20	23	137	86	569	--	--
Xeric	40189	399	147	27	42	47	113	71	446	123	22
Mesic1	52016	532	14	3	145	160	--	--	692	–123	–22
Mesci2	42036	422	124	23	98	109	51	32	531	38	7
Tucson											
Zero	40666	337	--	--	19	30	176	85	367	--	--
Xeric	31467	250	87	26	39	62	144	70	312	55	15
Mesic1	41987	344	–7	–2	127	206	--	--	550	–183	–50
Mesic2	35538	287	50	15	85	137	69	33	424	–57	–16

These findings suggest that Xeriscape designs are cost-effective compared to the increasingly popular Zeroscapes. Net savings of more than the 15-22% found here could be expected for older and less energy-efficient air-conditioned homes. The traditional Mesiscape designs may be more economical than Zeroscapes in Phoenix, but not in Tucson, where water costs are 20% higher. Although most homes recently constructed in Phoenix and Tucson are air-conditioned, about 40% of the single family housing stock in Tucson have evaporative coolers. Cooling savings are likely to be 75-95% less for evaporatively cooled homes than reported here for air-conditioned homes. The need for fewer hours of cooling due to shade from Xeriscape design is likely to result in minor energy and water savings for owners of evaporatively cooled buildings.

OFF-SITE WATER USE AND CARBON-DIOXIDE EMISSIONS

Landscapes that reduce cooling loads can also reduce water consumed by power plants, as well as carbon-dioxide emissions. Approximately 0.6 gals of water are consumed for each kWh of electricity produced by Tucson Electric Power's (TEP) generation facilities (J. Guenther, personal communication, Nov. 16, 1988). TEP's coal-fueled power plants also emit about 1 lb of carbon- dioxide per kWh of electricity generated (Akbari et al., 1988). An individual tree sequesters about 13 lb of carbon a year naturally. To estimate carbon assimilation from shrubs I calculated the ratio of shrub to tree crown volume and assumed similar foliage densities. The crown volume of one tree with canopy dimensions of 16' x 16' x 16' is equivalent to the volume of 64 shrubs, assuming each is 4' x 4' x 4' in size. As a first approximation, I assumed that each shrub sequesters 1.6% of the carbon assimilated annually by a tree, or 0.2 lb of carbon per shrub each year. Because lawn biomass is relatively small its effect was not included in this analysis. Carbon-dioxide sequestered annually by shrubs and trees in each design was estimated as follows: Zeroscape - 41 lbs, Xeriscape - 114 lbs, Mesiscapes - 92 lbs. Off-site conservation effects for the Xeriscape and Mesiscape designs around the Masonry 80 construction type are shown in Table II. Large-scale tree planting would be required to achieve the effects reported below.

Table II. Annual Off-Site Water and Carbon-Dioxide Emission Savings for Landscape Designs

Design	Cooling Energy (kWh)	Energy Saved (kWh)	Water Saved (Gal)	Water Saved ($)	CO_2 Saved (lb)
Phoenix					
Zero	4733	--	--	--	41
Xeric	3068	1665	999	1.58	1779
Mesic1	4436	297	178	.28	389
Mesic2	3327	1406	844	1.33	1498
Tucson					
Zero	3042	--	--	--	41
Xeric	1691	1351	811	1.87	1465
Mesic1	2866	176	106	.24	268
Mesic2	2150	892	535	1.23	984

Cooling energy savings for Xeriscapes were 1665 kWh and 1351 kWh in Phoenix and Tucson, respectively. These energy savings translated into a modest annual off-site water savings of 999 and 811 gals ($1.58-1.87). Off-site water savings represented 3% and 6% of total on-site landscape water costs for the Xeriscape designs in Phoenix and Tucson. Water conserved off-site was enough to provide the yearly irrigation requirements for one small tree and two large shrubs in the Xeriscape designs.

Carbon conserved (in the form of carbon-dioxide) due to the Xeriscape designs ranged from 1779 lbs in Phoenix to 1465 lbs in Tucson. The effect of shade on reducing power plant emissions was much greater than the effect of carbon-dioxide assimilation by the vegetation, a finding previously reported by Akbari and others (1988). Shading effects accounted for 65-95% of the total carbon conserved from the Xeriscapes and Mesiscapes. If evapotranspirational cooling effects were included these percentages would be greater. Thus, urban trees can provide significant off-site water and carbon conservation benefits that should be considered when assessing the full spectrum of benefits and costs.

DESIGN GUIDELINES

I estimate that about 9% of the total water demand in the Tucson Active Management Area is used for landscape irrigation. The average daily per capita water use by exterior residential landscape is about 82 gals in Phoenix and 36 gals in Tucson. Conservation goals established by the Arizona Department of Water Resources seek to reduce consumption of this water by 50% in Phoenix (42 gpcd) and 30% in Tucson (25 gpcd) by the year 2000. It will be necessary to judiciously select and locate plants to meet these conservation goals while still providing the many benefits associated with vegetation. Designers will need guidelines to determine how much vegetation is needed to achieve a desired cooling effect, which species perform the best, and where plants should be located to maximize benefits and reduce costs. The following section summarizes some recent research findings regarding tree location and selection for energy and water conservation in the desert Southwest.

Energy Savings

Factors influencing energy savings in the desert Southwest include: building/occupant features, side of building shaded, area shaded, location of shade (windows), shade density, ET cooling effects, plant growth rate, and energy prices. Previous research provides information concerning the relative importance of some of these factors (McPherson et al., 1988; McPherson & Dougherty, 1989).

Side shaded. West shade provides greater energy savings than identical amounts of shade on the east wall. One and two African sumac opposite the east wall of the Masonry 80 building gave energy savings of $25 and $39, respectively. The same plantings opposite the west wall provided energy savings of $40 and $61. Two trees on the east resulted in savings comparable to one tree on the west (McPherson & Dougherty, 1989).

Tree form and location. Broad trees shade more wall area than tall narrow trees, and this usually results in larger energy savings per tree. For example, shade from a 25' x 25' paraboloid shaped tree opposite the west wall of the Masonry 80 building in Tucson saved $40. Shade from an equally dense but ellipsoid shaped tree (25' tall x 13' wide) saved only $24. Broad trees that shade walls are more effective than tall narrow trees that shade roofs because they reduce large amounts of solar heat gain coming through windows and walls (McPherson & Dougherty, 1989).

Tree location is important with respect to the location of windows and existing trees. The greatest energy savings result from shade on windows and previously unshaded building surfaces.

Tree crown density. Dense trees provide more shade and greater energy savings than trees with open crowns. For instance, shade from a dense African sumac (85% interception) located to shade the west wall of the Masonry 80 building gave a $40 savings, while shade from a more open mesquite (75% interception) gave a $36 savings. However, tree form may be a more important factor influencing energy savings than crown density because of greater species variability. For example, crown diameter can vary from 5-50 ft, but summer crown densities usually range from 60-90% (McPherson & Dougherty, 1989).

Water Costs

Few studies have measured consumptive water use of isolated trees in Southwest landscapes. A myriad of factors influence landscape irrigation requirements including species factors (e.g., stomatal resistance, aerodynamic resistance, root development, leaf area, etc.) and site factors (e.g., microclimate, soil hydraulics, competition, plant vigor, etc.). The model (University of Arizona, 1976) I have used only considers plant size and a species-specific annual irrigation requirement (Table III). Water consumption is calculated as the product of a plant's crown profile area (ft^2) and irrigation requirement (in/year).

Data in Table III show an exponential increase in water costs with increasing crown diameter for each species. For example, annual water costs for the 40 ft wide mulberry are 4 times greater than for the 20 ft wide tree. Species related consumption is also important. One 20 ft wide mulberry costs 5 times as much to water as a similar sized mesquite.

Table III. Annual Water Costs for Three Tree Species

	Irr.	Crown Diameter (ft)			
Species	in/yr	10	20	30	40
Mesquite	10	1.05	4.20	9.45	16.79
Calif. Pepper	30	3.15	12.60	28.35	50.39
Mulberry	50	5.25	20.99	47.25	83.99

Data assume 1:1 crown ht/width ratio and 1988 Tucson Water Prices ($1.42 Ccf ave.).

These data can be used to evaluate water-energy tradeoffs associated with different types of trees in different locations. For instance, the ideal tree should have a dense broad crown and require little irrigation. Maximimum savings will result if it shades windows in the west wall and is cold deciduous.

Landscape Water Use Efficiency

The term Water Use Efficiency (WUE) has been used by investigators to compare how efficiently various agricultural crops use water (Taylor et al., 1983). It is often expressed as crop dry weight/transpiration water loss. The WUE concept can be adapted to express energy savings per unit landscape water use. I call this Landscape Water Use Efficiency (LWUE) and define it as follows for the purposes of this study:

$$\text{LWUE} = \$\text{ Annual Energy Savings } / \ \$\text{ Annual Landscape Water Costs}$$

LWUE could be calculated for individual plants or for entire landscapes. In either case, the higher the LWUE ratio the greater the net energy-water savings. A LWUE of 5 indicates that for each $1 spent to irrigate the landscape, there is a $5 energy savings. Landscape designs that maximize energy savings per unit of landscape water cost will achieve the highest LWUE ratio.

LWUE ratios were calculated using data previously reported (McPherson & Dougherty, 1989) for three shading scenarios: 1, 2, and 3 trees opposite the west wall of the Masonry 80 building in Tucson. Data are shown for four different species in Table IV.

Table IV. LWUE Ratios for West Shade on the Masonry 80 Home

Species	in/yr	1 Tree	2 Trees	3 Trees
Mesquite (75% dense)	12	5.1	4.0	2.8
African sumac (85%)	16	4.0	3.1	2.1
Polydan eucalyptus (84%)	20	4.6	4.0	3.5
Mulberry (74%)	45	1.3	1.0	0.7

Crown diameter of all species assumed to be 25' except 13' for Polydan eucalyptus. West wall is 40 ft long.

LWUE ratios ranged from 0.7 for 3 mulberry (water costs exceeded energy savings) to 5.1 for a single mesquite. Ratios for the polydan eucalyptus were surprisingly high given its relatively high water demand (20 in/year). However, because its crown diameter was half that of the other trees, the total amount of water consumed per tree was relatively less. Polydan eucalyptus had the highest LWUE for the 3 tree scenario, largely because the third tree shaded previously unshaded wall, which was not the case for the other species. The LWUE analysis is a promising method for evaluating energy-water tradeoffs, but more research is needed to refine the water use model and estimates of ET cooling effects before calculations such as these can be considered entirely dependable.

SUMMARY

Summertime temperatures have risen dramatically in Phoenix and Tucson during the past 40 years, and urban canopy cover has diminished. One dimensional policies that promote water conservation and reward conversion from Mesiscape to Zeroscape will exacerbate these trends. The result will be increased demands for cooling energy and landscape water, as well as increased carbon-dioxide emissions from power plants. One way to mitigate the growing urban heat island is through urban reforestation with low water use plants and Xeriscape design.

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THE ROLE OF LANDSCAPE VEGETATION IN URBAN HEAT ISLAND AMELIORATION: RESULTS OF A SCALE MODEL STUDY

J.R. Simpson and E.G. McPherson
Department of Soil & Water Science, and Landscape Architecture
University of Arizona

ABSTRACT

Increased pressure to conserve water may inadvertently exacerbate the growing urban heat islands in the cities of the arid Southwest. These water conservation efforts often fail to account for the increased building heat gain that results when vegetation is removed without consideration for other environmental effects.

In a recent study (McPherson et al, 1988), environmental measurements made in and around 1/4 scale model houses located in Tucson, Arizona, were used to investigate the effects of vegetation on residential building energy use in a desert environment (primarily for air conditioning). Landscape treatments surrounding the models were characterized by 1) turf and no shade, 2) rock mulch with shade from shrubs (no turf), and 3) rock mulch with neither turf nor shade (referred to as TURF, SHADE, and ROCK treatments, respectively).

Preliminary analysis of the data showed that the ROCK treatment required between 20 and 30% more energy for air conditioning than did SHADE or TURF treatments. This difference was explained by reduced insolation in the case of the SHADE treatment, and reductions in air temperature and incident longwave radiation in the case of the TURF. This energy savings was found to be enough to pay for irrigation water costs for low and moderate water use plantings, but not enough to cover the increased water demand by turf.

One of the surprising results of this study, given the large solar heat gains for the TURF compared to SHADE, was the similarity of energy savings for the TURF and SHADE treatments. In this paper, following a review of the aforementioned study, a more detailed analysis will be presented in an effort to better explain the relative importance of solar load, longwave radiation exchange and air-temperature reduction on building heat gains. In addition, further details of the various environmental measurements made during the experiment will be described.

NO PAPER SUBMITTED FOR PROCEEDINGS

Such information is essential if effective landscape design guidelines are to be established to minimize the use of both energy and water resources in the desert Southwest.

REFERENCE: McPherson, E.G., J.R. Simpson and M. Livingston (1988). Effects of three landscape treatments on residential energy and water use in Tucson, Arizona. Energy & Buildings (accepted for publication).

GLOBAL WARMING AND SPACE CONDITIONING USE IN CALIFORNIA: EFFECTS AND MITIGATION

Lester W. Baxter, Raul Herrera, Margaret Miller, and Glen Sharp
California Energy Commission

ABSTRACT

Part of the discussion on global warming focuses on the effects of climate change on electric utilities. A major consequence anticipated for electric utilities is a change in future space conditioning use. In this paper, we estimate changes in California's space conditioning by 2010 due to a temperature increase. We then examine the technical potential of urban tree planting and albedo modifications to mitigate the adverse consequences of global warming on cooling demand.

Two temperature change scenarios are adopted: a Low Temperature Scenario (which represents a 0.6° Centigrade increase over historical average annual temperatures) and a High Temperature Scenario (which represents a 1.9° Centigrade increase). Each temperature scenario is then used to produce an electricity demand projection using end-use energy demand models.

The effects of global warming on space conditioning use are moderate on a percentage basis, but because California's electricity system is so large, moderate percentage increases result in substantial changes in absolute demand. Net electricity use increases 758 GWh under the Low Temperature Scenario while peak demand increases by 221 MW to 967 MW. The High Temperature Scenario increases net electricity use by 4953 GWH and peak demand by 1648 MW to 1916 MW.

Using savings estimates developed at Lawrence Berkeley Laboratory, our results suggest that the potential savings from tree planting and albedo increases are large enough to offset the projected increase in statewide electricity use under the High Temperature Scenario. With the mitigation strategy, statewide electricity use increases only 350 GWh and peak demand is actually 1640 MW lower than the Base Case forecast.

KEYWORDS: energy conservation, energy forecast, utilities.

GLOBAL WARMING AND SPACE CONDITIONING USE IN CALIFORNIA: EFFECTS AND MITIGATION

Lester W. Baxter, Raul Herrera, Margaret Miller, and Glen Sharp[1]
California Energy Commission

INTRODUCTION

A warmer climate will change California's future electricity use patterns—the question is how much will current patterns change and what can be done to mitigate any adverse effects. In this paper we examine changes in California's electricity use in 2010 under two global warming scenarios. A mitigation strategy that combines two measures, urban tree planting and albedo[2] modifications, is explored to determine if increases in cooling demand due to global warming can be reduced.

A few key uses of electricity in California are quite sensitive to temperature changes. These key uses are the heating and cooling of buildings (i.e., space conditioning) and the pumping and transport of water for agricultural and urban uses. Uses such as refrigeration and water heating are not affected nearly as much by temperature changes and are not examined here.

We focus on the changes in the space conditioning of California's residential and commercial buildings that could result from an increase in mean global temperatures. Agricultural and urban water use is not considered in our analysis.[3] Thus, our results understate the overall effect of global warming on electricity use.

In a comprehensive assessment of the potential effects of global warming on electricity demand, Linder et al. (1988) describe two techniques used to estimate the sensitivity of demand to temperature: the statistical approach and the structural approach. The goal of both approaches is to estimate quantitative relationships between temperature and annual electricity use and peak demand, i.e., temperature sensitivity relationships.

The statistical approach estimates quantitative relationships between historical temperatures and aggregate electricity use. Using this approach, Linder et al. find that annual electricity use in New York and at a Southeastern utility will increase 0.12 percent and 3.58 percent, respectively, for each 1 ° Centigrade (C) increase in temperature.[4]

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[1] We thank Hashem Akbari for his technical advice, Michael Jaske for his review of an earlier draft, and Susan Mattox for her preparation of this manuscript.

[2] Albedo is a measure of the reflectivity of an object. The higher an object's albedo the more light reflected from its surface.

[3] An agricultural and urban water use study is underway and will be included in a subsequent analysis.

The temperature sensitivity of peak demand is estimated to be 2.14 percent in New York and 6.77 percent in the Southeast. Temperature sensitivities are higher in the Southeast due to the heavy use of air conditioners in that part of the country.

The structural approach entails a much greater level of disaggregation by measuring the underlying temperature sensitivities of end-use energy models. These underlying temperature and energy use relationships are derived from statistical techniques and detailed computer simulations of building thermal performance. The temperature sensitivities, in conjunction with data about appliance saturations and use rates, are used to develop detailed end-use energy forecasts. Forecasts of utility system loads are made by aggregating across end uses, building types, and customer sectors. Under this approach, Linder et al. estimate that annual electricity use in New York will increase 0.43 percent and peak demand will increase 4.09 percent for each 1 °C increase in average annual temperature. The structural approach yielded higher temperature sensitivities than the statistical approach in the one area, New York, where both were applied.

The interpretation of temperature sensitivities depends on the assumptions underlying each application. The statistical approach estimates a short-term response to temperature increase because the relationships estimated by Linder et al. are made over a short enough time period that air conditioning stocks are essentially fixed. In contrast, the structural approach accommodates changes in air conditioning stocks. For example, Linder et al. assume that in a warmer world New York residents will purchase more air conditioners than they would in the absence of climate change. Of course, the structural approach will also provide short-term temperature sensitivities if air conditioner purchases are assumed to follow historical trends.

Because we want to estimate the temperature sensitivity of the Commission's end-use models we use the structural approach. Temperature data from weather stations throughout California are used in conjunction with the Commission's end-use energy demand models to quantify the relationship between temperature and electricity use. A long-run electricity forecast recently published by Commission Staff serves as the Base Case to 2010. The increase in air conditioner saturations in the long-run forecast is consistent with recent historical patterns. California's new homes already have high air conditioner saturations compared to older homes; thus, the global warming scenarios assume no increase in air conditioner saturations over the Base Case.[5] As a result, the temperature sensitivities we estimate reflect California's response to global warming given today's appliance purchase behavior.

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[4] The temperature sensitivity of demand is expressed as the percent change in total demand for a 1 °C increase in average annual temperature.

[5] In California's largest planning areas, the majority of new homes have space cooling equipment. New home surveys by Pacific Gas and Electric (1986) and Southern California Edison (Garwacki 1986) indicate that the saturation of electric central air conditioners is two to three times greater in new homes (i.e., those built about 1980 or later) than old homes.

Tree planting and albedo modifications are two measures researchers suggest be used to mitigate the effects of urban heat islands. We explore their use in the urban environment to mitigate the increased cooling demand from global warming. Cooling savings estimates for these two measures are derived from building simulation work at Lawrence Berkeley Laboratory (LBL). We then apply these cooling estimates to the cooling demand projections from our worst case global warming scenario. The results show the technical potential of urban tree planting and albedo increases to reduce the adverse effects of global warming on space cooling requirements.

Our results suggest that by 2010 statewide annual electricity use will increase by 0.26 percent to 1.69 percent with a 0.6 ° C or 1.9 ° C increase in average annual temperature. These percentage changes translate into absolute increases of 758 gigawatthours (GWh)[6] to 4953 GWh by 2010 over the Base Case forecast. Statewide noncoincident peak demands[7] will increase by 0.34 percent to 1.51 percent with a 0.6 ° C increase in average annual temperature; the increase will be 2.57 percent to 2.99 percent for a 1.9 ° C average annual temperature rise. By 2010 statewide peak demands will increase 221 megawatts (MW)[8] to 967 MW with a low temperature increase. A high temperature increase will increase peak demands 1648 MW to 1916 MW by 2010. The peak demand results are quite sensitive to the assumed effect of global warming on daily temperature patterns.

We also find that energy savings from urban tree planting and albedo modifications nearly offset the increase in net annual electricity use from our worst case global warming scenario. With the combined effect of these two measures, statewide electricity use increases only 350 GWh. Savings from tree planting and albedo increases more than offset the increase in peak demand under the worst case scenario. Instead of increasing by 1916 MW, peak demand instead declines by 1637 MW.

ESTIMATING THE EFFECTS OF GLOBAL WARMING, URBAN TREE PLANTING, AND ALBEDO MODIFICATIONS ON SPACE CONDITIONING USE

In this study we project global warming's effect on space conditioning in California and estimate the effect of urban tree planting and albedo modifications on summer air conditioning use. A key result of our analysis is an estimate of the temperature sensitivity of space conditioning. We estimate temperature sensitivities with the structural approach using the Commission's detailed end-use forecasting models and tri-hourly temperature data from nine California weather stations. The Base Case forecast is made in the absence of climate change. We then adopt two temperature increase

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[6] A gigawatthour is one million kilowatthours, which has the heat content of 3.34 million cubic feet of natural gas or 586 barrels of oil.

[7] California's utilities all experience their peak demands during the summer, but rarely all peak at the same time. Thus, the statewide peak impacts are reported as the sum of each individual planning area's impact. See footnote 10 for the definition of a planning area.

[8] A megawatt is one thousand kilowatts, or enough energy to provide electricity for about 250 households.

scenarios and run the end-use models to produce annual electricity and peak demand projections for the year 2010. The energy projections estimate absolute changes in electricity use for each global warming scenario and temperature sensitivities of space conditioning demand.

We then examine the potential for urban tree planting and albedo modifications to ameliorate the effect of global warming on cooling demand. Tree planting and albedo increases are strategies originally proposed to mitigate the effects of summer heat islands on air conditioning demand. Estimates of cooling energy savings from these two measures are from work by Lawrence Berkeley Laboratory (LBL) researchers. We apply the LBL results to the energy demand projections from our most adverse global warming scenario.

DATA AND METHODS

Our analysis consists of five steps. First, we make a Base Case electricity projection under the assumption that current climatic conditions remain unchanged in the future.[9] Second, we adopt two global warming scenarios. Third, we modify temperature data used by the Commission for long-run energy forecasting to be consistent with the two global warming scenarios. Fourth, we use Commission Staff's end-use models to project annual electricity use and peak demand in 2010 with the modified temperature data. Finally, we apply modeling results from LBL to estimate the effect of urban tree planting and albedo modifications on projected air conditioning use under our most adverse global warming assumptions.

Base Case Electricity Forecasts

The Base Case electricity forecasts are derived from a recently published Commission staff forecast (CEC 1988). The final year of the published forecast is 2007; we extrapolate these forecasts to 2010 using long-run demand growth rates. Thirteen climate zones are combined into the five largest electricity planning areas in California.[10] As indicated earlier, our Base Case forecast assumes that the climate in California represented by the 1976 to 1987 period remains unchanged. The only assumption changed in the projection scenarios is that of future climate, i.e., average temperatures. All other major assumptions, such as population and economic growth, building and appliance stocks, and the operation of appliances, are unchanged from the Base Case.

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[9] The assumption of a stable climate is the assumption currently used in all CEC long-run energy forecasts.

[10] A planning area is a geographic region around each of the state's major investor-owned or municipal utilities that includes the utility's retail customers as well as resale customers and self-generators. The CEC divides California into eight planning areas, but the five largest planning areas account for over 95 percent of total statewide electricity use and demand. The five largest planning areas are Pacific Gas and Electric (PGandE), Sacramento Municipal Utility District (SMUD), Southern California Edison (SCE), Los Angeles Department of Water and Power (LADWP), and San Diego Gas and Electric (SDG&E).

Global Warming Scenarios. The two global warming scenarios adopted are based on scenarios developed at the World Climate Programme's workshop on climate change held at Bellagio, Italy in November 1987 (Jaeger 1988). The Low Temperature Scenario (LTS) and High Temperature Scenario (HTS) result in increases in average annual temperature of 0.6 ° C and 1.9 ° C, respectively, by 2010.[11] These temperature changes are made with respect to a reference climate. The reference climate used by the Commission is derived from the long-run average weather conditions observed over the 1976-1987 period. Thus, we make our Base Case electricity projections with the assumption that future climate will resemble California conditions from 1976 to 1987. Table I provides a summary of the climate assumptions used in this study.

Table I. Climate change scenarios increase in average temperature by 2010 (° C)

	Low Temperature Scenario	High Temperature Scenario
Winter	0.72	2.28
Spring	0.60	1.90
Summer	0.48	1.52
Fall	0.60	1.90
Average Annual	0.60	1.90

Note: The reference climate is the average conditions observed in California from 1976 to 1987.

A synthesis of General Circulation Model (GCM) results suggests that the amount of predicted warming differs by season (Jaeger 1988).[12] For mid-latitude areas, such as California, winters are predicted to exhibit somewhat greater warming than summers. Table I shows the seasonal temperature changes assumed in each scenario. Average winter temperature increase 20 percent more than the annual average and average summer temperatures increase 20 percent less than the annual average.

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[11] The Low and High Temperature Scenarios in this analysis are consistent with the Medium and High Scenarios described in the Bellagio Report.

[12] A General Circulation Model attempts to represent the complex three-dimensional behavior of the earth's atmosphere and, in some cases, the earth's oceans. The GCM results reviewed in Jaeger (1988) are selected to reflect the range of results obtained from recent advanced scientific studies. The two models reviewed are from Hansen et al. (1984) and Manabe and Stouffer (1980).

Weather Data and the Energy Demand Models

The climate change scenarios from Table I are incorporated differently into the annual energy models and the peak demand model. The annual energy models use average annual heating and cooling degree days to project annual space conditioning use. The climate change scenarios are incorporated into these models by increasing the daily maximum and minimum temperatures by the amounts shown in Table I.[13] In the HTS, for example, we increase daily maximum and minimum winter temperatures 2.28 ° C and then recalculate annual degree days using the new daily values.

The peak demand model projects loads for each hour of the peak day. Projected cooling demand is sensitive to hourly temperature patterns on the peak day. Thus, an assumption must be made about how global warming might alter hourly temperature patterns on the peak day. An examination of California's historical temperature records since 1901 by Karl et al. (1988) suggests that daily minimum temperatures have increased over time. If such a pattern persists, future temperature increases will be concentrated during that part of the day when temperatures are at their lowest, i.e., the late evening and early morning hours.

Unfortunately, GCM results provide little guidance in this area. Very preliminary work by Hansen et al. (1988) suggests that it may be appropriate to assume that global warming will not substantively alter the current day-to-day variability in weather. Thus, it may be appropriate to simply superimpose any future temperature increase on existing weather patterns.

For purposes of modeling peak demand we assume two different patterns of temperature change on the peak day: a nonuniform change and a nearly uniform change. The nonuniform temperature change places most of the temperature increase in the late evening and early morning hours, consistent with Karl's observations. In the HTS, for example, the nonuniform change yields a 2.22 ° C increase at 3 a.m. and a 0.56 ° C increase at 3 p.m. on the peak day. The uniform temperature change results in a nearly uniform increase in temperature throughout the day. For example, in the HTS, the uniform change results in a 1.67 ° C increase at 3 a.m. and a 1.11 ° C increase at 3 p.m. Thus, our analysis of peak demand contains two additional scenarios: the LTS and HTS each have a nonuniform and uniform scenario to represent these two possible changes in daily temperature patterns.[14]

The weather data we use are collected at nine weather stations throughout California. These data include daily high and low temperatures and tri-hourly temperature. We estimate annual heating and cooling degree days with daily highs and lows; tri-

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[13] Annual degree days are calculated using daily maximum and minimum temperatures.

[14] Hourly temperature changes for the peak event are assumed to follow a sine function with an amplitude of twelve hours. For the nonuniform and uniform temperature changes in both the LTS and HTS, the maximum change in temperature occurs at 3 a.m. and the minimum change occurs at 3 p.m.

hourly readings are used to approximate hourly temperature patterns. These data are collected over the 1976 to 1987 period and are used to represent the local climate conditions in thirteen California climate zones.

These weather data are used directly in the detailed end-use energy models developed at the Commission. The residential and commercial models generate forecasts by energy end use, building type, and climate zone. The space conditioning portion of the residential model includes four conditioning end uses, three building types, and thirteen climate zones (Hogstad et al. 1988). The space conditioning portion of the commercial model includes two conditioning end uses, eleven building types and thirteen climate zones (Nguyen et al. 1988).

The peak demand model operates at the same level of detail as the residential and commercial models (Baxter 1988). This model estimates daily air conditioning load shapes using the hourly temperature and humidity profiles on the peak day in conjunction with air conditioning response matrices. These matrices contain measured or estimated air conditioning loads for virtually any possible combination of temperature and hour of the day.

Estimating Effects of Mitigation Strategies

Urban heat islands, the increase of summer temperatures in urban areas over that experienced in the surrounding countryside, pose higher air conditioning requirements for city dwellers. Earlier studies suggest strategies to mitigate this negative effect (Landsberg 1978; Thurow 1983). Our intent is to explore two of these suggestions, urban tree planting and albedo modifications, as a strategy to help mitigate the increased cooling loads that result from global warming.

Work at LBL attempts to quantify the effects of techniques to reduce urban heat islands. The LBL researchers model tree planting and albedo modifications in terms of direct and indirect effects. The direct effects of tree planting and albedo changes on a building are to provide shade, increase the amount of reflected solar radiation, and to thus alter the energy balance of the building and cooling requirements of the occupants. Indirect effects ensue when trees are planted and albedos modified on a city-wide basis, thus changing the energy balance of the whole city.

Our analysis attempts to account for both direct and indirect effects. Following assumptions made by LBL researchers, the effects of planting three trees per air conditioned residence in California Standard Metropolitan Statistical Areas (SMSAs) were estimated. The albedo of individual residences is increased from 30 percent to 70 percent and that of the entire city from about 25 percent to 40 percent. By 2010 we assume these two measures achieve a 50 percent penetration of the total stock of air conditioned residences and small commercial buildings located in SMSAs.

We take savings estimates directly from work published by LBL researchers. Annual cooling savings from urban tree planting and albedo modifications are from Table 3 in Akbari et al. (1988). Peak savings are based on modeling buildings in Sacramento. For the effect of urban tree planting on peak cooling demand, the source of our estimates is Table 1 in Akbari et al. (1987). Peak savings due to albedo modifications are interpolated from values found in Table 4 of Taha et al. (1988).

The focus of the heat load simulations at LBL is on residential prototypes and the estimation of direct effects. Fewer simulations have been made for the indirect effects on residential buildings and for both direct and indirect effects on commercial buildings. We estimate ratios of commercial to residential annual cooling savings from Table 3 in Akbari et al. (1988) and then apply these ratios to residential peak savings derived from Akbari et al. (1987) and Taha et al. (1988) to produce direct and indirect savings for commercial buildings.

GLOBAL WARMING AND SPACE CONDITIONING BY 2010

Annual and Peak Impacts by 2010

Table II reports the planning area changes in annual electricity use from the Base Case due to global warming. The PG&E planning area exhibits the largest changes in heating, cooling, and net electricity use. On a statewide basis, the LTS results in a net increase of 758 GWh, which represents a 0.26 percent increase in total demand. The HTS yields a more dramatic net increase of nearly 4953 GWh or 1.69 percent. The net change in the HTS consists of a 7460 GWh increase in statewide cooling requirements and a 2507 GWh decrease in heating needs.

Because California utilities typically peak in the summer these increased cooling requirements lead to higher peak demands. Table III shows projected effects of global warming on planning area peak demand by 2010. For the LTS, the total increase in noncoincident peak demand ranges from 221 MW to 967 MW depending on how daily temperature patterns change. For the HTS, the total increase in noncoincident peak demand ranges from 1648 MW to 1916 MW. Under both scenarios, the largest planning areas, PG&E and SCE, exhibit the greatest absolute increase. The percentage change in demand is generally 2.0 percent or less in the LTS and 2.0 percent to 3.0 percent in the HTS.

Temperature Sensitivity of Space Conditioning Demand

Another key result of our study is an estimate of the temperature sensitivity of space conditioning. Tables IV and V provide these temperature sensitivity estimates for annual electricity use and peak demand, respectively.

Table IV reveals that in every planning area but SMUD the increase in cooling from global warming more than offsets the decrease in heating. The temperature

Table II: Estimated effects of global warming on annual electricity use by 2010

Gigawatthour (%) Change From Base Case

Planning Area	Base Case	Low Temperature Scenario			High Temperature Scenario		
		Heating[1]	Cooling[2]	Net	Heating[1]	Cooling[2]	Net
PG&E	118330	-315 (-0.27)	684 (0.58)	369 (0.31)	-958 (-0.81)	3399 (2.88)	2441 (2.07)
SMUD	12492	-96 (-0.77)	57 (0.46)	-39 (-0.31)	-298 (-2.39)	255 (2.04)	-43 (-0.35)
SCE	110717	-249 (-0.22)	549 (0.50)	300 (0.28)	-732 (-0.66)	2415 (2.18)	1683 (1.52)
LADWP	30520	-89 (-0.29)	152 (0.50)	63 (0.21)	-256 (-0.83)	662 (2.17)	406 (1.34)
SDG&E	21598	-97 (-0.45)	162 (0.75)	65 (0.30)	-263 (-1.22)	729 (3.38)	466 (2.16)
Total	293657	-846 (-0.29)	1604 (0.55)	758 (0.26)	-2507 (-0.85)	7460 (2.54)	4953 (1.69)

Notes:

1. The projected heating impacts are made under the assumption that average winter temperatures increase by 0.72 °C in the Low Temperature Scenario and 2.28 °C in the High Temperature Scenario.
2. The projected cooling impacts are made under the assumption that average summer temperatures increase by 0.48 °C in the Low Temperature Scenario and 1.52 °C in the High Temperature Scenario.

sensitivities of cooling in the LTS are all nearly 1.0 or greater and range from 0.96 percent to 1.56 percent. The HTS values are greater than the LTS estimates and range from 1.34 percent to 2.22 percent. These values imply that a 1 °C increase in average summer temperature will result in a 0.96 percent to 2.22 percent increase in total planning area electricity use due to the greater need for space cooling. In the LTS the temperature sensitivity of heating ranges from -0.31 to -1.07. For the HTS, the temperature sensitivities are very similar to the LTS, albeit slightly smaller.

Table III: Estimated effects of global warming on peak demand by 2010

Megawatt (%) Change from Base Case

Planning Area	Base Case	Low Temperature Scenario Nonuniform[1]	Low Temperature Scenario Uniform[2]	High Temperature Scenario Nonuniform[1]	High Temperature Scenario Uniform[2]
PG&E	24188	10 (0.04)	297 (1.23)	618 (2.56)	742 (3.07)
SMUD	3257	25 (0.77)	74 (2.27)	98 (3.01)	98 (3.01)
SCE	24896	132 (0.53)	479 (1.92)	655 (2.63)	729 (2.93)
LADWP	7455	20 (0.27)	65 (0.87)	134 (1.80)	160 (2.15)
SDG&E	4302	34 (0.79)	52 (1.21)	143 (3.32)	187 (4.35)
Total	64098	221 (0.34)	967 (1.51)	1648 (2.57)	1916 (2.99)

Notes:

1. The nonuniform case places most of the temperature increase in the early morning hours. In the Low Temperature Scenario, early morning temperatures increase by 0.56 ° C and mid-afternoon temperatures do not increase. In the High Temperature Scenario, early morning temperatures increase by 2.22 ° C and mid-afternoon temperatures increase by 0.56 ° C.
2. The uniform case assumes that the temperature increase on the peak day is nearly uniform. In the Low Temperature Scenario, both the early morning and mid-afternoon temperatures increase by 0.56 ° C. In the High Temperature Scenario, early morning temperatures increase by 1.67 ° C and mid-afternoon temperatures increase by 1.11 ° C.

The net result of a 1 ° C temperature increase for most planning areas is an increase in electricity use that ranges from about 0.50 percent or less in the LTS to over 1.10 percent in the HTS. Electricity use for cooling is much greater than for heating in most of California; this is particularly true for the commercial buildings sector, where electricity use for cooling is six to seven times that of heating (CEC 1988). In the residential sector, cooling electricity use is also greater than for heating, though the dominance of cooling is not nearly as striking as in commercial buildings (CEC 1988).

SMUD is the only planning area that shows a net decrease in total planning area electricity use. We note that SMUD has the largest electric heating use relative to cooling use of any planning area (CEC 1988). This characteristic in conjunction with the assumption that the increase in average winter temperature is greater than the increase in average summer temperature accounts for the net decrease in SMUD's annual electricity use.

Table V provides temperature sensitivities of peak demand for the five planning areas. The temperature sensitivities range from nearly zero to 4.11 percent. In the HTS, the temperature sensitivities range from 1.19 percent to 2.80 percent. In both scenarios, the temperature sensitivities are higher if the temperature increase occurs more uniformly throughout the day. The nonuniform case causes air conditioning demands to increase considerably at night. The proportionate increase in load is much lower during the afternoon, the time when California utilities typically experience system peaks.

Table IV: Temperature sensitivity of annual electricity use

Percent Change in Total Demand per
1 ° C Temperature Increase

Planning Area	Low Temperature Scenario			High Temperature Scenario		
	Heating	Cooling	Net[1]	Heating	Cooling	Net[1]
PG&E	-.38	1.21	.52	-.36	1.89	1.09
SMUD	-1.07	.96	-.52	-1.05	1.34	-.18
SCE	-.31	1.04	.47	-.29	1.43	.80
LADWP	-.40	1.04	.35	-.36	1.43	.70
SDG&E	-.62	1.56	.50	-.54	2.22	1.14

Notes:

1. The net temperature sensitivity does not equal the sum of the sensitivities for heating and cooling because the winter temperature increase is 1.2 times the average annual increase and the summer temperature increase is 0.8 times the average annual temperature increase.

The range in sensitivity between the nonuniform and uniform cases tends to be greater in the LTS. The peak demand model provides more stable estimates of temperature sensitivity when the average temperature increase is greater than 0.6 ° C. The model is less sensitive to temperature changes under 0.6 ° C because the temperature data used to simulate air conditioning load shapes are in 1 ° Fahrenheit (0.56 ° C) increments. A temperature increase smaller than 1 ° F does not change the pattern of the

Table V: Temperature sensitivity of peak demand

Percent Change in Total Demand per
1 ° C Temperature Increase

Planning Area	Low Temperature Scenario		High Temperature Scenario	
	Nonuniform[1]	Uniform[2]	Nonuniform[1]	Uniform[2]
PG&E	0.09	2.21	1.70	1.97
SMUD	1.72	4.11	2.01	1.94
SCE	1.20	3.46	1.75	1.88
LADWP	0.60	1.56	1.19	1.38
SDG&E	1.80	2.17	2.21	2.80

Notes:

1. The nonuniform case places most of the temperature increase on the peak day in the early morning hours. The nonuniform case attempts to reflect the pattern of change observed in California's historical temperature records by Karl et al. (1988).
2. The uniform case assumes that the temperature increase on the peak day occurs nearly uniformly across the hours of the day. The uniform case attempts to incorporate the preliminary GCM results of Hansen et al. (1988).

simulated air conditioning load shape. Thus, the sensitivity ranges produced from the HTS are more stable estimates of the underlying temperature sensitivity of the model. Nevertheless, considering sensitivities from both the LTS and HTS suggests that total planning area peak demand will increase by about 1.0 percent to 3.0 percent for each 1 ° C increase in average temperature due to the increase in air conditioning demand.

EFFECTS OF URBAN TREE PLANTING AND ALBEDO MODIFICATIONS BY 2010

As discussed earlier, planting trees around residential and small commercial buildings and increasing their albedo will alter building energy balances. Both measures will reduce cooling requirements. The effects of individual measures on individual buildings are the direct effects. The collective effects of city-wide measures alter the energy balances of entire cities. These are the indirect effects of tree planting and albedo increases.

Tables VI and VII provide estimates of residential and commercial space cooling savings from urban tree planting and albedo increases. Each table shows the percent savings estimates taken from LBL work and our estimates of absolute cooling savings. We estimate absolute savings by applying the LBL percentage estimates to the absolute levels of cooling required under the HTS.

Table VI contains annual cooling savings estimates. Total statewide savings by 2010 are projected to be 4603 GWh. About 2600 GWh of savings are from residential buildings. The remaining 2000 GWh savings come from commercial buildings, with the bulk of these savings from small commercial buildings.

Projected peak cooling savings are found in Table VII. Statewide savings by 2010 from tree planting and albedo increases are estimated to be 3553 MW. Peak savings from residential buildings account for nearly 2700 MW of the total. Commercial buildings account for the remaining 850 MW of peak cooling savings. The much greater percentage savings for residential buildings is consistent with the greater thermal responsiveness of houses versus commercial structures. Most residences have less thermal mass than commercial buildings. In addition, houses have much more surface area exposed to the environment relative to interior volume than do most commercial buildings. As a result, residential buildings and their occupants will have a faster and greater response to changes in building energy balance.

In Tables VIII and IX we express the projected effects of urban tree planting and albedo modifications in a different way. As in Table VI and VII, Tables VIII and IX are based on our worst case warming scenario. This worst case scenario, the HTS with a nearly uniform temperature increase on the peak day, assumes that by 2010 average annual temperature increases 1.9 ° C. The results in Tables VIII and IX assume, however, that the mitigation strategy is applied and achieves a 50 percent penetration by 2010. Thus, Tables VIII and IX reflect projected changes in electricity use from the Base Case under HTS assumptions of global warming with savings from tree planting and albedo increases.[15]

Table VIII reports changes in annual electricity use from the Base Case due to global warming with savings from tree planting and albedo increases. The increase in annual cooling use is only 2857 GWh versus the 7460 GWh increase seen in Table II. The net increase in statewide electricity use is now 350 GWh under the HTS instead of 4953 GWh reported in Table II. The difference between Table II and VIII, of course, is due to the projected effects of urban tree planting and albedo modifications.

The HTS effects on peak demand, with the mitigation strategy, are shown in Table IX. Here the effects are even more dramatic. Even with an increase of 1.9 ° C in average annual temperature, peak demand is actually lower than Base Case demand for all planning areas. The statewide reduction totals 1637 MW. Table III reports that the HTS with a nearly uniform temperature change will increase statewide peak demands by 1916 MW over the Base Case forecast. Yet even with HTS global warming, Table IX

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[15] In Table 8 and 9, space heating requirements are assumed to be unaffected by tree planting and albedo increases. In practice, these modifications should increase heating requirements No published estimates are available for the effect of tree planting on space heating. Preliminary estimates provided by Taha et al. (1988) for Sacramento suggest that the effect of albedo increases on space heating is small relative to cooling effects. Nevertheless, the net effects reported in Tables 8 and 9 are probably underestimated.

Table VI: Estimated annual cooling savings from tree planting and albedo increases by 2010

High Temperature Scenario

Annual Cooling Savings
Gigawatthours

Planning Area	Residential		Commercial				Total
			Small		Large		
	Direct	Indirect	Direct	Indirect	Direct	Indirect	
Percent Savings[1]	10	20	4	12	0	5	
PG&E	308	615	155	464	0	272	1814
SMUD	44	88	17	50	0	21	220
SCE	379	758	120	361	0	175	1793
LADWP	60	119	32	95	0	81	387
SDG&E	77	154	30	89	0	39	389
Total	868	1734	354	1059	0	588	4603

Notes:

1. Percent annual cooling savings from urban tree planting and albedo modifications are from Table 3 in Akbari et al. (1988).

Table VII: Estimated peak cooling savings from tree planting and albedo increases by 2010

High Temperature Scenario
Uniform Temperature Change

Peak Cooling Savings
Megawatts

Planning Area	Residential		Commerical				Total
			Small		Large		
	Direct	Indirect	Direct	Indirect	Direct	Indirect	
Percent Savings	9.5[1]	7.7[2]	3.8[3]	10.6[3]	0[3]	4.4[3]	
PG&E	303	565	79	221	0	272	1249
SMUD	72	132	11	33	0	21	259
SCE	422	788	58	162	0	175	1495
LADWP	67	124	17	48	0	81	285
SDG&E	78	146	8	25	0	39	265
Total	942	1755	174	489	0	588	3553

Notes to Table VII:

1. Percent peak cooling savings are based on simulations for four July days in Sacramento. Table 1 in Akbari et al. (1987) indicates that planting three trees around an urban house will yield a direct reduction in peak cooling demand of 10 percent. Similarly, interpolating the values from Table 4 in Taha et al. (1988) suggests that increasing the albedo of an urban house from 30 percent to 70 percent will provide a 9.2 percent direct reduction in peak cooling demand. The direct effects of both tree planting and albedo modification per house are thus 0.107 + (1 - 0.107)*(0.092) or 18.9 percent. This number is divided by two because only 50 percent of air conditioned houses participate in the mitigation strategy.
2. Percent peak cooling savings from the indirect effects of tree planting and albedo modifications equal total savings minus direct savings. Total savings are taken from the sources cited above for tree planting and albedo increases, respectively. Akbari et al. (1987) estimate that planting three trees around an urban house will result in a 34.4 percent total reduction in peak cooling demand, considering both direct and indirect effects. Interpolation of estimates in Taha et al. (1988) suggests that an increase in albedo from 30 percent to 70 percent will provide a 30.6 percent total reduction in peak cooling demand. The total direct and indirect effects of tree planting and albedo increases per house are thus 0.344 + (1 - 0.344)*(0.306) or 54.5 percent. Only half the houses take these measures so the final estimate of total savings is 27.2 percent. The indirect savings are thus 27.2 percent minus 9.5 percent, or 17.7 percent.
3. Percent direct and indirect peak cooling savings for commercial buildings are assumed to exhibit the same relationship to residential peak savings as found in the annual savings estimates from Table VI. Thus, direct peak savings for small commercial buildings equals (4/10)*(9.5 percent) or 3.8 percent. Similarly, indirect peak savings are (12/20)*(17.7 percent) or 10.6 percent.

Table VIII: Estimated effects of global warming on annual electricity use by 2010 with mitigation strategy

Gigawatthour (%) Change from Base Case

Planning Area	Base Case	High Temperature Scenario Heating[1]	Cooling[2]	Net
PG&E	118330	-958 (1.81)	1,585 (1.34)	627 (0.53)
SMUD	12492	-298 (-2.39)	35 (0.28)	-263 (-2.11)
SCE	110717	-732 (-0.66)	622 (0.56)	-110 (-0.10)
LADWP	30520	-256 (-0.83)	275 (0.90)	19 (0.07)
SDG&E	21598	-263 (-1.22)	340 (1.53)	77 (0.36)
Total	293657	-2507 (-0.85)	2857 (0.97)	350 (0.12)

Notes:

1. The projected heating impacts are made under the assumption that average winter temperatures increase by 2.28 ° C and that urban tree planting and albedo increases have a negligible effect on heating requirements.
2. The projected cooling impacts are made under the assumption that average summer temperatures increase by 1.52 ° C.

reveals that peak demands are reduced by 1637 MW from the Base Case by planting more urban trees and increasing urban albedos.

Three important notes conclude this discussion. First, our savings estimates must be regarded as preliminary. The work on which these estimates are based is derived primarily from simulations of residential buildings. Much more work remains to be done on commercial buildings. In addition, field experiments must be conducted on both residential and commercial buildings before the technical potential of tree planting and albedo changes to reduce cooling requirements is known conclusively.

Second, California's climate may be especially suited for these measures. Much of California is characterized by mild winters; hence, the positive benefit of heat islands in

Table IX: Estimated effects of global warming on peak demand by 2010 with mitigation strategy

Planning Area	Base Case	Megawatt (%) Change From Base Case High Temperature Scenario Uniform[1]
PG&E	24188	-507 (-2.10)
SMUD	3257	-161 (-4.94)
SCE	24896	-766 (-3.08)
LADWP	7455	-125 (-1.68)
SDG&E	4302	-78 (-1.81)
Total	64098	-1637 (-2.55)

Notes

1. The uniform case assumes that the temperature increase on the peak day is nearly uniform. In the High Temperature Scenario, early morning temperatures increase by 1.67 ° C and mid-afternoon temperatures increase by 1.11 ° C.

reducing high winter heating loads are not realized. Reducing this benefit is unlikely to substantially alter heating requirements. California's summers are typified by warm days and cool nights. As a result, latent heat build-up contributes less to air conditioning loads because much of the day's heat dissipates in the cool evenings. Regions that do not share these climatic characteristics may not realize our estimate of California's net benefit.

Third, we do not consider questions about cost effectiveness. Preliminary cost effectiveness results by Akbari et al. (1988) seem promising. The Akbari study uses similar assumptions on the national level about a mitigation strategy that combines urban tree planting and albedo increase.

SUMMARY

The overall effects of global warming on the heating and cooling of buildings appears moderate on a percentage basis, but because California's electricity system is so large, moderate percentage increases result in substantial changes in absolute demand. California's greater need for cooling relative to heating means that global warming increases annual electricity use. The estimates presented here indicate a net increase of 758 GWh to 4953 GWh for a 0.6 °C and 1.9 °C temperature increase, respectively. Further, because California's electric utilities are summer peaking, in a warmer world these increases in cooling demand lead to higher peak demand.

The effect of warming on peak demand depends on how hourly temperature patterns might change. Under a 0.6 °C average annual warming, a nonuniform temperature change increases peak demand by 221 MW, but a nearly uniform temperature change increases demand by 967 MW. A 1.9 °C average annual warming leads to a 1648 MW increase in demand with a nonuniform temperature change and a 1916 MW increase with a nearly uniform change.

Preliminary work at LBL suggests that the technical potential for cooling savings from urban tree planting and albedo modifications may be large. The potential savings are large enough to offset the projected increase in total planning area electricity use under our worst case global warming scenario. With the mitigation strategies, statewide electricity use increases only 350 GWh and peak demand actually declines by 1637 MW from the Base Case forecast.

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UNIT COSTS OF CARBON SAVINGS FROM URBAN TREES, RURAL TREES, AND ELECTRICITY CONSERVATION: A UTILITY COST PERSPECTIVE

Florentin Krause and Jonathan Koomey
Lawrence Berkeley Laboratory

ABSTRACT

This paper compares the cost of sequestered and conserved carbon from rural tree planting, urban tree planting, and efficiency improvements, from the perspective of an electric utility and its ratepayers. Of these three options, energy efficiency appears to be the most widely applicable and attractive carbon mitigation measure from the utility's perspective. The majority of the demand-side resources we consider would allow carbon savings at negative net cost, while rural trees almost always have positive net cost to the utility. Urban trees can in many cases be comparable in cost to conservation, but are subject to a larger number of constraints (particularly in siting). For example, conservation can work in almost every type of building, while urban trees are most likely to be successful for some fraction of residential and small commercial buildings. Rural tree planting, both in the US and abroad, is an important tool in combating global warming; however from the utility's perspective, this option appears to be less cost-effective than conservation or urban trees under a wide variety of different assumptions.

Keywords: carbon, carbon dioxide, energy conservation, cost/benefit analysis, energy efficiency, global warming, greenhouse effect, urban trees.

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INTRODUCTION

Global warming has become of increasing concern both in the scientific community (Hansen 1988, Schneider 1989) and in the popular press (Begley et al. 1988, Lemonick 1989). Because the utility industry is responsible for a substantial fraction of carbon dioxide emissions in the U.S., this sector is likely to be an important focus of policies to mitigate these emissions. Recently, a variety of options, including energy efficiency and tree planting by utilities have been proposed to mitigate urban heat islands and to offset power plant carbon dioxide releases that contribute to global warming (Akbari et al. 1988, Dudek 1988).

This paper compares the costs of investing in energy efficiency to those of planting urban and rural trees from the utility perspective.[1] The main purpose of the analysis is to establish a consistent methodology for comparing the costs of carbon savings from these options, and to carry through the comparison using plausible assumptions. The methodology developed is more important than the actual numbers used, although 'we feel some broad conclusions can be drawn from the crude estimates of costs we present herein

The second section (after this introduction) sets forth the methodology for calculating per unit costs of reducing carbon emissions through conservation and the costs of sequestering carbon through tree planting. The third section explores the factors affecting the unit cost of saved and sequestered carbon. The fourth section presents the results of our survey of data sources and our

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[1] The comparison of these options from the societal perspective is more difficult, as described below.

subsequent analysis. The fifth section explores the size of the surcharge on U.S. electricity production needed to finance tree planting to offset the carbon emissions from that production. Finally, the sixth section compares the potential impacts on electricity rates from planting trees or implementing conservation.

METHODOLOGY

Societal Versus Utility Least-Cost Perspectives

In any comparative assessment of utility-related investments, it is important to specify the cost-benefit perspective that is being used. Over the last few years, standardized definitions of these perspectives have become available in the context of new regulatory and utility planning approaches known collectively as Least-Cost Utility Planning (LCUP) (Krause et al. 1988). One defining feature of LCUP is the integrated treatment in utility resource plans of conventional supply resources and previously neglected demand-side resources (load management and conservation).

Clarifying cost perspectives is always important, but it is especially crucial when costs and benefits of investments accrue to different members of society. Conservation and trees offer multiple, non-comparable benefits to utilities and to society at large. Conservation reduces energy consumption, avoids peak power, reduces carbon dioxide, NO_X, SO_X, and other emissions, creates more jobs per kWh than supply projects, and keeps more money in the state (or country) than supply projects. Urban trees reduce energy consumption, avoid peak power, reduce carbon dioxide, NOx, SO_X, and other emissions, supply yard shade, enhance property values, prevent erosion, control storm drain runoff, enhance groundwater recharge, provide wildlife habitat, supply wood and leaves, and sequester carbon (from tree growth). Rural trees reduce NO_X, SO_X, and other pollutants, create recreational opportunities, prevent erosion, protect watersheds, supply wood, leaves, fruits, animal habitat, and animal fodder, and sequester carbon (from tree growth).

From a societal perspective, all these and other benefits should be accounted for in determining the least-cost approach to reducing carbon emissions. From the perspective of a utility facing regulatory demands to reduce net carbon emissions, only a small subset of these benefits is relevant. In the case of rural trees, it is only the amount of sequestered carbon that is of interest.[2] The other benefits of rural trees accrue to the rest of society and are irrelevant to the utility's choice. However, urban shade trees planted in the utility's service territory save energy and peak demand, and both sequester carbon and reduce carbon emissions. Conservation saves energy and peak demand, and reduces carbon emissions.

The question of which investment *society* should choose is, of course, more complicated. For the purposes of this analysis, we assume that conservation and urban and rural tree planting offer societal benefits of comparable magnitude. We restrict our discussion to the utility's choice to plant trees or invest in efficiency.

Cost definitions

For energy efficiency investments, we use the concept of cost of conserved energy or CCE (Meier et al. 1983). Calculating CCE involves annualizing the capital cost of a conservation measure, and dividing by the number of kWh saved each year. This calculation yields a cost per kWh that is analogous and comparable to the delivered per unit cost of electricity from a power plant. However, this approach ignores the non-energy related benefits of conservation.

A modification of this concept can be applied to the carbon savings from efficiency investments. Previous analyses have calculated a cost of conserved carbon (CCC) by annualizing the total cost of the conservation investment, and dividing by the amount of carbon saved annually (Akbari et al. 1988). This approach is equivalent to a single-attribute analysis that neglects the non-carbon related benefits of conservation. In the analysis below, we present a two-attribute method for calculating the cost of conserved and sequestered carbon that integrates the energy and carbon benefits.

Calculating the Cost of Conserved and Sequestered Carbon

We use a simple two-attribute model to represent the utility's least-cost choices: utility avoided cost savings, and avoided carbon

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[2] Some utilities may choose to plant trees on watershed lands that they own or control in connection with hydroelectric facilities. In this case, the benefits of such tree planting are relevant and can in some cases be quantified.

releases to the atmosphere. We first quantify the *value* of the energy and peak demand savings from conservation and urban trees, and subtract this value from the *cost* of installing efficiency or planting urban trees. This procedure yields a *net* cost of conserved energy, which can then be converted to a cost of conserved carbon. This cost of conserved carbon can then be directly compared to planting rural trees *from the utility's perspective.*[3]

The cost of conserved energy (CCE) is defined as the annualized cost[4] of the conservation investment divided by the annual energy savings. More formally, this definition is

$$\text{CCE (\$/kWh)} = \frac{\text{(Capital Cost)(CRF)}}{\text{(Energy Savings/yr)}}$$

where CRF is the capital recovery factor used to annualize the capital cost of the conservation measure.[5] A net CCE can be calculated using some estimate of benefits (i.e., utility costs avoided by the conservation measure). We have chosen levelized avoided costs of $0.05/kWh, which includes avoided variable costs and avoided capital costs.[6]

$$\text{Net Cost} = \text{Costs} - \text{Benefits}$$

$$\text{Net CCE (\$/kWh)} = \text{CCE} - \text{Avoided Costs} = \text{CCE} - \$0.05\text{/kWh}$$

The net CCE is negative if conservation is economically attractive.

The cost of conserved carbon to the utility is defined as

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[3] We assume in our analysis that the regulators have instituted some mechanism to remove the utility's short-run disincentive to conserve (due to revenue losses), such as California's Electricity Revenue Adjustment Mechanism (Krause et al. 1988)

[4] This cost may just be the capital cost, as shown here, or include program costs or the present value of additional operation and maintenance costs due to the conservation measure.

[5] The CRF is equal to $(r(1+r)^n)/((1+r)^n-1)$ where r is the discount rate and n is the lifetime of the investment.

[6] This estimate is meant to be plausible and conservative, not precise. We sidestep the task of calculating appropriate avoided costs, since the intricacies of these calculations are strongly dependent on the characteristics of conservation measures and the particular utility system under consideration (Krause et al. 1988, NERA 1977).

$$\text{CCC (\$/t-C)} = \frac{(\text{Net CCE})(1{,}000{,}000)}{\text{CB}}$$

where CB is the carbon burden (i.e., the amount of carbon saved, in g-C/kWh) and 1,000,000 is the number of grams per metric ton Unlike conventional approaches, this equation explicitly accounts for the value of energy and peak demand savings from conservation when calculating CCC.

For a rural tree, the cost of sequestered carbon can be defined as

$$\text{CSC (\$/t-C)} = \frac{(\text{Capital Cost})(\text{CRF})}{(\text{C sequestered/yr})}$$

For an urban tree, the calculation is a little more complicated since carbon is both saved and sequestered. The cost of sequestered/saved carbon (CSSC) for urban trees can be defined as

$$\text{CSSC (\$/t-C)} = \frac{(\text{Net CCE})(1{,}000{,}000)}{(\frac{\text{SR}}{\text{ES}} + \text{CB})}$$

where SR is the sequestration rate of the tree (g/tree/year), and ES is the annual energy savings per tree (kWh/tree/year).[7]

Carbon Saving Benefits of Energy Efficiency

The carbon savings can be computed from energy savings using knowledge of which utility plants are likely to be curtailed in response to a change in load (i.e., the marginal units), the carbon

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[7] This formulation of CSSC for urban trees leads to an inversion of scale when the net CCE is negative, since adding the sequestration rate to the carbon burden leads to a less negative CSSC. This subtlety makes *exact* comparison between urban trees and conservation measures difficult within this framework whenever the net costs of conserved energy are negative. We ignore it because all negative cost investments are extremely attractive, and other benefits are liable to be important when considering the societal perspective. In addition, the sequestration rate is typically only 10% of the energy-related carbon savings per tree (Akbari et al. 1988), so the error introduced is small. The methodology is correct for positive net CCEs, when accurate comparisons are most important.

burdens of each fuel, and the transmission and distribution losses. Typical direct carbon burdens for each fuel (based on lower heating values) are shown in Table I, along with the carbon burden associated with consumption of electricity generated by those fuels, calculated using a heat rate of 10,000 Btus/kWh[8] and a transmission and distribution (T&D) system loss factor of 6%. The direct carbon burden for each fuel is higher than that released in the burning of the fuel because it includes the carbon released from energy consumption when extracting and processing the fuel (Unnasch et al. 1989).

The marginal power plants are those that will curtail their output if conservation or urban trees reduce load below the expected level. The fraction of time that oil, gas, and coal-fired plants are on the margin is a crude measure of what fraction of the electricity savings is generated by each fuel,[9] and can be used to calculate a weighted average carbon burden for energy savings. These "marginal fractions" more accurately characterize the carbon *savings* per kWh than carbon burdens based on the fraction of *total* generation from each fuel.

We calculated the appropriate marginal fractions for the U.S using the methodology described in US DOE (1988c).[10] Table I shows these fractions, the resulting carbon burden for energy savings, and the carbon burden calculated using total generation and the 1987 fuel mix. The carbon burden for energy savings is higher than that based on the 1987 fuel mix because the marginal fuels are oil, natural gas, and coal, while 27.4% of net generation in 1987 is from carbon-free hydroelectric and nuclear power (US DOE 1988a), which are rarely used on the margin in most of the U.S.

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[8] Conventional oil and gas power plants are typically less efficient than baseload coal plants, which may somewhat offset the lower direct carbon burden of these fuels. We ignore this effect here.

[9] This approach assumes that the energy savings is spread evenly over the year.

[10] Like all simplifications of complicated phenomena, these estimates of marginal fractions submerge important details. They are useful for order of magnitude estimates, but calculations for a particular utility should use estimates of marginal fuels and avoided costs appropriate in that context. These estimates can be derived from typical utility system simulation models (Marnay et al. 1989).

Fuel prices to utilities in 1987 (US DOE 1988b) and the assumptions in Table I for marginal fractions, heat rates, and T&D losses, imply short run variable costs of $0.021/kWh. For comparison, the operating costs of existing power plants in Michigan is $0.03-$0.04/kwh (Krause et al. 1987). Combined with our assumption of $0.05/kWh total avoided costs, these assumptions imply an avoided capital cost of $0.029/kWh.

Carbon Sequestering Benefits of Tree Planting

In tree planting, carbon sequestering can be discussed at the level of the tree and at the level of a land area that is being reforested or afforested.[11] We discuss the dynamics from the perspective of reforestation of an area. Here, one must distinguish between the sequestering capacity of the forest growth (which is equivalent to the electricity production capacity of a power plant or capacity savings of an efficiency investment) and the cumulative carbon sequestered by the trees.

The sequestering capacity is a function of the annual biomass yield of the forest. For a natural forest, net sequestering occurs only during the growth period of the forest, i.e., during the movement of the forest area toward a steady state (when carbon released by decay is equal to carbon uptake by photosynthesis). The sequestering capacity varies over time, beginning at low values at the seedling stage, to the peak period of early growth, followed by a declining carbon intake as the forest matures.

The cumulative carbon sequestered by a reforested area is the average carbon held in the forest area over the cycle of growth and harvesting. If the reforested area is left in its natural state, the long-term, steady-state carbon storage is equal to the integral of carbon sequestered during all stages of growth and maturation. If the forest is periodically clear-cut and replanted or otherwise managed, the average carbon storage per hectare will be lower (see Figure 1), since

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[11] In the context of reducing net fossil carbon releases, we refer to reforestation as an activity that improves the stocking of previously forested land over current, steady-state, non-forested conditions. It does not refer to the replanting of forests after harvest to maintain current yields. Afforestation means planting trees on non-forest land.

the carbon fixed in the natural forest now cycles back and forth between the terrestrial biosphere and the atmosphere. But it is still higher than on unforested land. As a rule, managed temperate forests contain about 80 percent as much carbon in their vegetation as natural forests (Houghton 1987). In a short-rotation fuelwood plantation, the stored carbon fraction would be significantly lower. The speed at which wood products are consumed or burned,[12] and the manner of harvest, shape the balance between sequestering and carbon releases over time.

The net sequestering rate of a reforested area is simply the average rate of carbon intake between the point of planting and the point at which the first planting reaches the carbon storage level that will be maintained over the planting and harvesting cycle in the long-term. The net sequestering rate is a function of the type of forest management and species selection. A managed forest or plantation maximizes growth rates at the expense of cumulative carbon storage. If a reforested area is left unmanaged, it will grow more slowly, but will eventually achieve a higher carbon storage per unit area, due to the efficiency of plant diversity and biological succession in utilizing sunlight and soil resources. Since forests provide economically valuable products, the maximum feasible carbon storage will usually not be reached in reforestation or afforestation schemes.

Simplified Treatment of Average Cumulative Storage and Yields

Data on forest growth are usually given in terms of harvestable annual biomass yields in tonnes/ha or m^3/ha. These values typically refer to the point in forest growth where harvesting yields the maximum economic benefit, i.e. before forest growth slows down due to maturation. For temperate forests, this point may be 30-50 years after replanting.

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[12] Some of these products include fuel that may be burned to displace fossil fuels or construction products that may be used in buildings that will last for decades. We have ignored the potential carbon savings or carbon storage from these uses of wood because of lack of data on how much harvested wood is used for various purposes. More research is needed to collect these data and include them when estimating net carbon sequestration rates from tree planting.

To calculate the average cumulative storage benefit of tree planting, one must distinguish between afforestation for commercial purposes and afforestation for the purpose of creating natural forests. We concentrate on the former case. To illustrate the overall method, we discuss the case of planting temperate forests. For these, we assume that trees are harvested after 40 years. We further assume that growth is reasonably linear, and that the cumulative carbon storage achieved in the first growth cycle is forty times the rate of carbon fixing based on annual forest biomass yield. Over several growth cycles, the average cumulative carbon storage is assumed to be half this value as shown in Figure 1. During the first growth cycle, this long-term average level is reached after twenty years.

This assumption allows a simplified treatment of reforestation in which the cumulative carbon sequestration benefit is equal to the annual benefit multiplied by half the harvest rotation period, or, in our example, twenty years. The structure of the tree planting benefit then becomes the same as that from efficiency improvements, which save equal amounts of carbon each year over the life of the investment.

FACTORS AFFECTING THE UNIT COST OF SAVED CARBON

Many factors influence the cost of efficiency improvements, including the capital and installation costs, site suitability, the intensity of utilization of a particular device (hours per year, load factors), possible additional maintenance costs (not only to operate, but to ensure persistence of savings), the program overhead costs of utility or state conservation programs (administration, marketing, enforcement, etc.), the measure lifetimes, and the choice of discount rate. Here, too, local factors such as climate are important, as are non-carbon benefits (e.g. reduction in life cycle costs, savings in air pollution other than carbon dioxide, etc.).

A similar catalog of factors exists for sequestered carbon from tree planting. The main ones are seedling price, planting cost, maintenance cost (protection from animals, cars, etc. watering and fertilization), survival rate, land quality and climate (determining range of usable species and growth rates), the type of species planted, location (urban versus rural), the harvest rotation (average cumulative carbon storage over several harvest cycles), type of organization doing the reforestation (labor costs and overhead), land cost (rent, incentive requirements to compensate for lost opportunity costs), economic benefits other than carbon savings (soil conservation, energy conservation, etc.), and the discount rate used in calculating unit costs.

For urban trees, the factors affecting the cost of carbon sequestration are the same as for rural trees, but include other factors affecting energy savings, such as site suitability, air conditioner efficiency, leaf disposal costs, and water costs.

This list of factors underscores the point that an adequate determination of per unit costs requires detailed specifications and the investigations of specific circumstances. Only where a sufficient number of detailed analyses are available and typical or average applications can be reasonably well defined can more aggregate comparisons be made.

While the cost of conserved energy (and therefore, carbon) in the US electricity sector has been reasonably well established (Geller 1986, Hunn et al. 1986, Krause et al. 1987, Meier et al. 1983, SERI 1981), the cost of sequestered carbon from tree planting has been less well researched. This is due, in part, to the different focus of commercial forestry research and climate stabilization research. Also, from a climatic perspective, tree planting anywhere in the world is relevant, including in Third World countries with widely varying climatic and economic conditions.

In view of these limitations, we restrict ourselves to a preliminary analysis that establishes order of magnitude estimates for the cost of avoided carbon from tree planting, without attempting to systematize and bring into full consistency the various data. We have constructed carbon sequestration costs per ton using estimates from various sources on carbon uptake rates per tree, survival rates, costs per tree, and planting density. Instead of deriving one estimate, we have combined reasonable estimates of these parameters in a way that yields upper and lower bounds for tree planting costs. There are large uncertainties in any such estimates.

Data sources

Data on the cost of conserved energy were taken from analyses covering a large number of end-uses for entire utility service territories in Michigan (Krause et al. 1987) and in Texas (Hunn et al. 1986). We summarized these data by cost of conserved energy: we grouped them as low (from $0.0 to $0.03/kWh saved), medium (from $0.03-0.05/kWh saved), and high (from $0.05-0.085/kWh saved). To make the residential estimates from the Michigan Electricity Options Study (MEOS) and the commercial estimates from the Texas study comparable, we express the quantity of energy savings 20 years from the forecast's base year as a fraction of *total utility system* electricity sales in that year. We also express carbon savings as a fraction of total utility system carbon emissions in the same year (using the U.S. average and marginal carbon burdens for simplicity). We adjusted the costs in the Texas study, which assumed a 10% real discount rate, to reflect a 7% real discount rate. Table II summarizes the data on the cost of conservation, and Figures 2 and 3 show the aggregated supply curves of conserved energy and conserved carbon. The figures summarize the CCEs, net CCEs, and costs of conserved or sequestered carbon.

Table III shows a plausible range of estimates for the carbon yields and costs of rural tree planting and reforestation. The carbon yields are from a wide variety of sources in the literature (Dudek 1988, Dyson et al. 1979, Harte 1985, Marland 1988, Postel et al. 1988, Ranney et al. 1987, Steinbeck et al. 1976, USFS 1982, Woodwell 1987). The cost data we reviewed show a wide range, since they often reflect personal estimates of individuals working for the US Forest Service, non-government organizations in the US involved in tree planting, commercial US nurseries, local governments, official development assistance and United Nations agencies, private development assistance organizations, and tree planting movements in Third World countries (Dudek 1988, Fortune 1975, Leach et al. 1988, Pilarski 1988).

In all cases, we used a 7% real discount rate and estimates of the *establishment cost* of the tree, including seedling cost, watering cost, and the cost of protecting the seedlings from animals and other hazards. Under schemes that would reward tree planting with subsidies from carbon taxes on energy use, some categories of land that could support trees could become economically valuable, changing the leasing or purchase price of such land. We have sidestepped this issue by calculating only the establishment cost as a lower bound to the cost of tree planting. We used 20 years as the investment life of rural trees, which is a conservative estimate given the many uncertainties. We assumed that urban trees would live for 30 years.

Table IV shows the costs and energy savings benefits from urban tree planting from Akbari et al. (1988). We use establishment costs from $5-25/tree and relatively high survival rates of 0.85-0.95. We also assume that urban trees do not yield energy savings for ten years, and escalate the cost of the tree at the discount rate before annualizing the investment over 20 years. Akbari et al. calculated average energy savings to be 18.6% of cooling energy in 7 U.S. climates. We use 12% savings to be conservative. We assume cooling energy consumption of 2000 kWh, multiply this number by 0.12, and divide by 3 trees per house to get the energy savings per tree (80 kWh/year).[13]

DISCUSSION OF COST ASSUMPTIONS

The cost reports for tree planting differ enormously for different settings. For example, planting and protecting a young street tree in Los Angeles is estimated to cost $100, while planting a tree in a rural community fuelwood lot in India can cost as little as 25 cents. We have attempted to supply reasonable numbers for a few key parameters, such as sequestration rates, establishment costs, and survival fractions, and used these estimates to derive costs of sequestered carbon from the bottom up.

Range for Rural Trees

The range of costs of sequestered carbon (CSC) spans more than two orders of magnitude, ranging from a low estimate for third world rural trees of about $4/t-C, to a high estimate of more than $1000/t-C for high cost rural trees in the U.S. This large range is due to the

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[13] The calculation assumes that these energy savings accrue due to shading of the house. It ignores heat island mitigation, which occurs if enough trees are planted throughout a city to reduce overall average temperatures.

wide range of reported establishment costs (up to one and a half orders of magnitude) and a smaller range of sequestration rates (a factor of 2-5). The range of survival fractions chosen adds almost another factor of two.

Rural Tree Planting in the US and the Third World: Comparison

Our estimates of the utility's CSC for rural tree planting in the U.S. range from about $8/t-C to more than $1000/t-C, while the range for CSC of rural tree planting in the third world is from $4/t-C to about $500/t-C. For U.S trees, we have assumed slightly higher establishment costs and survival rates than those for third world trees, while the sequestration rates are lower to reflect the slower growth of temperate forests compared to tropical forests. Figure 3 shows lines representing our medium estimates of the CSC of rural trees in the Third World and in the U.S.

Range for Urban Trees

Table IV shows that planting urban trees is comparable in cost to efficiency resources, and can be far cheaper than planting rural trees for sequestration alone. Because of the energy savings provided by urban trees, the CSSCs for low and medium cost assumptions are negative. They range from -$109 for the low cost assumptions to $65/t-C for the high cost assumptions. Figure 2 shows lines representing the cost (and net cost) of conserved energy for urban trees based on the medium cost assumptions ($15/tree, 90% survival rate, 4.0 kg/yr sequestration rate). Figure 3 shows the CSSC for the same assumptions.

Range of US Electricity Efficiency

The net CCE is actually negative for the low and medium cost conservation, since the cost of conserved energy in these two cases is less than the assumed avoided costs. The lowest CCC is -$149/t-C, while the highest is +$113/t-C. Under our assumption about avoided cost, in the Michigan and Texas cases more than 90% of the potential energy and carbon savings in the residential and commercial sectors *can be captured at negative net cost to the utility and its ratepayers.* By contrast, carbon savings from planting rural trees will always have a positive net cost to the utility.

SIZE OF ELECTRICITY SURCHARGE TO FINANCE TREE PLANTING

The utility's choice of carbon-saving techniques depends on the unit cost of saved carbon and on the size of carbon savings that can be obtained from each resource in the aggregate. For example, utilities that are trying to fulfill a certain carbon-reduction target may need to plant rural trees in addition to investing in urban trees and low-cost conservation. While the latter options often have negative net costs to the utility, rural trees have positive costs. How much would it cost the utility to pursue rural tree planting, if such tree planting is to be financed by a per kWh surcharge?

The average carbon burden of US electricity production (based on the 1987 fuel mix) is 224 g/kWh delivered. Based on the data in Table III, the surcharge needed per kWh to offset these carbon emissions with rural tree planting in the U.S. ranges from \$0.002/kwh to \$0.23/kWh, with the middle estimate at about \$0.007/kWh. For third world rural trees, the range is from \$0.0009/kWh to \$0.11/kWh, with the medium estimate at \$0.006/kWh.

IMPACTS ON RATES

Utility-financed rural tree planting will increase electricity rates. Depending on the cost estimate used, this impact could be as little as about \$0.001/kWh for the cheapest rural trees in the third world to as much as \$0.23/kWh for expensive rural trees in the U.S. Assuming a medium value of \$0.006/kWh, the rate impact would be of the order of ten percent or less of current electricity prices.

The impact of demand-side resources and urban tree planting on rates depends on the marginal cost structure of the utility. Where utilities face rising marginal costs, energy savings will reduce rates. Where short-run marginal costs are lower than average rates, energy savings will cause rates to increase (to offset lost sales and cover fixed costs). The impact of demand-side programs on rates is typically on the order of a few percent of the electricity price (Krause et al. 1988).

With the appropriate caveats regarding the uncertainty of costs for tree planting, these figures suggest that rate impacts from either option will be comparable in magnitude. However, efficiency investments and urban trees lead to reductions in utility bills that rural trees do not offer. If rate impacts are comparable, the most attractive options to the utility would then be urban tree planting and efficiency investments that can deliver carbon savings at negative net cost.

CONCLUSIONS

Investments in energy efficiency and rural and urban tree planting can help reduce net utility carbon emissions. For utilities and their ratepayers, it is important to deploy these options according to least-cost principles. At this time, data on the cost of conserved carbon from tree planting vary over a wide range, and case studies of successful planting programs are needed to narrow the range of plausible costs. Nevertheless, some broad patterns suggest themselves from our review:

- Utility programs to plant trees or implement energy efficiency offer carbon mitigation at negative to slightly positive unit net cost.
- Rate impacts from utility investments in these carbon-saving measures would be limited to a few percent of the electricity price in many cases.
- Among the three utility options investigated, utility-sponsored energy efficiency programs appear to be the most widely applicable and attractive carbon-saving investment. The majority of these demand-side resources would deliver carbon savings at negative unit cost to the utility.
- Urban trees can in many cases be competitive with the cheapest conservation, but are subject to a larger number of constraints (particularly in siting). For example, efficiency measures can be installed in almost every type of building, while urban trees are most likely to be successful for only a fraction of residential and small commercial buildings.

- Rural tree planting, both in the US and abroad, is an important tool in combating global warming; however from the utility's perspective, this option appears to be less cost-effective than conservation or urban trees.

These conclusions are robust under a wide variety of different assumptions. Future work should attempt to estimate the carbon sequestration and savings potential available from urban and rural trees, in the same way that estimates of the conservation potential have been developed in the past fifteen years

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Table I. Carbon burdens of fossil fuels and electricity

	DIRECT[a] G-C/KWH	ELECTRIC GENERATION G-C/KWH
NATURAL GAS	60.7	189
OIL	83.0	258
COAL	103.4	321
US AVERAGE		
MARGINAL (FOR ENERGY SAVINGS[b])		265
AVERAGE (BASED ON 1987 FUEL MIX)		224

ASSUMPTIONS
T&D losses: 6%
Heat Rate: 10,000 Btus/kWh
Adjusted Heat Rate: 10,600 Btus/kWh
Marginal Oil Fraction: 15%
Marginal Gas Fraction: 35%
Marginal Coal Fraction: 50%

[a] Carbon burdens for fuels are from Unnasch et al. 1989, and are based on lower heating values. The direct carbon burden for each fuel is higher than that released in the burning of the fuel because it includes the carbon released from energy consumption when extracting and processing the fuel

[b] Carbon burdens for energy savings calculated using marginal fractions from US DOE 1988c. The marginal carbon burden represents a crude estimate of the amount of carbon savings from each kWh of energy savings, based on information about which power plants will be curtailed in response to a demand reduction (i.e., which power plants are marginal).

Table II. Summary of typical conservation supply curves for residential and commercial sectors

	WEIGHTED AVERAGE CCE $/KWH	NET CCE $/KWH	CCC $/T-C	ENERGY SAVINGS AS % OF TOTAL SALES	CARBON SAVINGS AS % OF TOTAL C EMISSIONS
MICHIGAN ELECTRICITY OPTIONS STUDY (RESIDENTIAL MEOS)					
LOW	0.013	-0.037	-138	3.1	3.6
MEDIUM	0.044	-0.006	-23	0.6	0.7
HIGH	0.080	0.030	113	0.2	0.2
ALL	0.022	-0.028	-106	3.9	4.6
TEXAS STUDY (COMMERCIAL)					
LOW	0.010	-0.040	-149	3.1	3.6
MEDIUM	0.039	-0.011	-43	0.7	0.8
HIGH	0.053	0.003	11	0.5	0.6
ALL	0.020	-0.030	-113	4.3	5.1

MEOS TOTAL ELECTRICITY SALES 20 YEARS FROM BASE YEAR (TWH)	81
MEOS TOTAL CARBON EMISSIONS 20 YEARS FROM BASE YEAR (MT)	18
TEXAS TOTAL ELECTRICITY SALES 20 YEARS FROM BASE YEAR (TWH)	289
TEXAS TOTAL CARBON EMISSIONS 20 YEARS FROM BASE YEAR (MT)	65

	RANGE OF COST OF CONSERVED ENERGY (CCE)
LOW	< $0.03/KWH
MEDIUM	$0.03-0.0499/KWH
HIGH	$0.05-0.085/KWH

AVOIDED COSTS ($/KWH)	0.05
DISCOUNT RATE	7%

NET CCE = CCE - AVOIDED COSTS

REFERENCES:

Krause et al. 1987
Hunn et al. 1986

Table III. Cost of rural trees

	COST TO ESTABLISH $/TREE	SURVIVAL FRACTION	SURVIVING TREES/HA	COST TO ESTABLISH $/HA
THIRD WORLD				
LOW	0.25	0.8	1000	313
MEDIUM	0.8	0.6	1000	1333
HIGH	8	0.5	1000	16000
UNITED STATES				
LOW	0.5	0.9	1000	556
MEDIUM	1	0.75	1000	1333
HIGH	9	0.6	1000	15000

	SEQUESTRATION RATE KG-C/TREE/YR	SEQUESTRATION RATE T-C/HA/YR	ANNUALIZED COST $/HA/YR	CSC $/T-C
THIRD WORLD				
LOW	7.50	7.50	29	*3.93*
MEDIUM	5.00	5.00	126	*25.17*
HIGH	3.00	3.00	1510	*503.43*
UNITED STATES				
LOW	6.50	6.50	52	*8.07*
MEDIUM	4.00	4.00	126	*31.46*
HIGH	1.35	1.35	1416	*1048.81*

ASSUMPTIONS

REAL DISCOUNT RATE	7%
INVESTMENT LIFE (YEARS)	20
CAPITAL RECOVERY FACTOR	9.4%

REFERENCES: *Carbon yield assumptions adapted from:*
Dyson et al. 1979, Harte 1985, Marland 1988, Postel et al. 1988, Ranney et al 1987, Steinbeck et al. 1976, USFS 1982, and Woodwell 1987.

Cost assumptions adapted from:
Dudek 1988, Fortune 1975, Leach et al. 1988, and Pilarski 1988

Table IV. Cost of urban trees

COST	COST TO ESTABLISH $/TREE	SURVIVAL FRACTION	COST PER SURVIVING TREE $/TREE	COST AFTER TEN YRS @ 7% $/TREE	SEQUESTRATION RATE KG-C/TREE/YR
LOW	5	0.95	5.26	10.35	6.5
MEDIUM	15	0.9	16.67	32.79	4
HIGH	25	0.85	29.41	57.86	1.35

COST	C SAVED + C SEQUESTERED KG-C/TREE/YR	ANNUALIZED COST $/TREE/YR	CCE $/KWH	NET CCE $/KWH	CSSC $/T-C
LOW	27.7	0.98	*0.012*	*-0.038*	*-109*
MEDIUM	25.2	3.09	*0.039*	*-0.011*	*-36*
HIGH	22.6	5.46	*0.068*	*0.018*	*65*

ASSUMPTIONS:

COOLING ENERGY USAGE (KWH/HOUSE)	2000
COOLING SAVINGS	12.0%
TREES/HOUSE	3
ENERGY SAVINGS (KWH/YEAR/TREE)	80
REAL DISCOUNT RATE	7%
CAPITAL RECOVERY FACTOR	9.4%
LIFETIME (YEARS)	30
GROWTH PERIOD (YEARS)	10
AVOIDED COSTS ($/KWH)	0.05
CARBON BURDEN FOR SAVINGS (G/KWH)	265

REFERENCES: Akbari et al. 1988

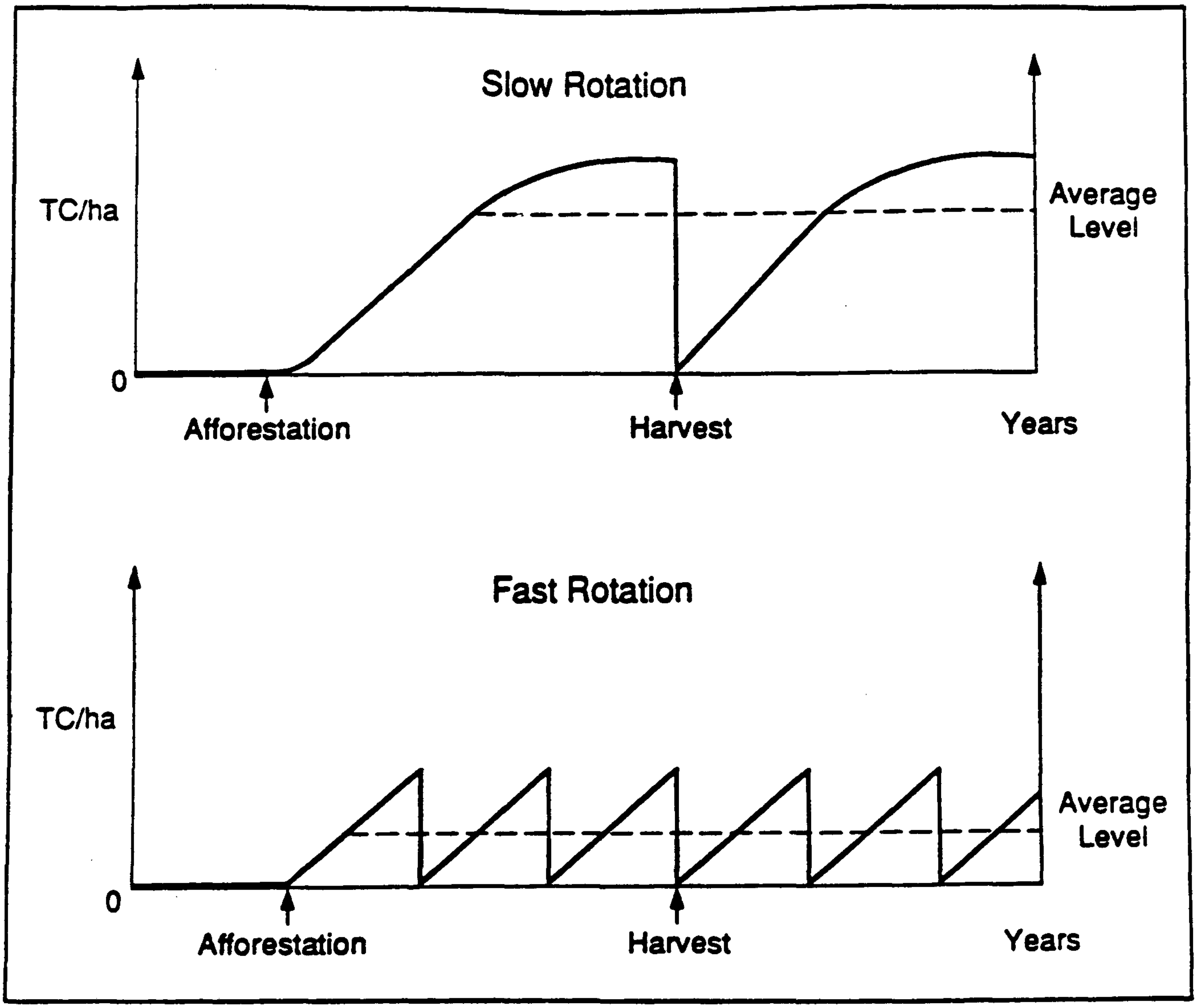

Figure 1. Simplified relationship between harvesting and carbon storage for sustainable yield forestry

The figure shows the level of carbon storage over time and the consequent average carbon storage in the forest for slow and fast rotations. If the forest is clear cut frequently, the time-averaged carbon storage level will be lower than if it is allowed to grow for many years.

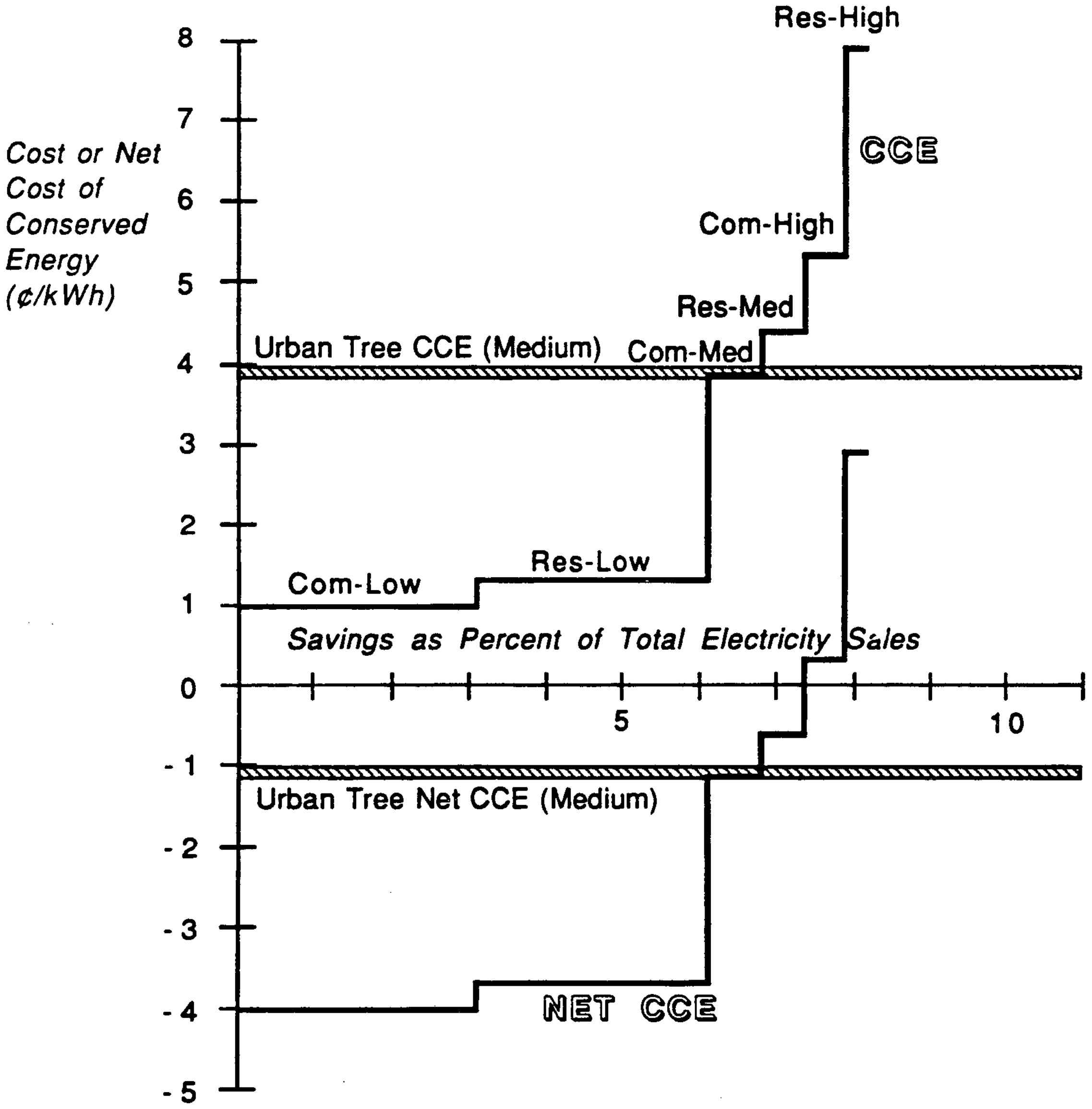

Figure 2. Aggregate supply curve of conserved energy

This graph shows typical values for the CCE and net CCE of energy efficiency and urban trees. Energy savings are expressed in terms of percent of total system electricity sales twenty years from the forecast's base year. The discount rate is 7% real.

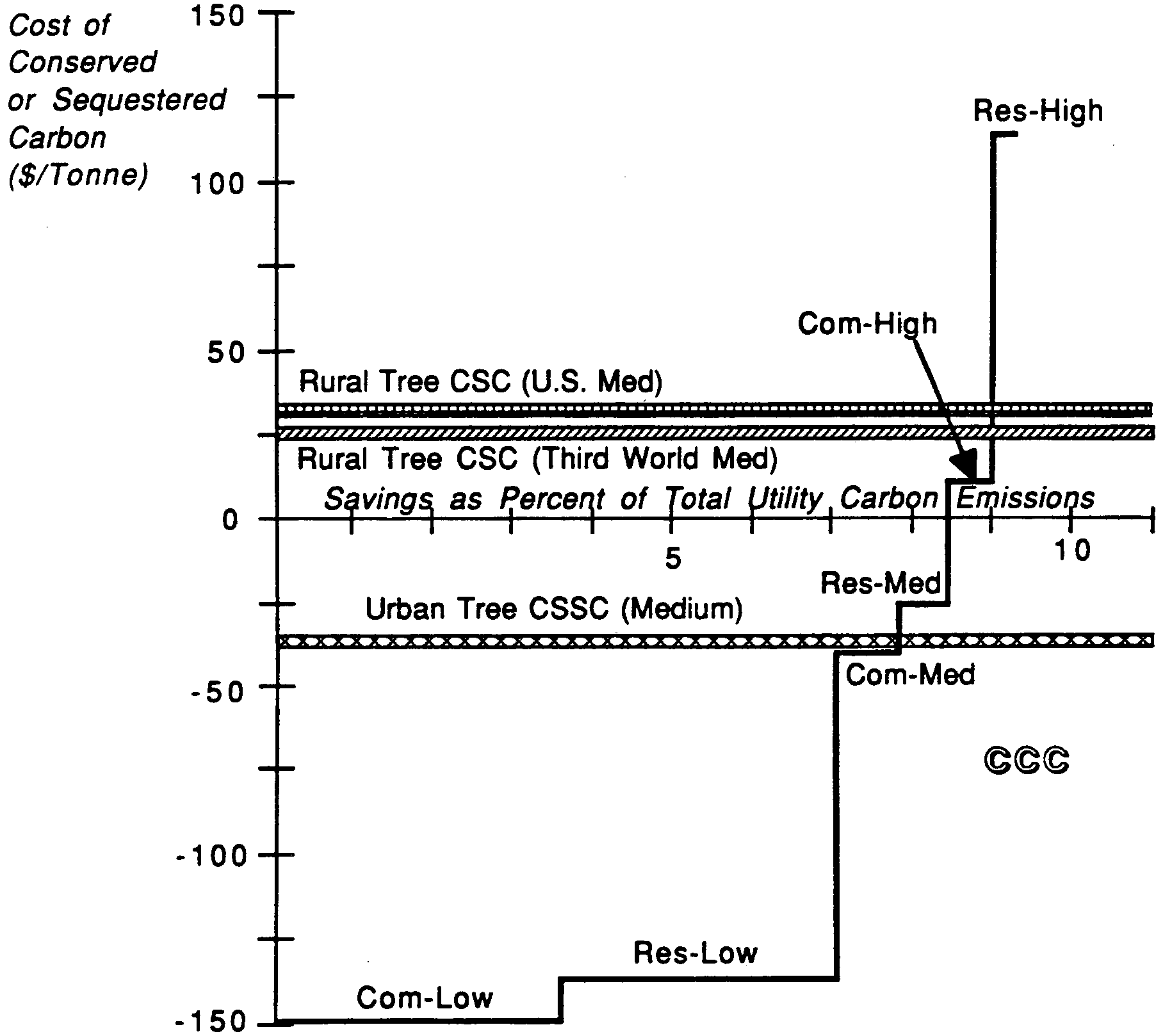

Figure 3. Aggregate supply curve of conserved carbon
This graph shows typical values for the CCC, CSC, and CSSC of energy efficiency, rural trees, and urban trees (respectively). Carbon savings are expressed in terms of percent of total utility system carbon emissions twenty years from the forecast's base year. Discount rate is 7% real.

CHAPTER 3

Modeling the Urban Climate

Chapter 3

MODELING THE URBAN CLIMATE (Editors' Summary)

Urban climate models are important tools for understanding urban heat islands and predicting changes in heat island intensity based on changes in meteorological conditions, urban surface characteristics, and other anthropogenic effects. This chapter presents two reviews of different types of urban climate models, a description and output from a particular model, and some discussion of evapotranspiration and urban surface properties necessary for modeling the urban climate and its effect on energy use.

Bornstein describes various microscale (canopy layer) and mesoscale (boundary layer) climate models and discusses the outputs produced and the limitations of each type of model. **Martien** *et al.* evaluates which type of models produce the most useful data for evaluating the effect of heat islands on energy use in buildings, and discusses an approach for using these models for such a purpose. In particular, **Martien** *et al.* concludes that canopy layer models (which describe the near-surface in the vicinity of buildings) usually do not predict air temperatures necessary for estimating building-energy use. Even those that do require specification of the air temperature above the canopy as input to the model. This means that the effect of altering urban surfaces cannot be directly simulated by canopy layer models since alteration of surface properties will also alter the boundary temperature. Boundary layer models (which incorporate the air mass up to one to two kilometers above the surface) can predict the effects of generalized changes in surface conditions but only for the region above the canopy layer. Some combination of these two types of models must therefore be used to predict conditions relevant to energy use by buildings.

In the introduction to Chapter 1 we raised the question of the potential of increased tree coverage and increased urban albedo to alter urban climate at the mesoscale as well as the microscale. The paper by **Pielke and Avissar** and the abstracts (papers not submitted) of **Oke** and **Paw U** begin to address this issue. **Pielke and Avissar** present results of a modeled comparison between two urban regions: one located in bare, dry surroudings; the other in an area completely covered with unstressed vegetation—the urban areas themselves being identical. Their model predicts that the urban area in vegetated terrain will be a few degrees cooler than the other, and that the surface temperature of built-up areas within the city will be 10-15 °C warmer than vegetated surfaces and 20 °C warmer than free water surfaces. Although these predictions are for surfaces only, they provide an indication of the substantial effect of trees in modifying urban climate. A significant component of the Pielke and Avissar model is the parameterization of the sub-grid scale surface, particularly of vegetation and the soil. This approach could prove useful in estimating the effects of increased albedo and vegetation within the urban area as well as estimating effects due to changes in the surface of the surrounding region. As mentioned above, for the purposes of estimating the effects on cooling-energy use or air-pollution formation, it will still be necessary to translate predictions of surface temperatures into predictions of near-surface air temperatures, and as in all boundary layer models, resolution is limited by fairly large grid size.

The final presentation by **Monismith,** for which no paper was submitted, summarized data and analytical (closed form differential) models of the thermal properties of asphalts, aggregates, and their combinations, and reviewed data on the light-reflecting properties of paved surfaces. Such information must be included in microclimate and building-energy models to account for the effects of thermal storage in building materials and reflected short-wave radiation.

NATURE, LIMITATIONS, AND APPLICATIONS OF URBAN CLIMATE MODELS

by

R.D. Bornstein

Department of Meteorology
San Jose State University
San Jose, CA 95192

ABSTRACT

A review of the classes of urban climate models is presented for both the urban canopy layer and the urban boundary layer. The classes include statistical models, canyon energy models, wind tunnel models, advective integral models, and dynamic differential models. The basic workings of each type of model is reviewed with respect to assumptions, equations, boundary conditions, parameterizations, numerics, grids, and initial conditions. Also discussed are outputs produced, evaluation techniques, and limitations associated with each type. Each class of model is evaluated with respect to features of urban climate that it can and cannot accurately reproduce. The role of such models in city planning is evaluated. Finally, possible future developments in urban climate modeling are explored.

KEYWORDS: boundary layer, canopy layer, city planning, numerical modeling, urban climate, wind tunnels

1. INTRODUCTION

Atmospheric models serve many useful purposes, from forecasting the weather to the siting of power plants. A potential important use of such models is in the planning of urban development so as to create urban climates more (and not less) healthy for urban dwellers. Urban climate models have been previously reviewed by Taylor (1974), Oke (1974,1979), Landsberg (1981), Bornstein and Oke (1981), Bennett and Saab (1982), and Bornstein (1984).

Following the suggestion of Oke (1976) this paper summarizes atmospheric models of both the microscale variations within the (below roof level) urban canopy layer and the mesoscale variations within the (above roof level) urban boundary layer. The basic working of each type of model is reviewed with respect to assumptions, equations, parameterizations, boundary conditions, numerics, grids, and initial conditions. Also discussed are outputs produced, evaluation techniques, and limitations associated with each type. The role of such models in city planning in general, is evaluated. Finally, possible future developments in urban climate modeling are explored.

2. MODELING STUDIES

A. Canopy layer models

Microscale canopy layer models can be classified as statistical, canyon, or wind tunnel.

Simple regression of urban-rural climatic differences against one or more meteorological parameters is one of the oldest forms of urban modeling, e.g. see the work of Goldreich (1974), Unwin and Brown (1975), Conrads (1976), and Hernandez et al (1984).

A more sophisticated statistical model is the harmonic analysis used by Preston-Whyte (1970) to summarize surface temperature distributions in Durban, South Africa. A sophisticated eigenvector analysis was used by Clarke and Peterson (1973) to study the relationship between surface heat island and land use in St. Louis.

The coefficients of such statistical relationships are different for each city, and thus such relationships cannot be used for planning urban development in other locations. Statistical models generally do not require large computing facilities, but do require good data bases to develop accurate predictor equations. While they can be used to forecast urban climatological parameters, they don't generally provide significant insight into the basic physical processes producing urban climate.

Canyon models generally simulate energy exchanges either around a single building, in a single urban canyon, or for a series of urban canyons. The various canyon models seek to evaluate some or all of the terms in the surface energy balance equation, as opposed to simulating resulting meteorological distributions, e.g., see Terjung and Louie (1973,1974), Unsworth (1975), Nunez (1975), Nunez and Oke (1976,1977,1980), Cole (1976a,b), Arnfield (1976,1982), and Terjung and O'Rouke

(1980a,b). The most complex of these models involves multi-building canyon geometry factors (Terjung and O'Rouke, 1980b).

Canyon energy exchange models yield important information on microscale variations of the surface energy balance. They also provide estimates of the various urban radiation parameter needed in the mesoscale urban planetary boundary layer (PBL) models discussed below.

Wind tunnel studies have also provided much insight on flow patterns within the urban canopy layer. Some work deals with effects of single buildings (e.g., Newberry et al, 1973; Isyumov and Davenport, 1975; Penwarden and Wise, 1975), while others concentrate on flows within complex urban canyons (e.g., Cermak et al, 1974; Hoydysh et al, 1975). A discussion of the "similarities" required between real and wind tunnel atmospheres is given below in the section on wind tunnel models of the urban PBL.

B. Boundary layer models

Mesoscale boundary layer models can be classifies as energy balance, advective integral, dynamic differential, or wind tunnel.

The earliest of the energy balance models sought to predict surface temperature at a single point at a given time from solutions to the surface energy balance equation. Such an energy balance model was applied to Sacramento, California by Myrup (1969a,b) and Myrup and Morgan 1972). The city was divided into 152 squares and a detailed analysis of land usage patterns carried out to obtain the surface characteristics necessary to calculate the energy balance in each of the squares. Similar models have been used by Bach (1970), Outcalt (1972a,b), Nappo (1972), and Miller et al (1972).

The main limitation of these early energy balance models is the lack of feedback between the SBL and the rest of the PBL, i.e., meteorological parameters at the top of the SBL remain constant in time. The models, however, require considerably less computer power than those containing such feedback.

Later one-dimensional energy balance models generally contained two atmospheric layers, i.e., a lower analytical constant flux SBL (of about 50 m in depth) and an upper finite-difference transition layer (of about 2 km in depth). Finite difference solutions to the basic PBL equations over homogeneous urban surfaces were obtained by Tag (1969), Atwater (1970,1971a, b,1972a,b), Bergstrom and Viskanta (1972,1973a,b,1974), Lal (1975,1976), Torrance and Shum (1976), Zundkowski et al (1976), Venkatram and Viskanta (1976a,b,c,1977), Ackerman et al (1976), Ackerman (1977), and Dieterle (1979).

Boundary conditions at the top of the model and at the bottom of the soil layer (if included) generally specify constant values, i.e., no affect of surface processes. The temporal variation of surface temperature is either specified or predicted from the surface energy balance equation in a manner similar to the earlier models; however, simulation of non-steady PBL profiles allows for time varying meteorological parameters at the SBL top.

Various finite-difference schemes exist, each with problems that will be discussed below. Initial conditions can consist of (unsmoothed or smoothed) observed profiles or equilibrium model profiles. Observed profiles could contain inconsistencies, e.g., between energy and mass fields, which could cause the model to become unstable, while equilibrium model profiles may be unrealistically simplified. In either case, the extreme PBL forcing associated with the diurnal variations in the surface energy budget should make initial conditions unimportant after relatively few hours of simulated time.

Results generally show one-dimensional PBL models fairly accurate in simulating surface fluxes over homogeneous (i.e., generally rural) surfaces. Such models are also used in parametric studies in which single urban parameters are systematically varied. These models have also generally shown gaseous pollutants (mainly via radiative flux divergence) producing only small atmospheric and surface temperature changes, except in near calm conditions; however, dense aerosol layers can produce significant atmospheric temperature changes.

In summary, one-dimensional PBL models have been useful in evaluating current and future effects of urbanization on the thermal structure of mid-latitude cities; however, Oke (1979) has pointed out that canopy layer effects need to be better incorporated into these models.

The steady-state advective integral model developed by Summers (1964,1974) predicts both the spatial distribution of early morning urban mixing depth (surface to base of first elevated inversion) and surface heat island magnitude, as anthropogenic heat is added to columns of stable rural air passing over an urban area.

The model requires only input values of rural lapse rate, mean PBL wind, and spatial distributions of source terms. The basic model was also used by Kalma (1974), Leahey (1975,1976), and Clark et al (1984).

The basic advective integral model was modified by Pasquill (1970) to allow general wind and temperature profiles, but this necessitates evaluation of additional empirical constants. The basic model was also modified by Leahey (1969), who extended its use to areas downwind of a city by the addition of several heat sinks. The new model was used by Leahey and Friend (1971) and Leahey (1972) in NYC, where it gave excellent agreement with observed mixing depth values. Non-planar topography was added to the modified model by Henderson-Sellers (1980).

Advective integral models are useful in estimating spatial variations in the effects of urbanization on the nocturnal PBL; they do not require much computer power. For more detailed studies of the nocturnal PBL, and for studies of the daytime urban PBL, it is necessary to use dynamic differential models.

Dynamic models over inhomogeneous terrain, e.g., shoreline, valley, or urban areas, obtain solutions to the basic PBL equations. The first solutions to the two-dimensional basic urban PBL equations were analytical solutions to the simplified linearized equations (e.g., Gold, 1956; Findlay and Hirt, 1969;

Vukovich, 1971,1973,1975; Olfe and Lee, 1971).

The first two-dimensional finite-difference solution to the basic urban PBL equations was obtained by Delage and Taylor (1970) for urban breeze development in an otherwise calm situation. Similar two-dimensional solutions to the basic urban PBL equations for non-zero regional flows were obtained by McElroy (1971,1972a,b,1973), Wagner and Yu (1972), Yu (1973), Lee and Olfe (1974), Yu and Wagner (1975), Welch et al (1978), Bornstein (1972a,b,1975), Gutman (1974), Gutman and Torrance (1975), Bornstein and Tam (1977), and Bornstein and Runca (1977).

Results generally show that two-dimensional finite-difference PBL models capable of reproducing observed features of the urban PBL. For example, the model of McElroy (1973) accurately simulated the thermal structure of the nocturnal PBL in and around Columbus, Ohio. Likewise, the model of Bornstein (1975) reproduced deceleration due to increased surface roughness at the upwind urban edge, urban heat island induced maximum wind speed at the downwind urban edge, and weakened near surface return flow downwind of the city.

Two-dimensional finite-difference models are better than one-dimensional finite-difference models, as they include effects of horizontal temperature gradients in producing vertical circulations, as well as horizontal and vertical advective effects; however, such models are only completely valid for infinitely long discontinuities, such as long straight shorelines. Since most cities are not infinitely long, three-dimensional models are necessary to reproduce some urban meteorological effects, e.g., changes in wind flow direction.

The first three-dimensional heat island model was that of Black et al (1971). It was a steady state analytical model of the flow over a heated industrial area in the presence of an imposed wind.

The first three-dimensional finite-difference urban PBL model was that of Atwater (1974,1975) and Atwater and Pandolfo (1975). The latter was a simulation of a hypothetical arctic city surrounded by tundra. Results showed stronger arctic summer daytime heat islands than generally found in mid-latitude cities.

A three-dimensional finite-difference urban PBL model of flow over St. Louis was developed by Vukovich et al (1976). It reproduced many features of the observed horizontal distributions of urban temperature, horizontal velocity, and vertical velocity. Model sensitivity tests by Vukovich and Dunn (1978) indicated heat island intensity and boundary layer stability the dominant factors in development of heat island circulations.

The model then studied interactions between intense heat island circulation and ozone distribution (Vukovich et al, 1979). Maximum ozone levels were predicted to occur in the zone of maximum heat island convergence. The model was further tested against four days of METROMEX meteorological data by Vukovich and King (1980). Results showed general agreement with observed meteorological parameters. An exception was during changing synoptic conditions, which the model formulation cannot accommodate.

A three-dimensional finite-difference mesoscale model was used by Hjelmfelt (1980,1982) to simulate effects of St. Louis on mesoscale airflow. Results were consistent with the hypothesis that observed cloud and precipitation anomalies over St. Louis are related to perturbations in PBL dynamics due to the urban heat island and surface roughness.

Three-dimensional finite-difference models have also been applied to coastal urban areas to study interactions between urban and coastal mesoscale processes. The primitive equation model of Takano (1983) for the metropolitan Tokyo area utilized a "level 2" second order turbulence closure from Mellor and Yamada (1974).

The three-dimensional finite-difference coastal urban PBL model for the NYC area of Bornstein et al (1986) is an expansion of the two-dimensional URBMET vorticity model of Bornstein (1975). It utilizes two hydrostatic vorticities. The model also has a soil sub-layer which soil temperature and moisture are computed. This allows for simultaneous prediction of surface temperature and moisture from surface heat and moisture balance equations by a double interactive technique.

While three-dimensional finite-difference models provide better insights into the complex urban meteorological processes than the other numerical models described above, they require the greatest amount of computer power, i.e., they are the most expensive numerical models. There are, however, techniques to reduce these costs, e.g., variable horizontal grid spacings (greatest resolution in areas of maximum interest) allows for fewer grid points.

An early approach to urban boundary layer modeling was the outdoor 1:1000 scale model of Davis (1968) and Davis and Peason (1970), used to simulate flow over Ft. Wayne, Indiana. Hot wires and roughness elements were embedded in the ground, and measured temperatures to heights of 1.5 m within the model were compared (via a Monin-Obukhov) parameterization to observations on a 300 m urban tower. Moderate success was claimed in reproducing stability variations across the urban complex.

Wind tunnel urban PBL simulations with adiabatic layers were carried out by Counihan (1971,1973,1975) and Cook (1973,1974), but the most extensive wind tunnel scale modeling efforts of the urban PBL have been conducted at the Colorado State University. This facility allows stratified boundary layers to be simulated (Yamada and Meroney, 1971; Meroney and Yamada, 1971,1972; Yamada, 1972; Meroney et al, 1973; SethuRaman, 1973,1976; Cermak, 1970,1975; SethuRaman and Cermak, 1974a,b,1975). Electrical heaters simulate heat island effects and aluminum blocks form street-block patterns. Passive smoke allows flow visualization, while mean wind speed and turbulence are monitored with temperature-compensated hot-wire probes. Many of these studies were carried out in conjunction with two- and three-dimensional finite-difference modeling studies.

Bennett and Saab (1982) describe the new meteorological wind tunnel facilities at the Ecole Centrale de Lyon, the Hochschule der Bundeswehr in Munchen, and the National Institute for

Environmental Studies in Japan. They also describe the similarities that must be achieved in a wind tunnel, i.e., topography, Reynolds number, Prandtl number, Rossby number, Richardson number, and boundary conditions.

They conclude that wind tunnel simulations are tempting, given the difficulties associated with numerical models; however, they also conclude that wind tunnel modeling has problems associated with achieving the required similarities.

3. CONCLUSION

A review of the classes of urban climate models has been presented for both the urban canopy layer and urban boundary layer. The basic workings of each type of model has been reviewed with respect to assumptions, equations, boundary conditions, parameterizations, numerics, grids, and initial conditions.

The most useful of the numerical urban models, in increasing order of computer power requirements, are the advective integral models, one-dimensional energy balance models, and the two- and three-dimensional dynamic differential models. Wind tunnel scale models for stratified flow situations are also useful by themselves or in conjunction with numerical models.

Urban climate models can do a good job in simulating the nighttime surface urban heat island and the daytime urban PBL lapse rate. They can also accurately reproduce nighttime heat island induced convergences and surface roughness induced decelerations.

Although these models are capable of reproducing many of observed characteristics of the urban meteorological fields, certain areas need additional development. One of these is prediction of the evolution of daytime urban mixing depths, which grows due to convergence of sensible heat from below due to thermal convection and from above due to penetrative convection. Recent theoretical advances in predicting this have only so far been incorporated into analytical urban PBL models by Barnum and Rao (1974,1975) and Carlson and Boland (1978).

Urban climate models do not accurately reproduce or parameterize the exact urban surface. For example, when assigning values of thermal and radiative parameters to a mesoscale grid containing a variety of land use types, it is as if all of these land use elements are "ground-up" into sand and used to fill a "ground level" sunken sand box.

The physical processes forming the elevated nocturnal urban temperature inversion are still not completely understood, and hence such layers are not reproducible in urban climate models.

Many non-urban two- and three-dimensional finite-difference PBL models utilize coordinate transformations to simulate topographic effects on mesoscale flows. This technique needs to be incorporated into future urban PBL models, so they can be applied to cities with significant topographic features.

Effects of changing synoptic conditions on urban meteorological distributions cannot currently be simulated properly with existing PBL models. One method of dealing with this problem is to utilize time and/or space varying upper boundary conditions in the models. These variations can be specified for typical cases (as was done by Reichenbacher and Bornstein, 1979) or can be obtained from output from larger weather forecasting models.

Another weak point of urban PBL models is that they don't fully utilize knowledge gained from urban canopy layer models. Better use of this formation would produce better lower boundary conditions for the PBL models.

Remote sensing information from aircraft and satellites on land use patterns would also aid in development of better lower boundary conditions for urban PBL models. Utilization of such data has already started, e.g., see the work of Ellefen et al (1976), Carlson et al (1977,1981), Dabberdt and Davis (1978), and Goldreich (1984).

Recent observations have documented that daytime surface heat islands (as determined from surface radiative temperatures) are stronger than 1.5 m heat islands (as determined from air temperatures), e.g., see the analyses of Imamura (1986,1988, 1989). This information has implications for future urban climate modeling studies, with respect to surface versus roof level temperatures and urban canyon versus urban canopy layer temperatures.

Finally, comparison of predicted and observed values is encouraged for an increased confidence in modeling as an urban planning tool. Statistical techniques for model evaluation are becoming more formalized and standardized (Fox, 1981). Such evaluation, of course, requires continued use of existing urban data bases such as the RAPS, METROMEX, and NYC/NYU (Bornstein, et al 1977a,b) sets. In addition, it requires collection of new data in coordination with the increasing initialization and verification requirements of urban modelers.

The roles of urban models in city planning are many. They include analysis of factors creating existing urban observed meteorological and climatological patterns. This is accomplished by model simulations carried out with one or more urban physical characteristics removed or modified within the model, a situation that cannot be duplicated in the real world. In addition, models can be used in planning future urban developments in existing and new cities. Different building materials and/or building configurations can be tested in the computer to help select those which will create a new climate that will be more (and not less) healthy for future urban dwellers.

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APPROACHES TO USING MODELS OF URBAN CLIMATE IN BUILDING-ENERGY SIMULATION

P. Martien, H. Akbari, A. Rosenfeld, and J. Duchesne

Applied Science Division
Lawrence Berkeley Laboratory

ABSTRACT

Architects and building-energy scientists commonly use numerical models to evaluate the energy performance of buildings. Recently, building-energy researchers have become interested not only in representing existing urban climates, but also in quantifying the effects of changes in urban-surface characteristics on urban climate and consequently on energy consumption in buildings. In particular, a relevant question to energy-conservation efforts is how increasing urban vegetation and urban albedos can reduce the energy used in buildings within cities.

In this paper, we discuss the use of urban-climate models with the building-energy model DOE-2 to investigate the potential for reducing energy consumption in buildings by modifying urban-surface characteristics on the scale of an entire city. We review the capabilities of a number of representative urban-climate models to predict the climate variables required by DOE-2. After evaluating the relative strengths and limitations of both canopy-layer models and boundary-layer models, we conclude that a boundary-layer model augmented with algorithms from a canopy-layer model is required for simulating the effect of city-wide changes in climate and the consequent changes in building energy use; however, a number of important limitations exist to using climate models for this purpose.

From the perspective of building-energy modelers, the most significant limitation of climate models arises from the difficulty of specifying surface parameters to represent various land types. The discussion of these issues is intended to coordinate the efforts of building-energy modelers and urban-climate modelers in reducing the energy consumption of urban buildings.

KEYWORDS: boundary layer, building-energy, canopy layer, energy conservation, numerical modeling, urban climate

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INTRODUCTION

About 10% of the total electrical energy consumed in the United States powers residential and commercial air conditioners. Since cooling is required during the hours of peak electrical power demand--indeed it often defines the peak--cooling energy is particularly expensive, for both utilities and consumers. Preliminary studies by Huang et al. (1987), Taha et al. (1988), and Akbari et al. (1988) demonstrated the potential energy benefits of adapting urban designs to reduce summer temperatures in cities. They proposed two cost effective measures to reduce urban temperatures and summertime cooling loads: planting urban trees and increasing urban albedo. These investigators predicted significant savings in summertime cooling, with little or no increase in energy used for winter heating. In fact, Huang et al. estimated that trees can actually decrease winter heating by reducing ground-level winds. Estimates by Akbari et al. (1986) emphasized that reducing urban temperatures would not only reduce cooling-energy consumption, but could also save gigawatts of summertime peak power.

Huang et al.(1987) and Taha et al. (1988) noted a number of issues which should be reexamined in future modeling studies. For example, Huang et al. used a one-dimensional, predictor for the boundary-layer height to investigate the effects of additional trees on urban climate. The model makes several tentative assumptions. It assumes that the cooling effect from plant evapotranspiration is well mixed within the boundary layer, whereas it is more likely that more cooling occurs in the canopy than in the upper portion of the boundary layer. It further assumes that the cooling achieved by increasing the plant canopy does not alter the heat balance of the urban surface, contradicting the fact that within the model drybulb temperatures are depressed. A more realistic model would avoid these assumptions.

Taha et al. (1988) used a one-dimensional, boundary-layer model to predict the effect of urban albedo on local climate. This study, while more sophisticated in its level of climate modeling, only simulated the effects of modifying albedo. Future studies should examine the effects of trees and light surfaces in combination. This is essential to forming quantitative recommendations tailored to fit the needs of specific climates since the relative benefits and costs of trees versus light surfaces will vary significantly among different climates. Both Huang et al. and Taha et al. based their studies on one-dimensional models. Additional study is needed to investigate the effects of spatial inhomogeneity and the importance of advection.

In this paper we build on the work of and Huang et al. (1987) and Taha et al. (1988) by investigating the application of different climate models to the analysis of energy use in buildings. We are particularly interested in using climate models to quantify the importance of both the long-range dispersion of cooling and the localized cooling effects of trees and high-albedo surfaces. First, we identify the climate variables important for modeling energy use in buildings. We specifically consider the climate input required by the building-energy model DOE-2 common to the studies mentioned above. We then turn to a number of representative urban-climate models--canopy-layer and boundary-layer models--describing their domain, the data input they require, and their output. Finally, we propose ways in which the climate models can be used effectively to help predict changes in building energy consumption produced by changes in urban-surface properties. One of the primary reasons for providing this analysis is to coordinate the efforts of building-energy modelers and urban-climate modelers in creating tools for reducing the energy use of urban buildings.

CLIMATE INFORMATION REQUIRED FOR SIMULATING BUILDING ENERGY USE

Definitions and Objectives

To predict changes in building energy use that result from city-wide modifications in vegetation and albedo, one needs to predict changes in the climate near the ground caused by these modifications. **The climatic variables that are important for simulating building energy use and that are significantly affected by surface modifications are drybulb temperature, wetbulb temperature, and wind speed and wind direction.** These variables largely determine the level of space conditioning required in buildings. For convenience, we will refer to these variables as "**conditioning**" variables. Accurate predictions of conditioning variables require that other variables--such as surface temperatures and fluxes--are also predicted; but these are a secondary concern for simulating building energy use.

We are interested in knowing the conditioning variables in the vicinity of buildings at a height of roughly two to ten meters. For simulating the energy use of a particular building, it is ideal if the bulk temperature and wind are determined for the air adjacent to the building, in the so-called "canopy layer." However, we are less concerned with the conditions around a particular building than with an area-averaged set of conditions within a portion of a city. While climate can vary from one "urban canyon[1]" to another, for our purposes it is sufficient to predict average conditioning variables, where the averaging is done over an area on the order of a square kilometer. Similarly, simulations of building energy use do not require a detailed temporal climate analysis. For these simulations, we require, instead, time-averaged climate variables, where the averaging period is one hour.

Thus, for the purposes of this analysis, the important variables are drybulb and wetbulb temperatures and wind speed and direction at a height of about two to ten meters, averaged over an area of about a square kilometer and over the period of an hour.

DOE-2.1C and its Climate Input

The analyses of building energy use by Huang et al. (1987) and Taha et al. (1988) were based on the building-energy program DOE-2.1C (DOE-2). DOE-2 is a public-domain program that simulates the hourly energy performance of a building, incorporating information on its climate, type of building envelope, equipment use, and occupant schedules (U.S. Dept. of Commerce, 1980). For its climate input, DOE-2 uses hourly weather tapes which are available from a number of sources, including the U.S. National Oceanic and Atmospheric Administration (NOAA). The weather data, generally from a local airport, are taken to be representative of conditions around the modeled building. **Table I**, below, lists the weather variables required by DOE-2.

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[1] An urban canyon is the "canyon" formed by rows of buildings along a street.

DOE-2.1C CLIMATE INPUT	
VARIABLES SPECIFIED HOURLY	VARIABLES SPECIFIED MONTHLY
• Drybulb temperature* • Wetbulb temperature* • Wind Speed* • Wind Direction* • Solar--Either measured surface-level values for direct normal and diffuse horizontal energy fluxes or cloud amount (in tenths of coverage) and cloud type (code for cirrus, stratus, etc.) • Atmospheric Pressure*	• Clearness number (atmospheric transmissivity) • Sub-surface ground temperature (single value, depth unspecified)

Table I. Hourly and monthly weather data required by the building-energy analysis program DOE-2.

* Specified at ~ 10 meters above surface.

The direct effects of shading and changes in surface-reflection properties of a single building can be modeled with DOE-2 alone. These direct effects of trees and albedo modifications are relatively well understood and are presently adequately modeled. More challenging is the quantification of effects which DOE-2 cannot directly simulate: the changes in conditioning variables from additional trees and shrubs within a city; the changes in conditioning variables from changes in albedo, thermal mass, and conductivity of the urban surface; and the effects of parks and greenbelts on conditioning variables outside park boundaries. Understanding these effects is important for designing optimal cooling strategies for a particular urban climate. The primary objective then of the climate/building-energy simulation effort is to supply DOE-2 with climate input reflecting various combinations of trees and surface color changes. A conceptualized version of these objectives is presented in **Figure 1**.

In the studies of Huang et al. (1987) and Taha et al. (1988), the original weather tapes were modified, rather than replaced, by the output of a climate model. A climate model was first run with a set of base-case conditions. The conditions were modified in subsequent runs and the difference in weather variables between the modified and base-case conditions were added to the original weather tape. The advantage of this method is that the climate model is not used to predict absolute weather, only to predict the modifications in weather from changes in surface characteristics. To ensure accurate predictions of energy use, we will continue to use this method. However, a caution that should be emphasized is that airport weather data may not match the simulated, base-case weather--we would not expect them to if the urban-surface parameters were different from those at the airport. In the future, we should ensure that the conditioning variables measured at an **airport** site are first modified to reflect the existing **urban** conditions before we introduce the effects of changes to the urban surface. Input other than the conditioning variables, such as shown in **Table I**, will be read from the tapes during periods which match the conditions assumed to exist during the simulations.

URBAN CLIMATE MODELS

Many investigators have applied mathematical models to analyze the effect of the urban environment on climate (Oke, 1974, 1979; Bornstein, 1984). Oke (1979) reviewed a great number of these models and introduced two classifications which distinguish the models based on the scale of their vertical domain: canopy-layer models and boundary-layer models. Canopy-layer models focus primarily on that portion of the city which is roughly below the building roof height (**Figure 2**). In contrast, boundary-layer models focus primarily on the region of the atmosphere above building roof height (**Figure 3**). These categories are useful because all models, even one-dimensional models, have a vertical dimension. However, meteorologists and climatologists frequently use the terms "microscale," "local-scale," and "mesoscale" to classify these same models. The micro-, local-, and mesoscale classifications distinguish models based on the scale of their horizontal domain. The horizontal domain of microscale models is about 100 meters, while the horizontal domain of mesoscale models is about 100 kilometers. The local scale fits between micro- and mesoscales, roughly 100 meters to 10 kilometers. In general, canopy-layer models are microscale models and boundary-layer models (even one-dimensional models) are either local-scale or mesoscale models.

Determining the effect of changes in urban-surface parameters on climate around a building involves accounting for interaction between "scales of climatic influence" ranging from the microscale to the mesoscale. An urban microscale climate is affected by changes in an individual building or backyard. If only a single backyard were modified, a purely microscale description would suffice. But if one considers changes in many backyards, the change in the surface energy balance becomes significant and the mesoscale climate is also affected. Advection couples individual sites to create a mesoscale region of influence that cannot be considered the sum of individual microscale regions. In addition, vertical mixing is an important mechanism for heat and moisture exchange in the atmosphere. If surface changes significantly influence the planetary boundary layer, a predictive model for conditioning variables must estimate boundary-layer dynamics, which extend well beyond the microscale level. The coupling of these scales contributes largely to the difficulty of quantifying changes in the urban environment on building energy use. However, since our intent is to quantify the city-wide cooling from light surfaces and trees, it is critical to consider changes in the boundary-layer when predicting changes at the level of buildings.

Urban Canopy-Layer Models

General Description. Canopy-layer models (CLMs) describe phenomena which exist below roof height, within the canopy layer. They resolve the scale of one or two buildings. (See **Figure 2**.) Most CLMs do not predict conditioning variables. Typically they use a set of energy-balance equations for various surfaces within the canopy to predict surface temperatures and surface fluxes. Bulk atmospheric properties, such as air temperature and wind speed are often assumed or provided by field measurements. The energy-balance equations include net shortwave and longwave radiation inputs to the surface and, in some cases, an input contribution from anthropogenic heat sources. Heat is dissipated by longwave re-radiation, conduction to buildings and street surfaces, turbulent diffusion of sensible and, usually, latent heat. A few models contain algorithms for evaluating the energy balance within vegetated canopies. Models may be either two dimensional, assuming streets of infinite length, or three dimensional, allowing buildings or blocks to be spaced irregularly.

Even if a CLM does predict conditioning variables, using finite-difference solutions to fluid transport equations for a turbulent atmosphere, it still relies on specified boundary conditions to link it to climate outside the canopy. By definition, existing CLMs do not interactively link the canopy to the rest of the planetary boundary layer. Because CLMs require boundary conditions which are determined at the

mesoscale level, even those which predict conditioning variables cannot simulate changes in building energy that occur as a result of the local-scale and mesoscale dispersion of the climatic effects of modifications made throughout a city.

Some models do not predict the dissipation of input energy. Many of these models, concentrate on estimating the radiation budgets of urban surfaces in order to predict net radiative parameters for urban street canyons. For example, there are models which predict urban albedo as a function of the geometry of urban street canyons. The potential uses of CLMs can be more fully explored after considering some specific examples. The main features of the models reviewed in this section are presented as a matrix in **Table II**. Results from a CLM are presented to illustrate the output it supplies.

Reviews and Examples. Terjung and Louie (1974) modeled urban absorption of shortwave and longwave radiation and the dissipation of that input via re-radiation, conduction, convection, and evaporation. This model was the first detailed three-dimensional CLM. To describe the complex radiation exchange that occurs in an urban landscape, the model considers an "ideal" city in which all streets are either parallel or perpendicular (N-S or E-W). The model includes a very simple representation of a typical building (four walls, glazing, a roof, and a floor) within which building interior temperatures are specified. A "radiation neighborhood" is defined by the facing sides of two adjacent buildings, their roofs, and the street connecting them. An average view factor is computed for sunlit and shaded portions of all sets of surfaces within the radiation neighborhood. A distinguishing feature of this model is the systematic geometric determination of shading from obstructing buildings within a specified radius.

Given temporal, geographical, and climatic input data--including hourly values of wind speed, relative humidity, and air temperature--the model generates the following hourly output for streets, walls, rooftops and lawns: absorbed diffuse, direct, and terrain-reflected shortwave radiation; total incident and emitted longwave radiation; net global radiation; convection; conduction; evaporation; and surface temperatures. These variables are available for streets, walls, rooftops, and lawns. Anthropogenic heat is not modeled. The model does not predict conditioning variables and omits any feedback between surface heating and air temperature. The input conditioning variables apply to all structures and are not modified by surface heat fluxes.

Terjung and O'Rourke (1980) described a similar model, which has the added capability of modeling vegetated canopies. This algorithm uses a heat balance equation of a leaf to construct an aggregated description of a multi-tiered canopy. Like the model of Terjung and Louie (1974), this model only predicts surface fluxes and surface temperatures. Because conditioning variables are fixed, the model does not predict the advection of energy or moisture from one portion of the system to another.

Figure 4 shows the results of a sample simulation of a dry urban canyon shown in **Figure 5**. The input weather data and surface characteristics, chosen to represent conditions in Los Angeles, are identical to the sample input data presented in Terjung and O'Rourke (1980).

Arnfield (1982) presented a two-dimensional model for computing net radiative parameters of an urban street canyon. The parameters computed are the net reflection coefficients for direct and diffuse shortwave and incoming longwave radiative fluxes and the emissivity for outgoing longwave radiative flux. As input, the model requires the incoming shortwave and longwave radiation and the reflectivity, emissivity, and temperature of individual surfaces. Arnfield's approach to modeling the redistribution of radiation within the urban canopy is similar to that presented by Terjung and Louie (1974), although there are important differences. The Arnfield algorithms give a more general treatment of the diffuse radiation and a more complete computation of the multiple reflection process. In contrast to the model of Terjung and Louie, the Arnfield model can be used investigate the effects of spatial variations in building

FEATURES OF REPRESENTATIVE CANOPY-LAYER MODELS			
FEATURES	MODELS		
	TERJUNG (3-D)	ARNFIELD (2-D)	SIEVERS (2-D)
DOMAIN	• Urban canyon strip; can be repeated to model city with N-S & E-W oriented blocks • Substrate to top of buildings, excludes atmosphere	• Infinite urban canyon strip; can be repeated to model city with ~ 2-D canyons • Street surface to top of buildings, excludes atmosphere	• Domain includes atmosphere, represented with finite-difference grid • Substrate to ~ 10 building heights
EQUATIONS MODELED	• Energy balance of urban surfaces at the centerline of an urban strip • Formula for view factors	• Radiative energy balance of urban surfaces at the centerline of an urban strip • Formula for net reflection coeff.'s & emissivities	• Energy balance of urban surfaces • Incompressible continuity • Vorticity-mode momentum transport • Energy & humidity transport • Mixing length formula for exchange coeff.'s • Pollutant transport
SPECIAL FEATURES	• Shading by objects outside modeled strip • Moist surfaces • Optional veg. canopy • Default material properties for windows, walls, roof, & street • Fixed building interior temp.	• Calculates net reflection coeff.'s & emissivities for an urban canyon • Multiple reflections between canyon surfaces • (Subroutines only, user provides main program)	• Calculates atmospheric variables • Anthropogenic heat • Moist surfaces • Default material properties for buildings & streets • Fixed building interior temp.
INPUT	• Month, latitude, elevation • Hourly profiles of temp., relative humidity, wind speed, pressure, & atmospheric dust • Canyon geometry	• Solar irradiation, solar angles, LW radiation from sky • Reflectivities, emissivities, & temp.'s of surfaces • Canyon geometry & orientation • (Input as arguments to a subroutine)	• Date, location, atmospheric optical depth • Surface roughness of street • Specification of atmospheric variables at the top of the model • Canyon geometry, orientation • Anthropogenic heat
OUTPUT	• Energy fluxes & temp.'s for individual surfaces • Net energy flux out of canyon • All quantities specified hourly	• Radiative energy fluxes for individual surfaces & net canyon • Net reflection coeff.'s & emissivities • Call to subroutine as needed	• Atmospheric variables at grid locations • Energy fluxes & temp.'s at surface grid locations • Pollutant concentrations (Optional) • Output at multiple of model time step
ESTIMATES OF CPU RUN TIME ON VAX†	~ Seconds (based on model runs)	~ Seconds (based on comparison of code algorithms with those of TERJUNG)	~ Minutes (based on discussion with model originator, Zdunkowski)

Table II. Main features of representative canopy-layer models: TERJUNG refers to Terjung and O'Rourke (1980); ARNFIELD refers to Arnfield (1982); SIEVERS refers to Sievers and Zdunkowski (1986).

†CPU estimates representative of a 24-hour simulation of a single urban canyon. These estimates vary with the complexity of the urban canyon modeled, the options included, and the length of time simulated.

materials because it allows radiative parameters of individual surfaces to be varied explicitly.

While the Arnfield model is more complete in its treatment of the radiative properties and the reflection process, it assumes a two-dimensional geometry (no street intersections) and does not attempt to provide a simulation of the overall urban energy budget; that is, the model does not simulate dissipation of the input energy.

Sievers and Zdunkowski (1986) presented a model which does predict conditioning variables (velocity, temperature, and moisture fields) in a two-dimensional urban canyon. The top of the model is well above the canopy layer, roughly at ten building heights. However, since the focus of the model is on the canopy layer, we classify it with the CLMs. Whereas the Terjung and Arnfield models use algebraic equations to calculate surface quantities, this model uses finite differences to compute flow properties as well. The model uses a stream-function vorticity method appropriate for a turbulent atmosphere to solve the momentum equations and predicts turbulent exchange coefficients with a mixing-length formula. The energy budget of the canopy is described by a heat-transport equation which accounts for anthropogenic heat.

The model includes a transport equation for water vapor, a heat-conduction equation for the urban substrate, and a radiation balance equation which accounts for the multiple reflections of light between the walls and the base of the buildings. The shortwave radiation flux in the block configuration is calculated by the earlier model of Brühl and Zdunkowski (1983), while the longwave flux is obtained according to Zdunkowski and Brühl (1983). The water vapor flux is specified in terms of an evaporation coefficient, which is always assumed to be zero at vertical walls. The temperature gradient on building surfaces is proportional to the difference between the surface temperature and a fixed building interior temperature. For ground surfaces, the gradient is determined by the locally one-dimensional heat-conduction equation.

In making comparisons between this model and models which do not predict conditioning variables, one should note that this model requires significantly more computer resources to execute. (See **Table II** for example.) In three-dimensional models that predict conditioning variables, the amount of resources required becomes even greater.

Urban Boundary-Layer Models

General Description. Boundary-layer models (BLMs) focus on the atmosphere above the canopy layer. Some BLMs extend only to the top of the turbulent surface layer[2], roughly 50 meters in height, but more frequently they extend to the top of the boundary layer, as much as one to two kilometers in height depending on wind speed and surface heating. (See **Figure 3.**) In contrast to the CLMs, many existing BLMs provide dynamic feedback between the urban surface and the boundary layer. BLMs may also include predictions of the "mixing height," which critically effects conditioning variables in the boundary layer since it effectively determines the volume into which heat and moisture are mixed. Frequently, BLMs make use of these features to predict conditioning variables as well as surface fluxes and temperatures. Two- and three-dimensional BLMs include the effects of spatial inhomogeneity. Many BLMs predict surface equilibrium temperature by iteratively solving an energy-balance equation across the urban ground-to-air interface. The urban surface is not explicitly resolved within these models but, instead, is characterized by a number of global terrain parameters, such as average moisture availability, albedo, and roughness height. Some BLMs include the effects of a moist subsoil; a subset of these also

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[2] Models which do not include the upper portion of the boundary layer have also been called "surface boundary-layer models" (Bornstein, 1984).

include a representation of the effects of vegetation.

Most, if not all, BLMs contain a turbulent surface layer. This is because the dynamics of the atmosphere near the surface are extremely complex, especially when the terrain has large roughness elements. Rather than resolving the flow within the turbulent surface layer with a finite-difference representation, the BLMs use similarity theory, based on dimensional and empirical analyses, to represent the flow algebraically. In the mixing layer, the scales of the largest turbulent eddies are larger than they are in the surface layer. BLMs which contain a mixing layer are able to represent the transport of energy, momentum, and--frequently--moisture with a finite-difference approximation in this region. To represent the turbulent flow in both the mixing layer and the surface layer, BLMs use turbulent exchange coefficients which are either specified by specified profiles or calculated based on parameterizations of the flow.

To provide a more tangible basis for discussing the application of BLMs, the next section reviews a number of representative models from the literature. The main features of the models reviewed are presented as a matrix in **Table III**. Results from two of the models are presented to illustrate the output they supply.

Reviews and Examples. Outcalt (1972a, 1972b) developed a one-dimensional model, expanding primarily on the work of Myrup (1969) and Lettau (1969). The model is particularly notable for its simplicity, but retains elements typical of many BLMs. The model predicts surface heat fluxes and surface temperatures by iteratively solving a surface energy-balance equation. It includes only one atmospheric layer, a turbulent surface layer across which heat and moisture are assumed to turbulently diffuse. Within this layer, the turbulent heat fluxes are calculated using a form of mixing-length theory appropriate for the surface layer in a neutral atmosphere. However, Outcalt added an empirical correction factor to account for the effect of non-neutral stability on the diffusivities. Temperature, moisture, and wind speed at the top of the surface layer are fixed, but the height of the layer itself is allowed to vary as a function of wind speed and surface roughness. The substrate heat flux is estimated using a central-difference approximation to the heat-conduction equation in a homogeneous slab for which thermal diffusivity is empirically related to the surface wet fraction.

In some calculations, the model simulates the effects of vertical terrain elements. For example, a "silhouette ratio" is defined as the ratio of vertical silhouette area to the horizontal lot area (Lettau, 1969). The incident solar radiation, beam and diffuse, includes a contribution, proportional to the silhouette ratio, to represent effects from vertical surfaces. The ratio of shaded terrain is roughly estimated as a function of solar zenith angle. These approximations are introduced not only to include a contribution from diffuse radiation on rough terrain, but also to "parameterize" the shading within the canopy and locally increased absorption of direct radiation on vertical surfaces. Similarly, the thermal radiation flux from the surface is scaled by the view factor--one minus the silhouette ratio--again to represent the energy balance among the canopy terrain elements.

Outcalt's model requires the input of a constant air temperature, relative humidity, and wind speed at the height of the surface layer, in addition to a number of geographical variables and surface parameters. A sample of the model output, surface temperature and energy flux components, is shown in **Figure 6**. The input data were derived from the Sacramento study of Myrup and Morgan (1972).

Carlson and Borland (1978) produced a more detailed one-dimensional boundary-layer model. (See also Carlson et al., 1981.) This model is structured into four layers: 1) a substrate, with homogeneous thermal properties, but two moisture levels; 2) a transition layer containing surface obstacles where conductive and turbulent heat exchange coexist; 3) a turbulent surface layer 50 meters in height; and 4) a mixing layer with a height dependent on the amount of sensible heat passed from the surface layer. The

FEATURES OF REPRESENTATIVE BOUNDARY-LAYER MODELS

FEATURES	MODELS		
	OUTCALT (1-D)	CARLSON (1-D)	BORNSTEIN (3-D)
DOMAIN	• Substrate to top of surface layer • Model top is variable, a function of surface roughness & wind speed	• Substrate, viscous sublayer, surface layer, mixing layer • Model top is variable, given by Tennekes parameterization	• Substrate, surface layer, mixing layer • Model top is fixed at ~ 2 km
EQUATIONS MODELED	• Energy balance at effective surface • Simple empirical predictor for surface-layer height	• Energy balance at effective surface • Predictor for mixing height • 1-D momentum, energy, humidity transport in mixing layer (daytime & nighttime formulations)	• Energy balance at effective surface • 3-D Vorticity-mode, hydrostatic momentum transport • Energy & humidity transport • Optional turbulent kinetic energy transport
SPECIAL FEATURES	• Parameterization of canopy effects: surface shading, viewfactor	• Calculates atmospheric variables at 50 meters • Model can be "inverted" to calculate surface parameters from surface temp.'s observed from satellite • Optional veg. algorithms • Moist subsoil	• Calculates atmospheric variables at 12.5 meters over inhomogeneous flat, rough surface • Moist subsoil • Optional mixing-length formula for exchange coeff.'s • Anthropogenic heat • Variable grid spacing
INPUT	• Latitude, solar declin., atmospheric dust • Time-averaged air temp., relative humidity, pressure, & wind speed • Soil thermal properties, surface roughness, wet-area fraction • Effective albedo, emissivity, sky radiant temp.	• Date, location • Atmospheric input, e.g. sounding data • Soil thermal properties, surface roughness, initial moisture availability • Effective albedo, emissivity • Plant canopy input, e.g. stomatal resistance • Increments to parameters determined by "inverted" model	• Date, location • Specification of atmospheric variables at the top of the model • Grid spacing • Soil thermal properties, surface roughness, albedo, emissivity, initial soil moisture profiles and parameters • Anthropogenic heat • (Properties vary over 2-D surface)
OUTPUT	• Energy fluxes & temp.'s at effective surface • Temp. profile in soil • Output hourly	• Profile of atmospheric variables, lowest grid at 50 meters • Energy fluxes & temp.'s at effective surface • Output at intervals > 240 sec • "Inverted mode" gives surface parameters	• Atmospheric variables at grid locations, lowest grids at 12.5 meters • Energy fluxes & temp.'s at effective surface • Soil temp. & moisture profiles • Output at multiple of model time step
ESTIMATES OF CPU RUN TIME ON VAX†	~ Seconds (based on model runs)	~ Seconds (based on model runs)	~ Hours (based on model runs)

Table III. Main features of representative boundary-layer models: OUTCALT refers to Outcalt (1972a, 1972b); CARLSON refers to Carlson et al. (1989); BORNSTEIN refers to Bornstein et al. (1987).

†CPU estimates representative of a 24-hour simulations
These estimates vary with the options included and the length of time simulated.

model is used primarily to simulate surface fluxes and surface temperature, but it also estimates conditioning variables at a height of 50 meters. In the original model, surface fluxes are assumed to originate from a bare soil. More recently, however, Carlson et al. (1989) modified the model to include the effects of a vegetated surface.

Across the transition layer and the surface layer, the turbulent heat fluxes are calculated following the Monteith resistance formulation (Monteith, 1975). The turbulent exchange coefficients for heat and momentum in the surface layer are specified using a diffusivity integral during the day, and a scheme based on the bulk Richardson number at night. A logarithmic form of the heat-conduction equation is solved by finite differences to find the substrate heat flux. Soil moisture varies at two levels in the substrate layer and produces changes in the surface moisture availability. Anthropogenic heat is not included in the model. Radiation is calculated using a one-layer radiative transfer model. Albedo, for a bare or vegetated surface, can be supplied or calculated internally.

To more accurately predict the phase and amplitude of the surface temperature, a mixing layer is included to allow temperature and humidity to vary at the top of the surface layer. The mixing depth calculation is based on the scheme of Tennekes which relates the height to the flux of sensible heat from the surface layer (Tennekes, 1973; Zilintinkevich, 1975; Tennekes, 1975). Within the mixing layer, turbulent diffusivities of momentum and water vapor are assumed to follow an adjustable profile. The model requires a set of initial atmospheric conditions. These are provided by radiosonde measurements, which include air temperature, pressure, wet bulb depression, wind speed and wind direction at a number of sounding levels.

One of the most useful features of this model is what the authors term the "inversion," mode. In this mode, the function of the model is the reverse of its usual function: given a pair of surface temperatures measured at different times during the day, the model calculates two surface parameters--the effective value of moisture availability and thermal inertia. The surface temperature measurements supplied to the model should be determined remotely from aircraft or satellite measurements to obtain a spatially-averaged measurement for a local-scale region. The value of this feature is that it allows one to calculate effective surface properties that can then be used in subsequent simulations. This is an inventive way of overcoming the difficulty, encountered in all BLMs, of specifying surface parameters to represent an inhomogeneous surface.

Results of a sample simulation, in the non-inverting mode, are shown in **Figure 7**. To produce these results, the model was run without the vegetation algorithms, using input data of Carlson et al. (1989). These results show that the model predicts unrealistic jumps in the air temperature at the transition between day and night modes.

Bornstein et al. (1987) extended the two-dimensional vorticity-mode BLM of Bornstein (1975) to three dimensions by using a vector stream function. The model simulates time-varying, three-dimensional distributions of velocity, temperature, and sub-saturation moisture in the atmospheric boundary layer. Within the model, the earth-atmosphere system is divided into three layers: 1) a sub-surface soil layer in which soil temperature and moisture are obtained from finite-difference solutions to diffusion equations; 2) a turbulent surface layer in which mean field variables are predicted from one-dimensional, analytic equations; and 3) an upper mixing layer in which the hydrodynamic and thermodynamic equations describing atmospheric transport are solved by finite differences.

The model is a hydrostatic model; as such, it assumes horizontal length scales in the boundary layer are large compared to vertical length scales. This assumption simplifies the calculation of vertical velocities and reduces the amount of numerical computation[3]. However, the assumption also limits the

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[3] Note that even with this reduction, three-dimensional BLMs require significantly more resources than one-dimensional models. (See for example **Table III**.)

horizontal resolution of the model. In Bornstein's three-dimensional model, 1.5 kilometers is about the minimum horizontal grid cell dimension. Since several grids are required to resolve a given feature, this limitation restricts the use of this model to relatively large cities.

Turbulent exchange coefficients in the mixing layer can be computed by either of two methods in the Bornstein model. The first method uses an adjustable profile, while the second uses a mixing-length parameterization which allows for the advection of turbulent kinetic energy. In the surface layer, the vertical fluxes of momentum, heat, and moisture are independent of height, but vary with stability. Within the surface layer, the lowest grid points which predicts air temperature, humidity, and horizontal winds are at a height of 12.5 meters. The model does not require sounding data for initialization; it generates an equilibrium profile to match the upper boundary conditions. Anthropogenic heat flux is included in the model and is allowed to vary spatially and on a diurnal cycle.

Summary of Models

The CLMs and BLMs reviewed in this section form a representative cross-section of the various types of urban-climate models. To briefly summarize, CLMs operate on the microscale and require the specification of mesoscale conditions, either as a fixed profile in the case of the Terjung model or as boundary conditions in the case of the Sievers and Zdunkowski model. The model may or may not predict conditioning variables in the canopy; the amount of computing time required to perform the simulation increases significantly if it does.

Not all CLMs simulate the dissipation of energy input to the model. Some, such as that of Arnfield, simulate only a portion of the net energy flux. These models offer the potential to determine, for example, the albedo and net emissivity of an urban-canyon complex.

BLMs operate on the either the local-scale or the mesoscale and must parameterize the effects of the momentum, energy, and moisture exchange inputs from the canopy. BLMs, like CLMs, may or may not predict conditioning variables. Those which model both the upper boundary layer dynamics and the surface energy balance generally do predict conditioning variables, beginning at a height of about 10-50 meters.

APPLYING CLIMATE MODELS TO BUILDING-ENERGY STUDIES

Selecting an Appropriate Urban-Climate Model

Two- and three-dimensional BLMs allow us to represent the mesoscale climate, including advection and vertical mixing within the boundary layer. In contrast, CLMs cannot predict climate on the scale of the urban changes we wish to investigate. Primarily for this reason, a two- or three-dimensional BLM which predicts conditioning variables should occupy the central role in future simulations made for supplying DOE-2 with the input necessary to quantify the effects of changes in surface characteristics on building energy use. This section outlines additional reasons for this conclusion, while also describing the limitations of applying BLMs.

The most significant advantage of using a BLM, as opposed to a CLM, is that the scale of city-wide surface changes matches the mesoscale domain of the BLM. Two- and three-dimensional BLMs can be used to represent city-wide changes completely within the model domain. This is important because while the boundary conditions of a CLM could be significantly affected by city-wide modifications, those of a BLM would not.

A second important advantage of BLMs is that they have the capability to couple surface heating and cooling, surface evaporation, and surface wind defects to the mixing layer. Without knowing the effective mixing height and without the capability to model vertical mixing, it is not possible to accurately predict, for example, the cooling effects of surface evapotranspiration. This critical coupling does not exist in CLMs. Comparisons of BLMs with measured surface energy fluxes (Ross and Oke, 1988) suggest that models which include feedback between the turbulent surface layer and the rest of the atmospheric boundary layer are capable of estimating surface fluxes more accurately than models which only include a surface layer. Models with a mixing layer also appear to predict more realistic surface temperatures. Through the mechanisms of large scale advection and vertical transport, two- and three-dimensional BLMs can also simulate momentum, energy, and moisture exchange among various regions within a city. A two- or three-dimensional model thus allows us to make urban-rural comparisons.

A final advantage of using a BLM is that the conditioning variables these models predict near the ground are area-averaged quantities, where the averaging area is typically on the order of a square kilometer. In contrast, conditioning variables predicted by CLMs are provided at locations surrounding particular set of buildings--at a smaller scale than we require.

There are also several important limitations to using BLMs. From the perspective of building-energy studies, the most serious limitation of applying a BLM is the need to specify unknown surface properties. Ross and Oke (1988) compared surface energy fluxes predicted by BLMs with measured data and demonstrated the need for improved methods of determining average surface properties. Specifying surface properties for a CLM is also difficult, though less so since surfaces within CLMs are relatively well defined. In BLMs the surface is not well defined; often "the surface" is an imaginary plane whose properties must reflect those of extremely inhomogeneous terrain.

A second limitation of BLMs is that, because of their lack of resolution in representing "the surface," the conditioning variables they predict near "the surface" may not be representative of those at building height. In other words, canopy influences are not simulated. We emphasize that the predictions of conditioning variables within BLMs generally cannot be verified by measurements within the urban canopy, for example by standard 1.5 meter measurements. This is partly because the BLMs predict values averaged over grid cells, but also largely because of the idealized representation of variables within the turbulent surface layer.

Most two- and three-dimensional boundary layer models were developed primarily to investigate upper air dynamics. Consequently, they expend a significant amount of computer resources calculating wind fields above the surface layer. To perform simulations for many different cities and climates, it is important to minimize the use of computer resources. Hydrostatic models tend to be more conservative in their use of computer time than non-hydrostatic models, but require comparatively large horizontal grid dimensions (~ 1-2 kilometers) to prevent instabilities. This constraint is incompatible with resolving the effects of urbanization in small cities, or small features in large cities.

As a matter of practical concern, one final limitation should be mentioned. Both CLMs and BLMs--in particular those which predict conditioning variables--are primarily research tools in various stages of development. Documentation does not exist for most of these models. Although these models have been used successfully for specific applications by their authors, the task of importing the codes and using them for other applications remains a difficult one.

Future Prospects

In order to successfully apply BLMs to predict surface level climate, the limitations presented in the previous section must be overcome. **Figure 8** presents a more detailed version of the outline given in **Figure 1** and summerizes the main points of this section.

Improved methods of developing accurate input surface parameters are particularly important and deserve the highest priority. Several methods of improving the accuracy of these input parameters should be pursued. One possibility is that CLMs may be used directly to generate surface parameters. Models which predict albedo and net emissivities from various block structures and building surface characteristics (Arnfield, 1982; Aida and Gotoh, 1982) appear particularly useful in this respect.

A second possibility is that the output of a CLM of a "typical" urban canyon could be incorporated into interactive methods of determining surface parameters. For example, a CLM could be used to generate a lookup table for energy fluxes leaving the canopy as a function of land type and spatially averaged surface temperature and conditioning variables. A BLM could be used with an assumed set of surface parameters (e.g., albedo, moisture availability, and thermal inertia) to predict fluxes in the surface layer. These surface layer fluxes could then be compared to those determined using the lookup table. An optimization algorithm could iteratively adjust a surface parameter to produce surface layer fluxes which "most nearly" agree with the fluxes determined from the lookup table. This method makes a number of assumptions, the most important of which is that fluxes produced from CLMs are reliable. However, predicting moisture availability in urban canopies remains an unresolved problem. (See, however, Oke (1989) of these proceedings and Grimmond et al., 1986.) Without a model which accurately determines the available moisture in urban canopies, the relative contributions of sensible and latent heat will not be correctly determined.

Overcoming the difficulty of accurately specifying surface parameters will ultimately depend on detailed observations of climate and physical processes within cities. Ground based observations are needed for developing an understanding of moisture availability in urban canyons, as well as for developing correlations between land-use zones and area-averaged estimates of quantities such as thermal mass and conductivity. For example, if hourly profiles of the various energy fluxes leaving urban canyons or vegetated urban canopies were determined for a wide range of different land types and under different weather conditions, this would provide a more tangible basis for selecting surface parameters than currently exists.

Similarly, data from aircraft and satellite observations should also be used to develop more reliable estimates of surface parameters. These data can be used to determine the albedo parameter and to determine surface temperature and levels of vegetation, which can then be used to estimate additional parameters. Although large quantities of such data exist--particularly satellite data--the data are expensive and a significant amount of work is involved in discovering which sources of data are useful.

Finally, we should pursue techniques which combine the use of measurements and models for determining surface parameters. Carlson et al. (1981) demonstrated the use of their 1-D model in an "inverted" mode to uniquely predict moisture availability and ground thermal inertia using a pair of satellite measurements of surface temperature. This technique could be applied to other BLMs as well.

Another important consideration in using a BLM to predict conditioning variables near the surface is that the output may not accurately represent conditions within the canopy. This is especially critical for wind speeds which can vary significantly with height and which have a large effect on building energy use. In some cases, parameterizations have been introduced to correct for conditions **within** the canopy. This is the intent, for example, of the parameterizations based on silhouette ratio introduced in Outcalt's model (Outcalt, 1974a,b). These "canopy parameterizations,"--such as shading and viewfactor--which can adjust for effect of being in among the vertical elements which compose the canopy, require further investigation. Such parameterizations differ from "surface parameterizations"--such as moisture availability and albedo--which are used to describe the spatially-averaged energy balance at the surface.

An approach that explicitly adjusts the output of a mesoscale model to the canopy level was given by Eichhorn et al. (1989). Rather than parameterize the canopy layer effects, they used the output of a three-dimensional BLM to produce boundary conditions required for a three-dimensional CLM. Both the BLM and the CLM predict conditioning variables. A computationally less expensive method of explicitly adjusting the output from a BLM, would incorporate CLM algorithms directly into the DOE-2 model. For example, this might be appropriate for adjusting wind speeds and for including the contribution of radiant energy reflected from vertical structures to the modeled building.

We should emphasize that, for our analyses, the CLM algorithms could serve three distinct purposes. The first is to help establish surface parameters to be used in BLM's. The second is to obtain conditioning values representative of **"average canopy"** conditions, values representative of the 2-10 meter level. The third is to obtain conditioning variables in a **specific canopy**--for example one with more or less vegetation than the average. From the perspective of determining area-averaged conditioning variables, the first and second uses are most important. The third use of the CLMs would effectively refine our area-average estimate of the conditioning variables.

CONCLUSION

Energy analysts have begun to consider the costs in added building energy consumption of constructing cities without regard to their climate-modifying effects. The studies of Huang et al. (1987), Taha et al. (1988), and Akbari et al. (1988) demonstrate the potential energy benefits of planting trees and increasing the albedo of urban surfaces. Following the example of Huang et al. (1987) and Taha et al. (1988), this paper explores how climate models can be used together with the building-energy model DOE-2 to estimate the effects of changes in urban-surface characteristics, and consequent changes in urban climate, on the energy required in urban buildings. In particular, we are concerned with predicting the effects of city-wide changes in urban albedo and vegetative cover on cooling energy requirements. We would like to estimate the importance of long-range effects of these changes as well as the effects of changes in the immediate surroundings.

We have identified four climatic variables, that we call "conditioning variables," used by the building-energy program DOE-2 for simulating building energy use. These four variables determine the amount of space conditioning required in buildings and may be significantly affected by changes in characteristics of the urban surface. The conditioning variables include drybulb temperature, wetbulb temperature, wind speed, and wind direction. For the purposes of analyzing building energy use, the conditioning variables are required at a height of about two to ten meters, averaged over an area of about a square kilometer and over the period of an hour. After reviewing different types of urban-climate models, we evaluate the usefulness of such models for estimating changes in these averaged conditioning variables within the urban canopy from surface changes made on the scale of an entire city. A model with this capability can be used in conjunction with DOE-2 for predicting changes in the energy requirement of a typical building.

On the city scale, or mesoscale, evaporative cooling from increased vegetation can reduce the input of sensible heat and decrease the drybulb temperatures throughout the city. Similarly, if light surfaces replace dark surfaces over a significant fraction of the city, the net gain of radiant energy is reduced, producing lower city-wide temperatures. To quantify the importance of mesoscale advection and the effects of thermally driven mixing between the canopy-layer atmosphere and the boundary-layer atmosphere above it, it is critical to consider changes in the boundary-layer when predicting changes at the level of buildings. We therefore find the use of two- or three-dimensional boundary-layer models (BLMs) indispensable. However, BLMs cannot describe canopy-layer effects which can significantly alter conditioning variables at the height of buildings. Therefore, certain aspects of canopy-layer models (CLMs) are also necessary.

The most significant limitation of BLMs arises from the difficulty of specifying surface parameters to represent various land types. The determination of moisture availability in cities is particularly troublesome.

A suggested outline for using climate models together with DOE-2 is given in **Figure 8**. A two- or three-dimensional BLM occupies the central nexus in a network of climate algorithms. However, also required are improved methods for specifying surface parameters and canopy-layer algorithms to improve the description of conditions within the canopy layer. Improved parameterizations of average surface properties needed to run the BLM will depend largely on detailed analyses of ground-based, aircraft, and satellite observations. Methods of combining boundary-layer models and canopy-layer models may provide more accurate surface parameters, once the difficult problem of determining moisture availability in canopies is resolved. Using satellite observations in conjunction with a BLM to determine surface parameters (Carlson, 1980) appears particularly useful.

The output of the climate model is not used directly to run DOE-2. Instead, the difference in weather variables between the modified and base-case conditions are added to the original weather tape to produce modified weather data. Canopy-layer algorithms may be used to adjust surface-layer variables produced by the BLMs to improve the description of canopy conditions; though perhaps the most effective method of including canopy effects--such as the radiative exchange between nearby buildings--is to incorporate canopy-layer algorithms directly into DOE-2. Finally, with the modified weather data, building operations, and buildings characteristics, a version of DOE-2 can be used to predict building energy use.

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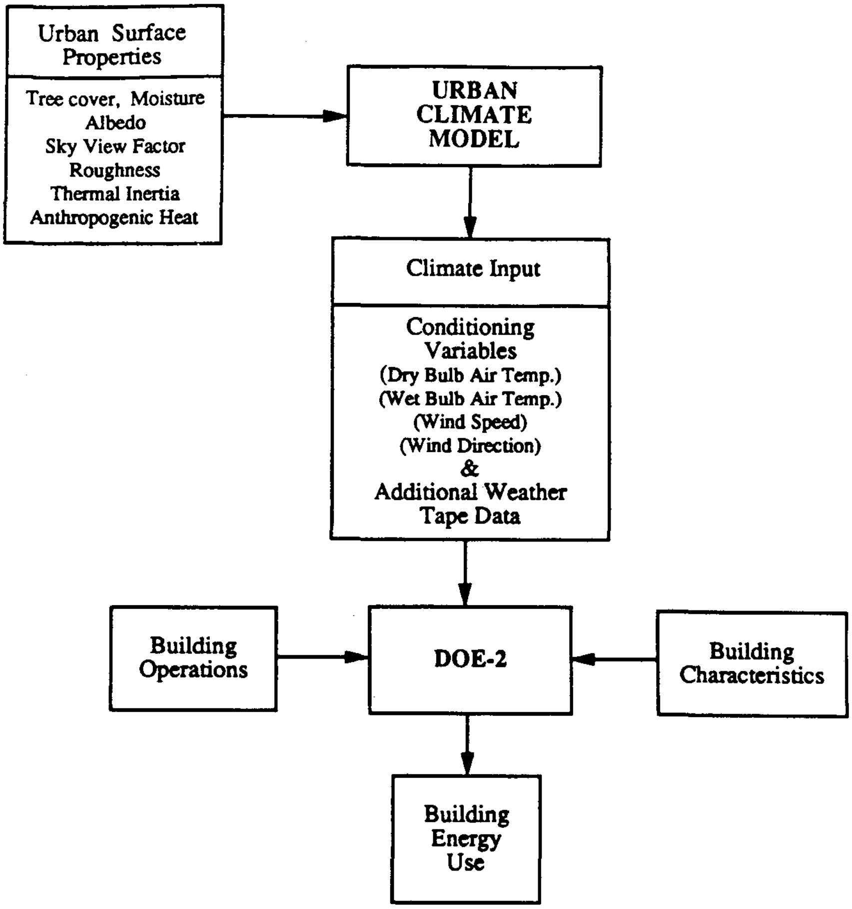

Figure 1. The process of combining an urban climate model with DOE-2, a building-energy model, is illustrated in schematic form.

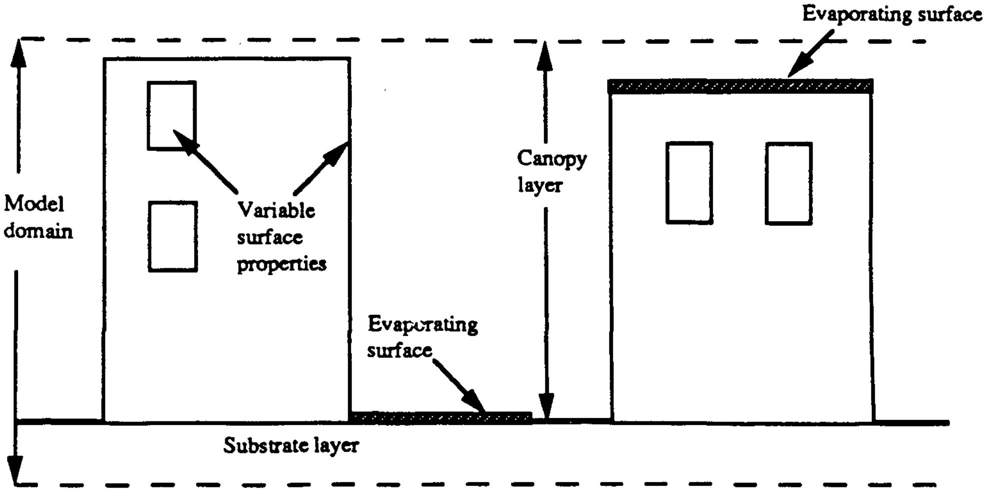

Figure 2. Schematic of the domain of a typical canopy-layer model, shown here to be divided into a substrate layer and a canopy layer. The "urban canyon" is formed between the rows of buildings.

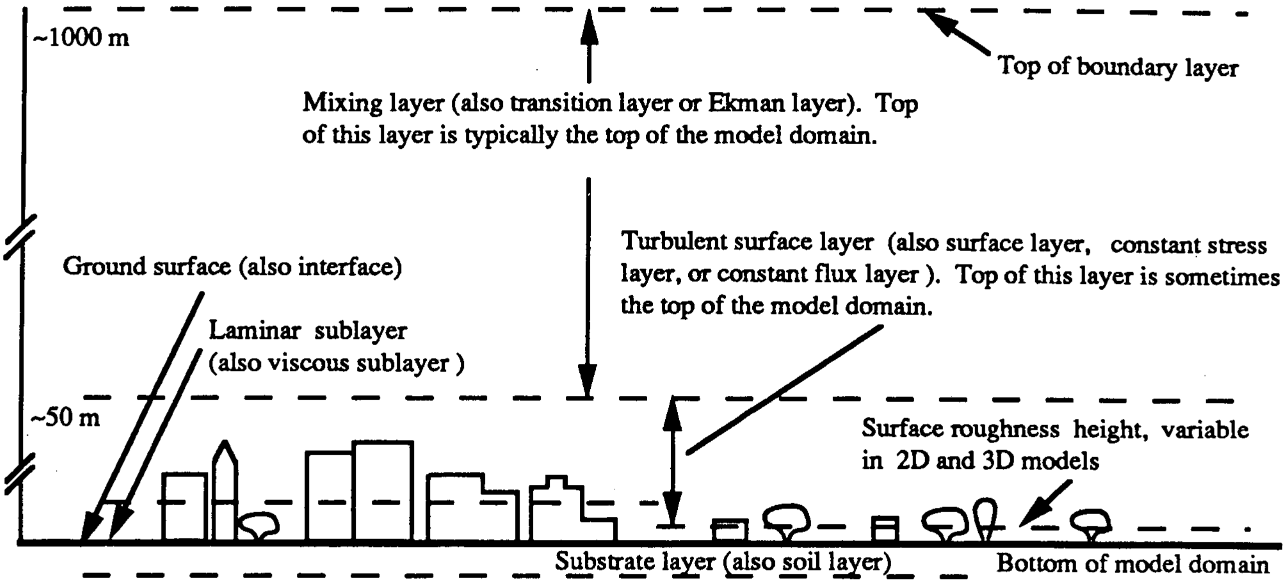

Figure 3. Schematic of the domain of a typical boundary-layer model (Not to scale). The domain has been divided into several layers*: the substrate layer, the laminar sublayer, the surface layer, and the mixing layer. A typical roughness height, a parameter used in many boundary-layer models, is also shown. The combination of all the layers above the surface is referred to as the planetary boundary layer. Frequently, the laminar sublayer, a very thin layer (~ several millimeters) adjacent to surfaces, is ignored in boundary-layer models. Note that although individual structures are shown in this figure, they are not within the resolution of boundary-layer models.

*The dimensions of the layers shown in this figure approximate the daytime structure of the boundary layer.

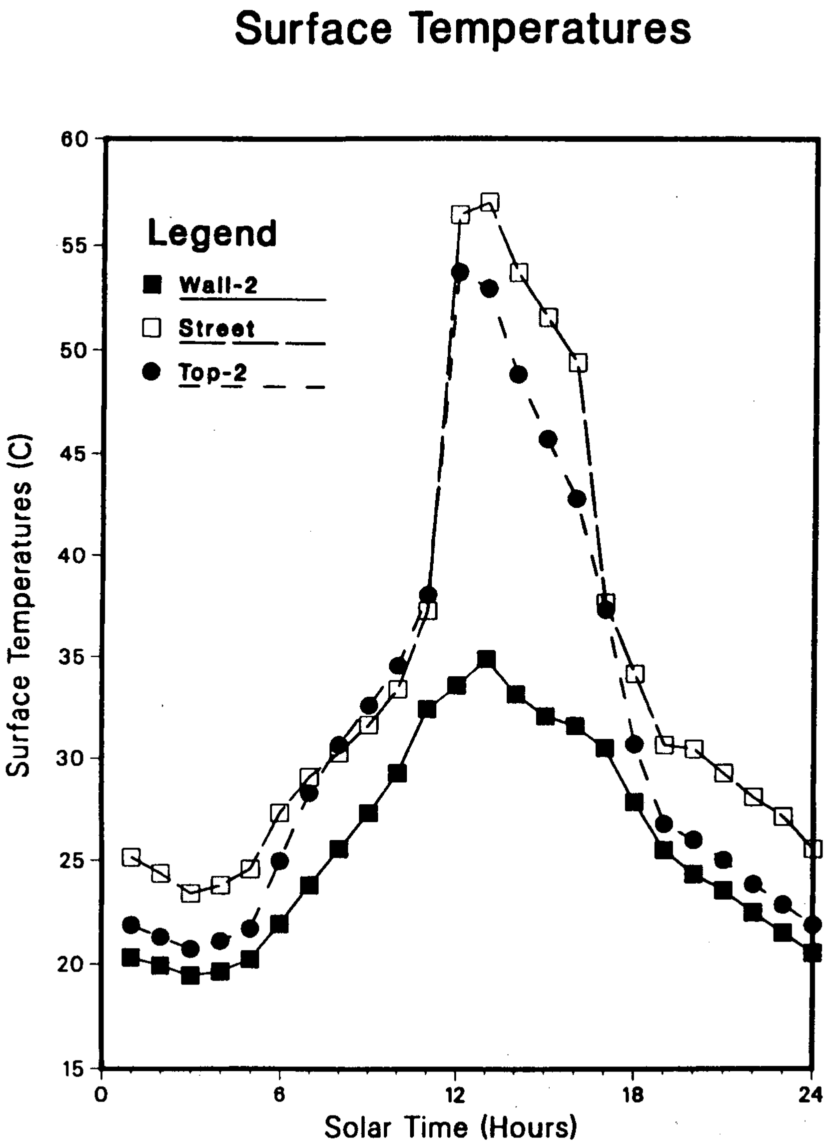

Figure 4a. TERJUNG MODEL. Surface temperatures predicted for a dry urban canyon in Los Angeles in August using the Terjung canopy-layer model (Terjung and O'Rourke, 1980). The input weather data and surface characteristics are those presented in Terjung and O'Rourke (1980). The block configuration--including Wall-2, Street, and Top-2--is shown in Figure 4.

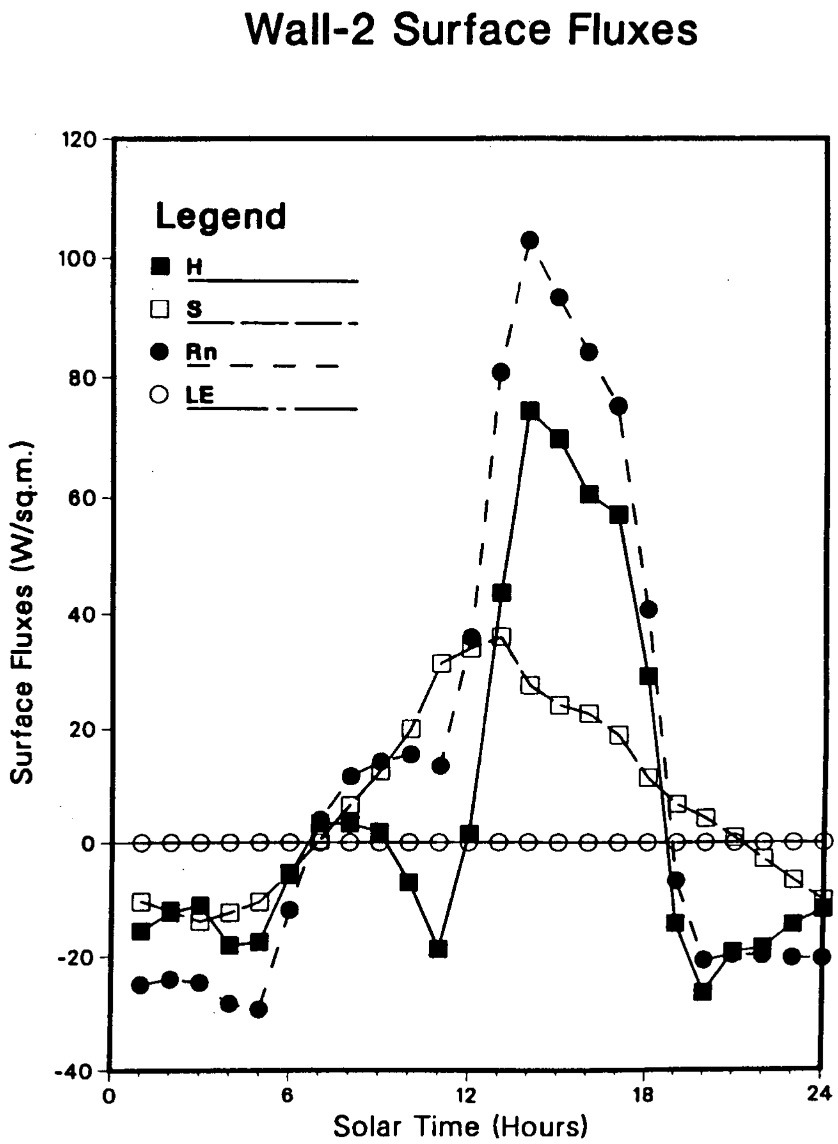

Figure 4b. TERJUNG MODEL. Surface fluxes predicted for a dry, vertical wall in an urban canyon in Los Angeles California in August using the Terjung canopy-layer model (Terjung and O'Rourke, 1980). Wall-2 is the east-facing wall of building 2 in the system illustrated in Figure 4. H represents the sensible heat flux; S, the substrate heat flux; Rn, the net radiative flux; and LE, the latent heat flux.

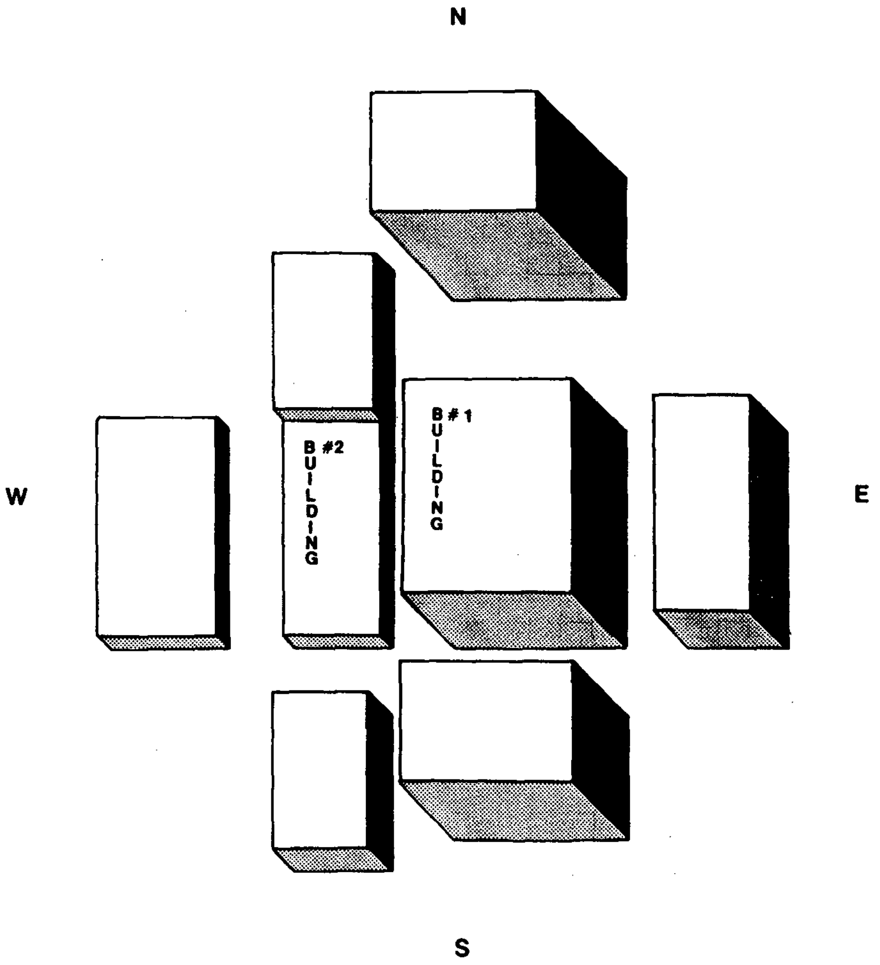

Figure 5a. Block structure and orientation of buildings modeled with the Terjung canopy-layer model.

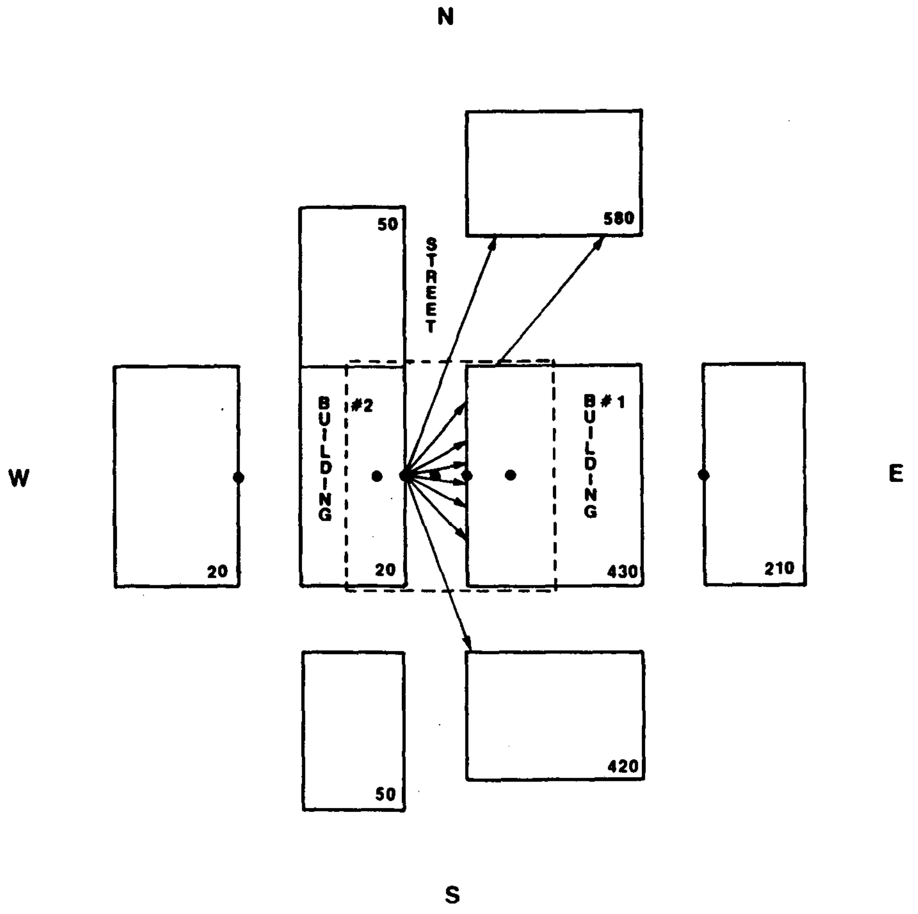

Figure 5b. Dashed lines show the "radiation neighborhood" for buildings 1 and 2. Also shown are building heights (in feet) and sample view vectors for Wall 2.

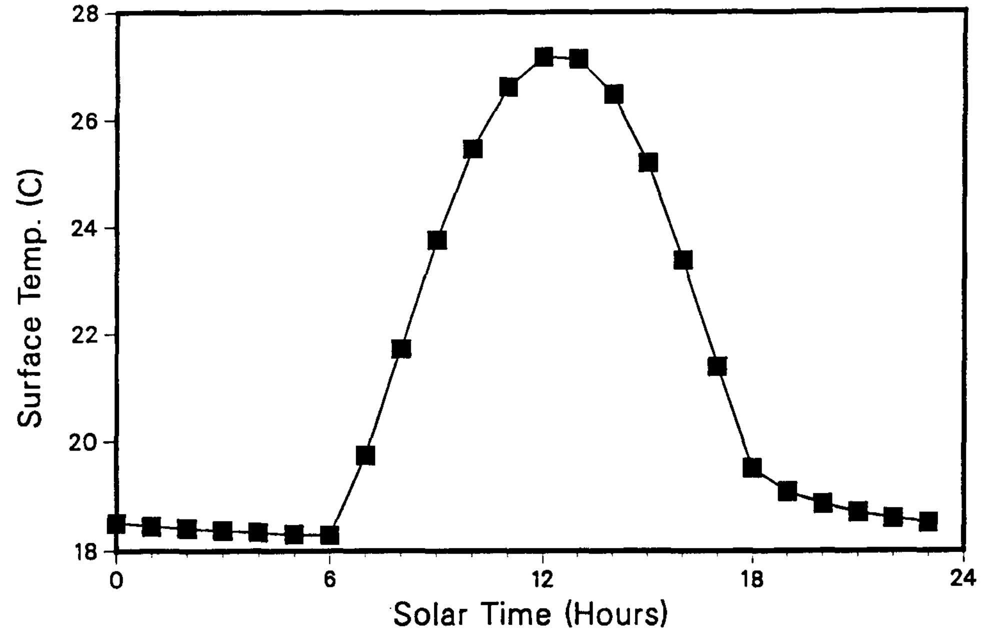

Figure 6a. OUTCALT MODEL. Surface temperature predicted with Outcalt's model (Outcalt, 1972a,b). Input climatic conditions are monthly averages for August in Sacramento California. Surface parameters are derived from Myrup and Morgon (1972).

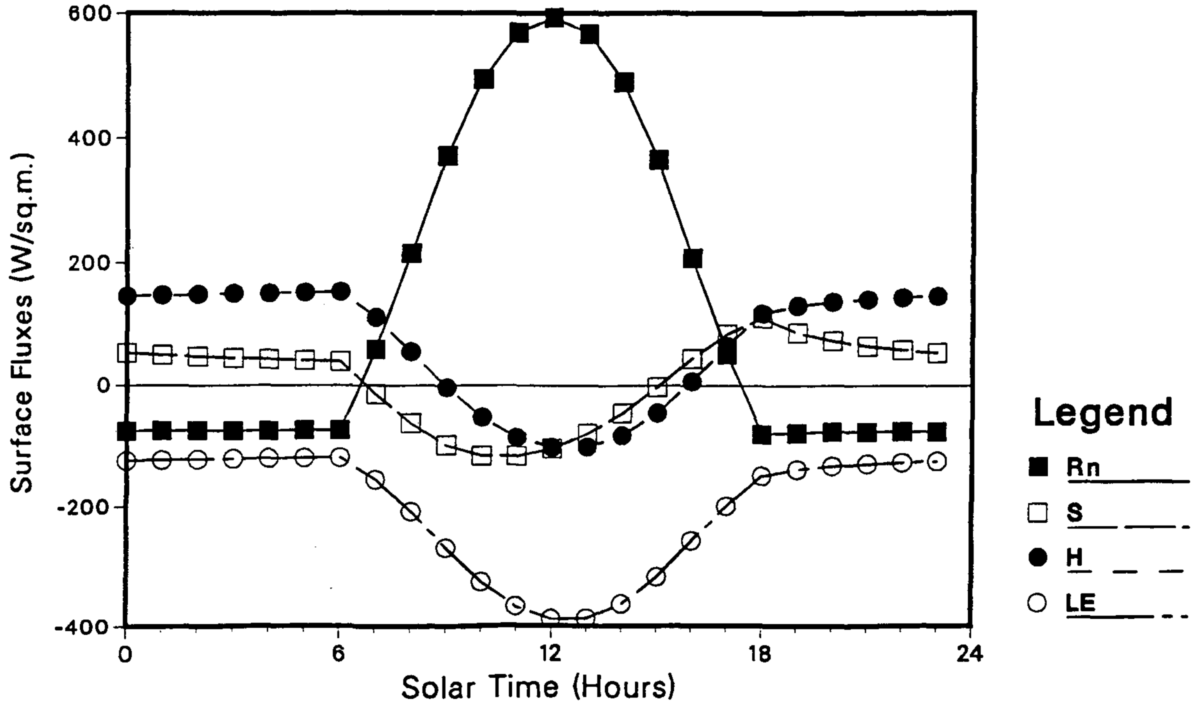

Figure 6b. OUTCALT MODEL. Surface energy fluxes predicted with Outcalt's model (Outcalt, 1972a,b). Conditions are those of Figure 6a. Rn represents the net radiative flux; S, the substrate heat flux; H, the sensible heat flux; and LE, the latent heat flux.

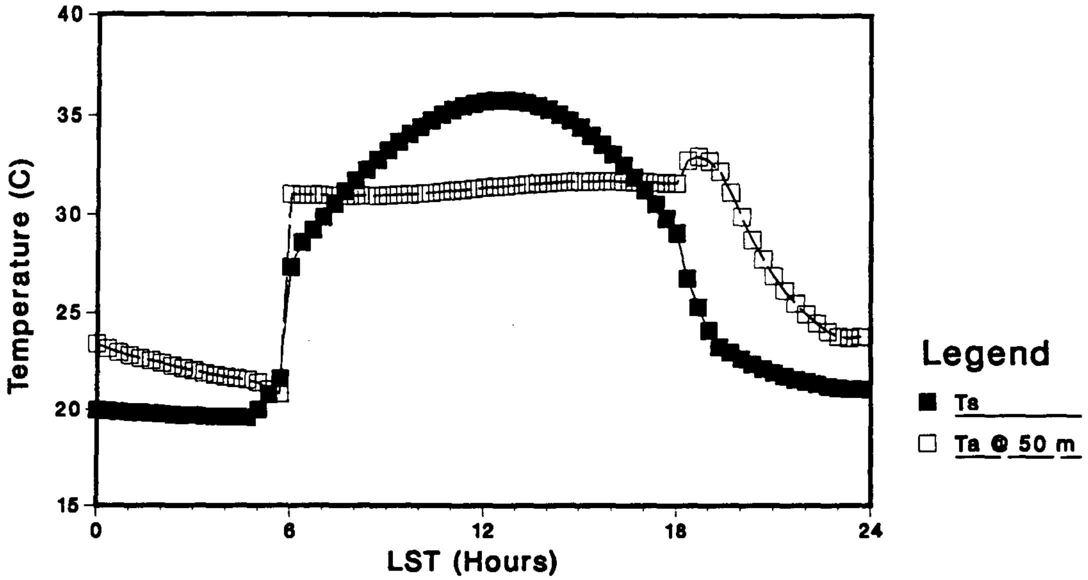

Figure 7a. CARLSON MODEL. Surface temperature and air temperature at 50 meters predicted with Carlson's model (Carlson et al., 1989). Parameters are chosen to be representative of mid-latitude, rural conditions in August. Geostrophic wind speed is roughly four meters per second.

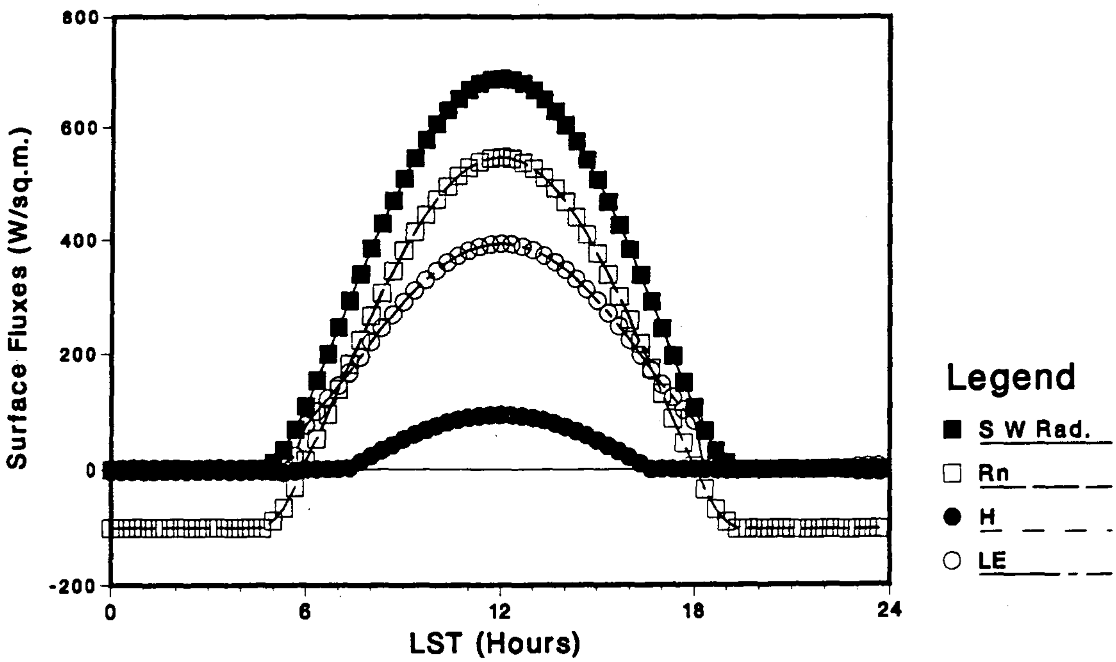

Figure 7b. CARLSON MODEL. Surface energy fluxes predicted with Carlson's model (Carlson et al., 1989). Conditions are those of Figure 7a. S W Rad. represents the incoming shortwave radiative flux; Rn, the net total radiative flux; H, the sensible heat flux; and LE, the latent energy flux.

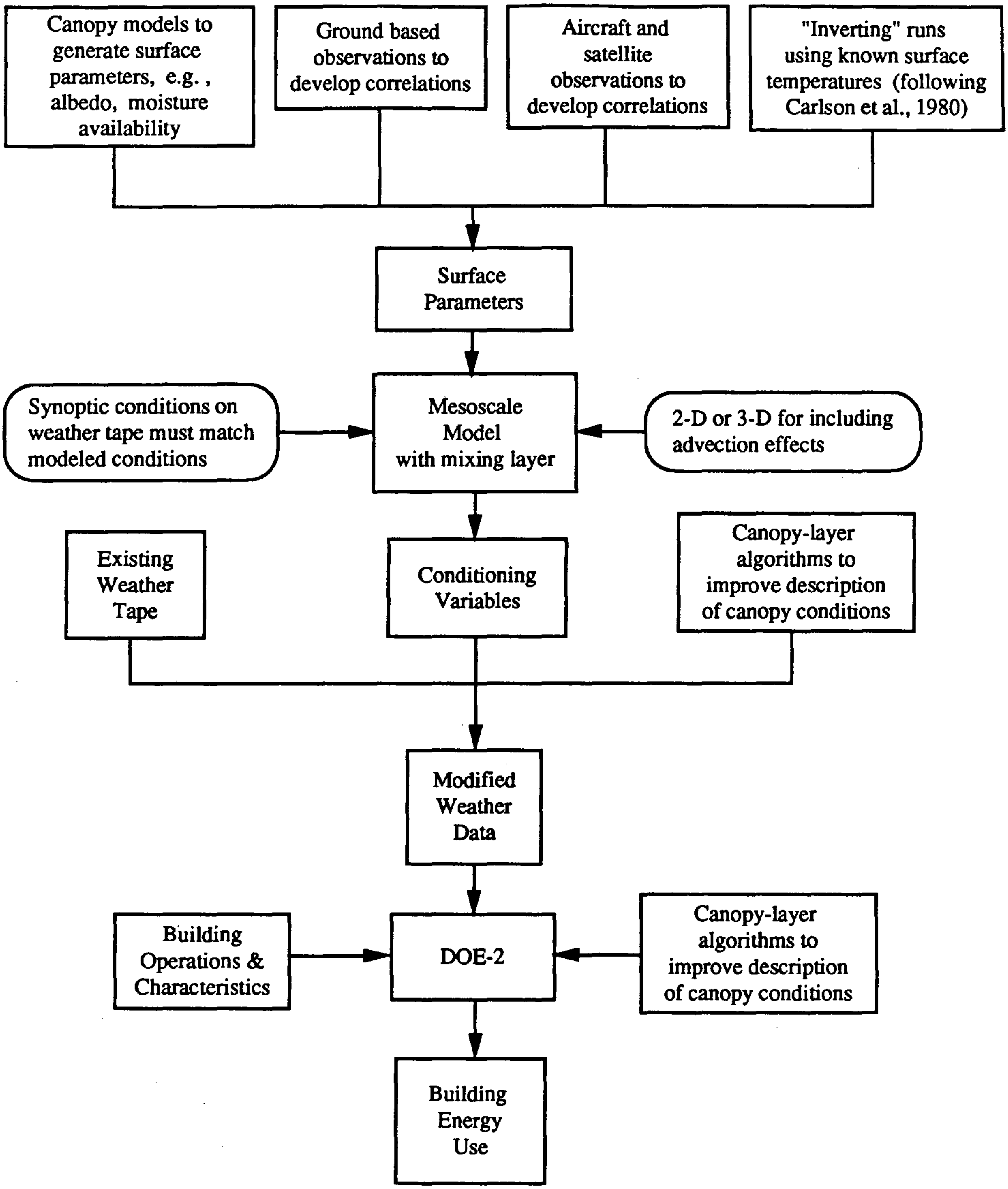

Figure 8. The process of using urban-climate models in conjunction with DOE-2, a building-energy model, is illustrated in schematic form. A mesoscale model, used to predict conditioning variables, is only a single element in this process. Also required are improved methods for specifying surface parameters and canopy-layer algorithms to improve the description of conditions within the canopy layer.

EVAPOTRANSPIRATION FROM URBAN SYSTEMS

T.R. Oke
Atmospheric Science Programme, Department of Geography
University of British Columbia

ABSTRACT

The energy associated with the loss of water to the air from urban surfaces, especially vegetation, is a powerful determinant of the thermal climate. Despite this, our knowledge of evapotranspiration is relatively thin. Available information is reviewed with emphasis on the summer daytime case.

The review is organized according to scale, starting with the case of the isolated tree or lawn, followed by that of a park, the integrated effects of a land-use zone and up to the whole city. Consideration is given to both the transfer of heat/mass and the thermal effects. The discussion is illustrated by reference to results from an extended series of observations in a suburb of Vancouver, B.C. The essential elements of a new urban evaporation model are presented. It is based on the Combination Model approach and has been tested against measurements gathered over a five-month period.

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EVAPOTRANSPIRATION FROM VEGETATION

Kyaw Tha Paw U
Department of Land, Air and Water Resources
University of California at Davis

ABSTRACT

Evapotranspiration from surfaces consists of evaporation from non-plant surfaces such as the soil or roads, etc., and transpiration from plants. Evapotranspiration (ET) cools vegetated surfaces when water is available; this cooling is so strong that sometimes the vegetated surfaces is over 10 degrees Celsius less than air temperature. It is clear then, that heat pollution mitigation techniques which employ well-water vegetated surfaces have some potential.

The transport of water from surfaces can be modeled at various scales and in differing degrees of detail. The simplest models use the general surface energy budget and are suitable for regional scale analysis of ET. With such models used to interpret remotely sensed data (from satellites and/or aircraft), it is visually striking how urban areas have little or no ET. More complicated models, which although designed for field-size analysis can be generalized to larger scales, allow the inclusion of the plant physiological controls on ET in addition to investigation of the effects of carbon dioxide concentration increases on ET. These models can employ advanced parameterization of the turbulent wind field (called 'higher-order closure') and are currently being modified to include advanced models for the plant physiological responses. It is possible that such models could be used for urban areas with suitable modification.

NO PAPER SUBMITTED FOR PROCEEDINGS

USE OF MESOSCALE METEOROLOGICAL MODELING AS AN ASSESSMENT OF SUMMER URBAN HEAT ISLANDS

Roger A. Pielke
Dept. of Atmospheric Science
Colorado State University

and

Roni Avissar
Dept. of Meteorology and Physical Oceanography
Cook College
Rutgers University

ABSTRACT

Modeling evaluations of the influence of vegetation on mesoscale climate have shown that evapotranspiration plays a major role in partitioning sensible and latent heat fluxes. For example, since urban areas in semi-arid and arid regions are often heavily irrigated because of lawns and residential vegetation, the summer urban climate will frequently be cooler and more humid than the surrounding natural areas. Examples of model results are presented in this paper, which illustrates how this tool can be used to assess the influence of an urban area on typical summer climate.

KEYWORDS: heat islands, modeling, transpiration, urban climate, urban meteorology, urban vegetation, wind simulation

USE OF MESOSCALE METEOROLOGICAL MODELING AS AN ASSESSMENT OF SUMMER URBAN HEAT ISLANDS

Roger A. Pielke, Colorado State University, and Roni Avissar, Rutgers University

INTRODUCTION

As documented in Pielke (1984), numerical models of local scale atmospheric features can be realistically simulated using the fundamental conservation relations of physics. Included in these local scale simulations, and as summarized in Pielke (1984, pgs. 482-492), are models of the influence of urbanized areas on local weather and climate. These models (and associated observations) have demonstrated the alteration of wind flow, for example, over urban areas as a result of their larger aerodynamic roughness (Loose and Bornstein, 1977). Also, cities have been found to enhance precipitation downwind; one suggested reason being the displacement of the urban heat island effect, and thus low-level wind convergence downwind of the urban area by the prevailing winds (Hjelmfelt, 1982).

Models offer a tool to evaluate planning strategies to mitigate the summer heat island effect. Once validated for current urban conditions, alternative land use strategies can be tested within the simulation model. In this paper, preliminary simulation results for idealized urban areas are presented.

THE MODEL

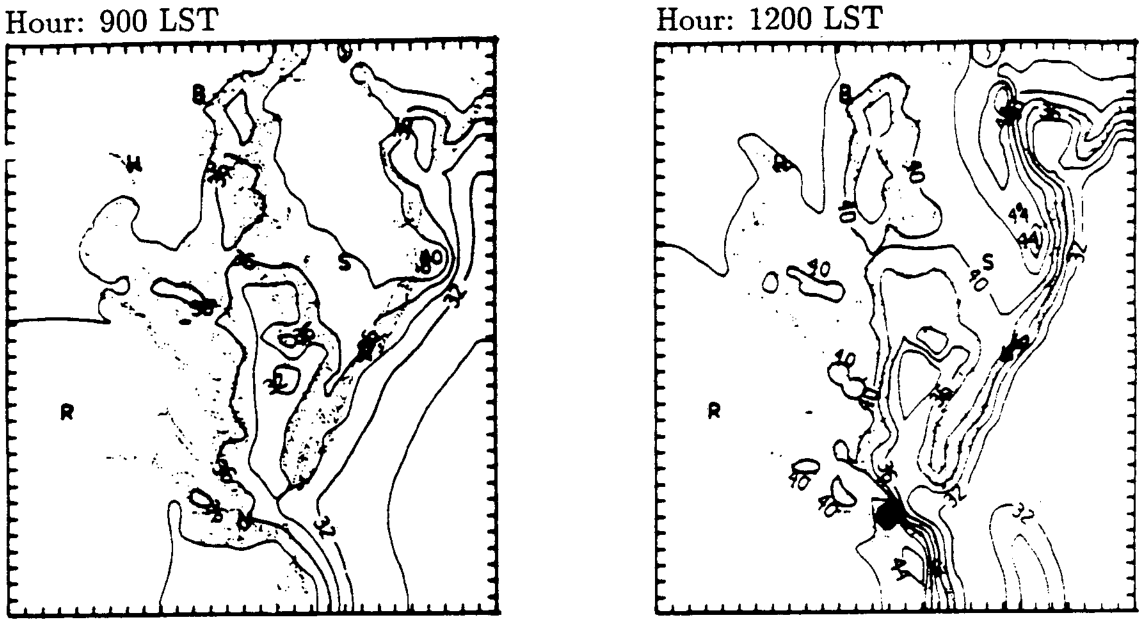
The mesoscale model used in this study has been applied to a wide range of meteorological studies. Segal and Pielke (1981) for instance, simulated biometeorological heat load in the Chesapeake Bay region during a typical summer day using this model. Among the results was the conclusion that even in the absence of urbanization, local areas are prone to higher discomfort indices than other regions as a result of the spatial structure of the sea breezes in this region (e.g. see Figure 1).

Basic Equations

The basic mathematical equations used in this study are:

$$\frac{du}{dt} = 2v\Omega \sin\psi - 2w\Omega\cos\psi - \theta\frac{\partial\pi}{\partial x} + \frac{\partial}{\partial z}\left(K_z^m \frac{\partial u}{\partial z}\right) + Fil(u) \qquad (1)$$

$$\frac{dv}{dt} = -2u\Omega \sin\psi - \theta\frac{\partial\pi}{\partial y} + \frac{\partial}{\partial z}\left(K_z^m \frac{\partial v}{\partial z}\right) + Fil(v) \qquad (2)$$



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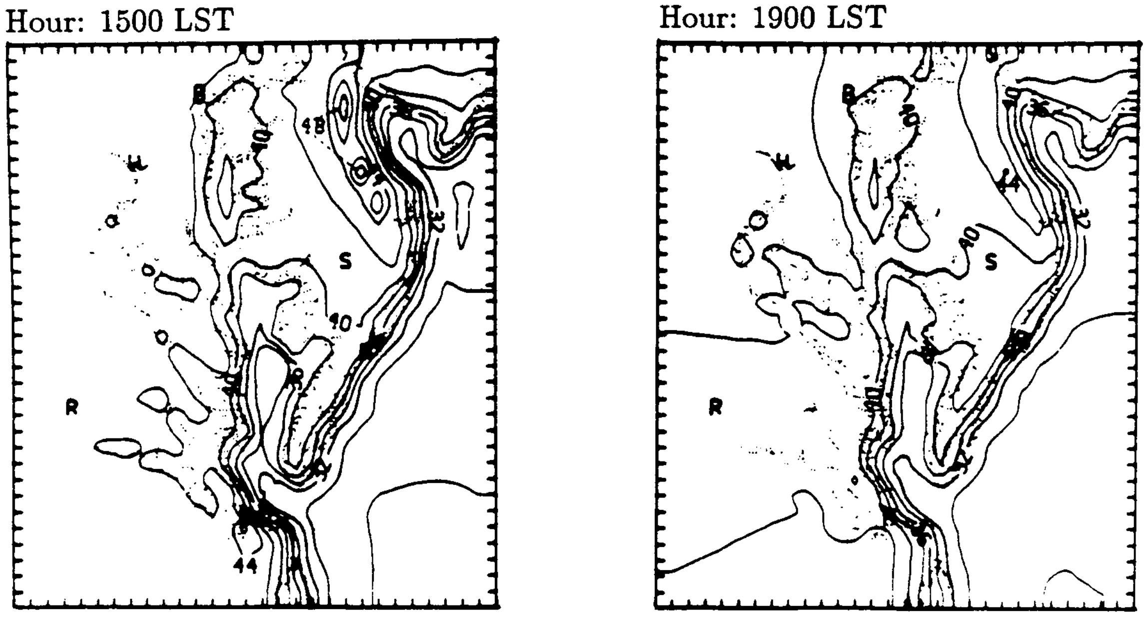

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Figure 1: The predicted skin-temperature (T_s) for 0900, 1200, 1500, and 1800 LST.

$$\frac{d\theta}{dt} = \frac{\partial}{\partial z}\left(K_z^\theta \frac{\partial \theta}{\partial z}\right) + Fil(\theta) + \left(\frac{\partial \theta}{\partial t}\right)_{\mathrm{Rad}} \tag{3}$$

$$\frac{dq}{dt} = \frac{\partial}{\partial z}\left(K_z^q \frac{\partial q}{\partial z}\right) + Fil(q) \tag{4}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{5}$$

$$\frac{\partial \pi}{\partial z} = -g/\theta \tag{6}$$

and

$$\frac{d}{dt} = \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z}, \tag{7}$$

where

u, v and w are the east-west (x), north-south (y), and vertical (z) components of velocity, respectively; Ω is the angular velocity of the earth; ψ the latitude; θ the potential temperature; q the specific humidity; g the acceleration of gravity; $(\partial\theta/\partial t)_{\mathrm{Rad}}$ the radiative cooling/heating of the atmosphere; and π the Exner function which is defined as

$$\pi = c_p \left(p/p_{00}\right)^{R/c_p} \tag{8}$$

where

c_p is the air specific heat at constant pressure; R the gas constant for dry air; and p and p_{00} are pressure and the reference pressure, respectively. The terms K_z^m, K_z^θ, and K_z^q are, respectively, the turbulent exchange coefficients for the vertical diffusion of momentum, potential temperature, and moisture. $Fil(\ )$ is a horizontal filter applied to the variable in parentheses in lieu of explicit horizontal turbulent diffusion.

Details of the model are given in Avissar and Mahrer (1988), and Mahrer and Pielke (1975, 1977), and are not repeated here. Perhaps the main component of the model with respect to summer urban meteorological simulations is the parameterization of soil and vegetation effects as a lower boundary condition of the model. Within a grid area of the model, various land use types can be specified including urban areas, forested areas, agricultural regions, etc., with relatively detailed characterizations of the surface such as leaf area index, root distribution with depth, soil type, stomatal resistance, etc. Details of this parameterization are discussed in Avissar and Mahrer (1988) and Avissar and Pielke (1989), with a summary of several results using the parameterization given in Pielke and Avissar (1989).

EXAMPLES OF MODEL RESULTS

Figures 2 through 4 represent two-dimensional summer mid-latitude simulation results for the influence of an urban area consisting of:

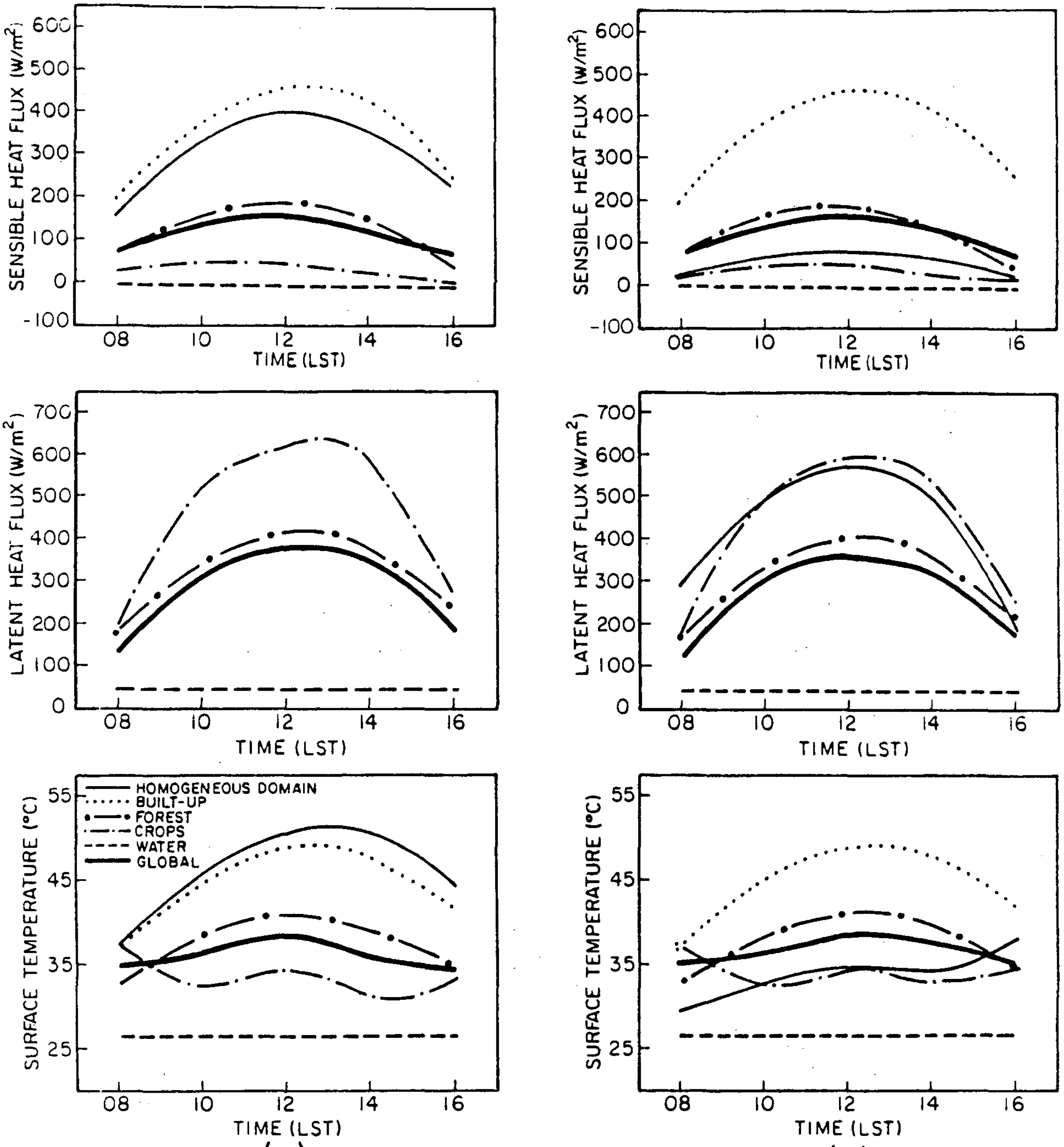
- 20% built-up areas
- 10% water bodies
- 40% agricultural crops
- 30% forests

within each grid interval of 6 km with the entire region having a size of 60 km, surrounded by either bare, dry soil (Figures 2a and 3a), or by unstressed vegetation (Figures 2b and 3b). The urban area surrounded by the arid ground is representative of cities in the southwestern United States (e.g. Denver, Phoenix), while the urban region with adjacent vegetation is typical of the eastern United States (i.e. Richmond, Hartford). Major differences in local weather are evident between the two simulations. With surrounding dry ground, for example, relatively high transpiration over the urban area results in cooler atmospheric temperatures in the lower troposphere and a flow of low-level air out from the city. (Such cooler temperatures over irrigated areas northeast of Denver during the summer of 1987 were observed by aircraft and balloon soundings; Segal *et al.*, 1989). In contrast, when the urban area is surrounded by unstressed vegetation, the greater transpiration in that region results in airflow into the city. When a city to rural area background windflow is present (Figure 4), the magnitude of the heat island effect is reduced, but is still evident in the model results, with an area of ascent downwind of the urban region.

From even these idealized results, it is evident that deliberate or inadvertent land use changes either within the urban area (i.e. by changing the % of coverage of specific types of surfaces within the city, the vegetation types; e.g. their leaf area index, stomatal characteristics, etc.) or surrounding the city can affect the urban climate. A desirable goal of this work is to perform model simulations for actual cities and, once validated with available measurement data, to test different planning configurations of land use so as to minimize the summer urban heat island effect. This work can also be compared with wind tunnel physical modeling of the same urban area.

CONCLUSIONS

Mesoscale meteorological models which include parameterizations for soil and vegetation physics can be used to evaluate different land use strategies to minimize the summer urban heat island effect. An example of the use of such a model for an idealized summer, mid-latitude situation of an urban area surrounded (i) by dry, bare soil, and (ii) by unstressed vegetation is presented. For both situations, the urban area is shown to exert a major role in modifying local climate.



(a) (b)

Figure 2: The diurnal variation of sensible heat flux, latent heat flux, and surface temperature simulated for a heterogeneous land surface which consists of 20% built-up areas and waste lands, 10% bodies of water, 40% agricultural crops, and 30% forests. The heterogeneous region is juxtaposed with a homogeneous domain of (a) bare, dry land or (b) land completely covered by unstressed vegetation. The global domain is composed of weighted contributions from the various urban land types.

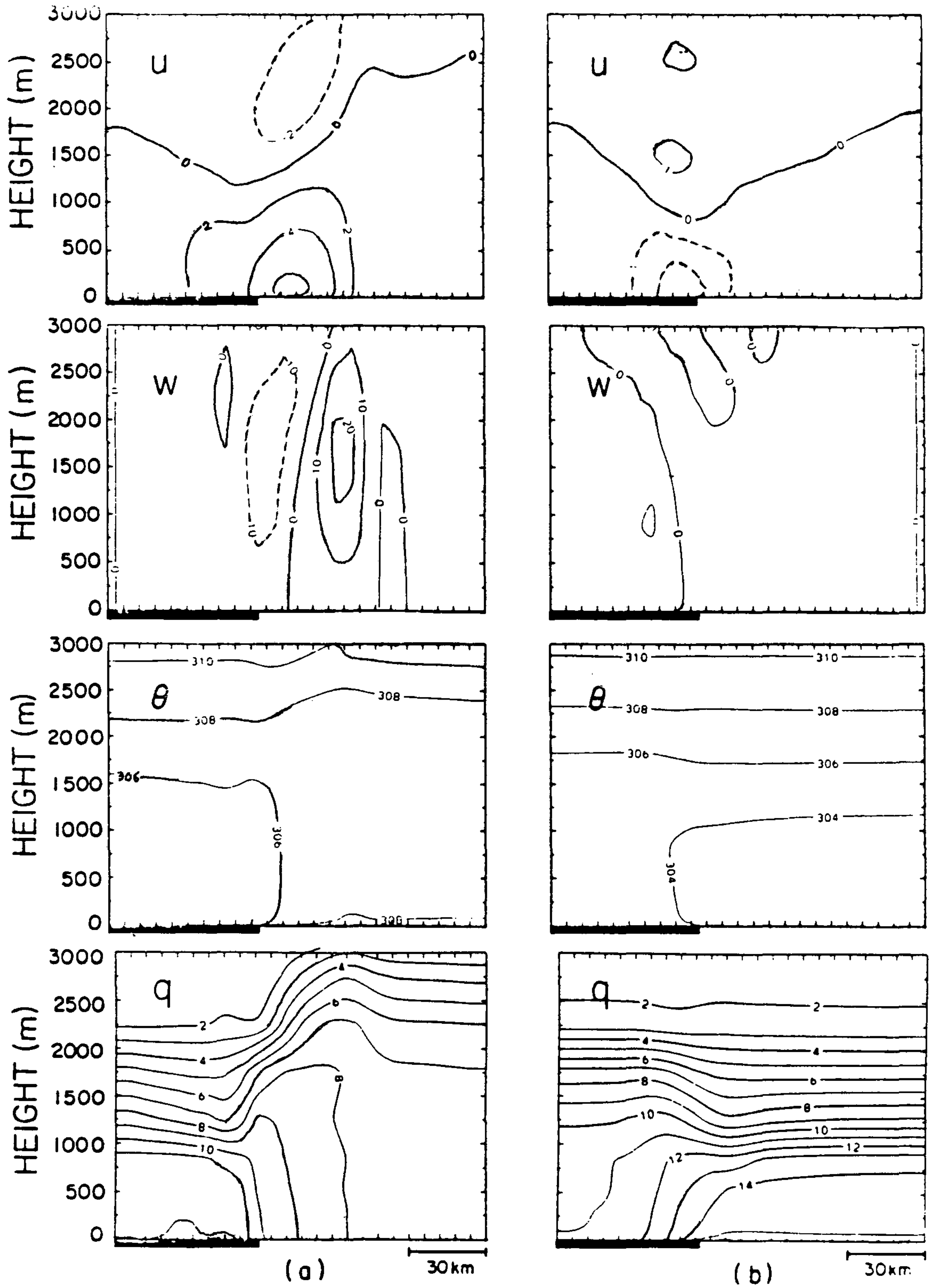


Figure 3: Vertical cross-section for the two cases presented in Figure 2 of the simulated region at 1400 LST for: (i) the horizontal wind component parallel to the domain (u) in m s^{-1}, positive from left to right; (ii) the vertical wind component (w) in cm s^{-1}, positive upward; (iii) the potential temperature (θ) in K; and (iv) the specific humidity (q) in g/kg, resulting from the contrast of a heterogeneous land surface which consists of 20% built-up areas, 10% bodies of water, 40% agricultural crops, and 30% forests. The dark line on the horizontal axis indicates the heterogenous urban region. The homogeneous region is to the right of the line.

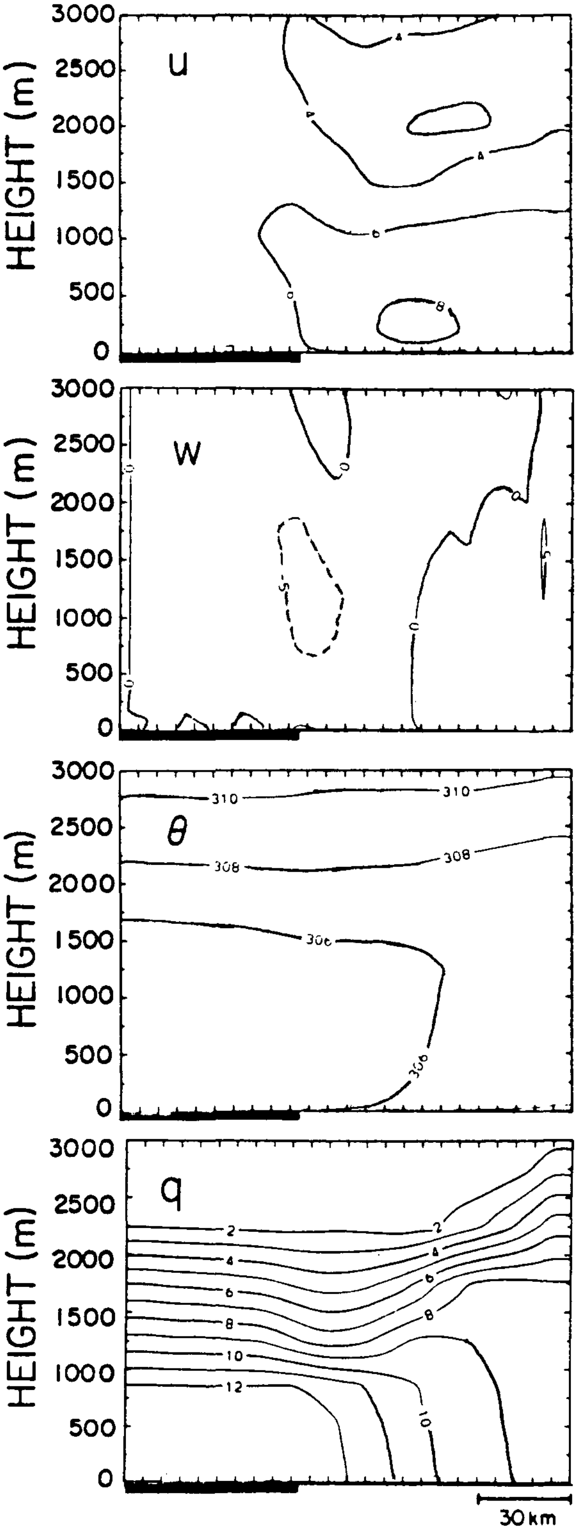


Figure 4: Same as Figure 3a except initialized with a moderate background wind of 5 m s^{-1} parallel to the domain (u positive).

ACKNOWLEDGEMENTS

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THERMAL AND REFLECTANCE PROPERTIES OF ASPHALTS, AGGREGATES, AND THEIR COMBINATIONS

C.L. Monismith
The Robert Horonjeff Professor of Civil Engineering
University of California at Berkeley

ABSTRACT

This paper briefly summarizes information on the thermal properties of asphalts, aggregates, and their combinations useful in estimating temperatures in systems composed of those materials that result from surface air-temperature variations.

A brief review of methodology used to calculate these temperatures is presented including closed form and numerical procedures (utilizing computer solutions) to illustrate, for example, the change in pavement temperature with time and depth as a function of surface air temperature. The influence of other factors such as cloud cover, solar radiation, and wind velocity are also illustrated.

In the field of highway lighting, surface-reflectance measurements of paved surfaces have been made. The light-reflecting properties are also briefly summarized.

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CHAPTER 4

Measurements of Heat Islands and Characteristics of the Urban Surface and Urban Climate

Chapter 4

MEASUREMENTS OF HEAT ISLANDS AND CHARACTERISTICS OF THE URBAN SURFACE AND URBAN CLIMATE (Editors' Summary)

This chapter presents seven papers and one abstract describing measurements of urban heat islands and related measurements of urban structure and meteorology. In particular, two papers present data characterizing the heat island itself, one examines the relationship between urban surface temperature and near-ground air temperature, one uses remotely sensed data to characterize the urban surface, one discusses measurements of urban albedo, and two discuss methods of measuring wind characteristics in cities.

In the first paper, **Schmugge** describes methods and problems of measuring urban heat islands with remote sensing techniques. Such measurements are based on the sensing of infrared flux from the surface, which can be correlated with surface temperature after correction for atmospheric absorption.[1] The author cites a number of remote sensing studies of the heat island phenomenon that found surface temperature differences of 10° C and higher between contiguous urban and rural areas. Traditionally, heat island measurements have been based on measurements of urban verses rural air temperatures. One urban area with a 5-6° C surface-temperature heat island was found to have only a 3° C heat island based on air-temperature measurements made 2-meters above the surface at the same time of year. The precise relationship between surface and air temperatures under various meteorological and surface conditions is not known. This is an important area for future research on heat islands since remotely sensed data are intrinsically suitable to their study because of the scale of the phenomenon, but the most important ramifications of heat island intensity (such as energy-use by buildings and smog formation rates) are related to air, not surface, temperature.

Imamura's work begins to investigate this issue. She verifies correlations between nighttime surface temperatures (as determined by ground-based measurements) and 1.5-m air temperatures in different landscapes. Such correlations suggest that it might be possible to develop a predictive equation between surface and air temperatures. The development of such an equation requires that future studies include the effects of meteorological conditions, terrain factors, time of year, and latitude. Future research should focus on the daytime relationship between surface temperature and 1.5-m air temperature, since both cooling-energy demand and concentrations of air-pollutants peak in the daytime.

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[1] The current inability to correct accurately for atmospheric absorption is a problem with this technique.

Although it is now accepted that the heat island is a common phenomenon in cities around the world, one might expect the characteristics of heat islands to differ among cities with large differences in urban morphology, anthropogenic heat output, and climate conditions: for example, between North American and Chinese cities. **Chow's** study—which documents the heat island of Shanghai, China, and its evolution over the last 20 years—reveals that the characteristics of the Shanghai heat island are remarkably similar to those observed in the West. For example, the largest urban-rural temperature difference occurs in the evening and nighttime and decreases during the day, and the intensity of the heat island is increasing with time, particularly in terms of higher minimum daily temperatures.

Modeling urban climates and estimating the potential for heat island mitigation requires an understanding of the structure and function of the urban surface and of how meteorological variables interact with and are affected by that surface. The papers of Ellefsen, Brest, Heisler, and Givoni describe measurements of various aspects of urban surfaces, and of wind/surface interactions.

Ellefsen describes the use of aerial pictures in studying the characteristics of urban areas, mainly: type of buildings, age, color, and density. In particular, he describes the Enviro-Pod camera system used for taking oblique aerial pictures of urban areas that provide information about vertical surfaces not available from most remotely sensed data. From these data Ellefsen identifies and describes different land use patterns.

A particularly important temperature-determining characteristic of the urban surface is its albedo (reflectivity). Simulation results have indicated that increasing the overall albedo of a city from a typical value of 0.15 to 0.4 could decrease urban temperatures by as much as 5 °C and reduce cooling-energy consumption in homes by as much as 50%. Our current ability to estimate overall albedo values for highly heterogeneous and complex surfaces such as cities is very limited. Remote sensing is a promising technique for determining such albedos.

In the fifth paper in this chapter, **Brest** analyzes data from 27 Landsat (satellite) scenes acquired between 1972 and 1978. He has defined 13 land cover categories and has estimated the monthly average infrared reflectance, visible reflectance, and the overall albedo for each land cover category. The resulting albedos are much lower than those published earlier using other sources of data, indicating the need for additional research to resolve the discrepancies. Despite the present short-comings of this approach and the need for additional research, the superiority of remotely sensed data over area-averaged reflectance is clearly demonstrated in this paper.

Wind and its interaction with the urban surface affects the relationship between air and surface temperatures, it both directly and indirectly influences the energy requirements for cooling and heating buildings, and it is a strong determinant of urban air quality. Air turbulence increases as wind passes over the rough urban surface creating vortices that mix clean air from above into polluted near-surface air, decreasing pollutant concentrations in the urban canopy and carrying heat away from the surface during the daytime. Wind also has a direct impact on the cooling- and heating-energy needs of buildings because of its direct effect on infiltration rates and convective heat loss from buildings.

Heisler points out that tree and building density, which influence heat island intensity, also influence wind speed. Any well-thought out plan to conserve energy by tree planting should, therefore, account for the effect of trees on wind speed and consequently on energy use. As is the case in the estimation of air temperatures, little information is currently available on the effect of trees and buildings on wind at or below roof height. Turbulence theory cannot predict the complex wind/surface interactions within the urban canopy layer. We must, therefore, rely on laboratory and field measurements such as those described by Givoni and Heisler to develop correlations between surface characteristics and their effect on wind.

Givoni summarizes earlier wind-tunnel research on the effects of building height and spacing on wind speed in the canopy. The result of the measurements are regression equations that can be used in urban climate models. **Heisler** describes measurements of mean wind speed in neighborhoods with single family residences with different amounts of tree cover. His study found that tree densities of 77 percent reduced wind speed by as much as 42 percent in the wintertime and 46 percent in the summertime relative to neighborhoods without trees. The effect of such reductions on summertime cooling-energy loads is not obvious. On the one hand, reduced wind can lessen cooling loads by decreasing the infiltration rate of warm air. On the other hand, reduced wind can increase cooling loads by decreasing convective heat loss from the building shell. An additional complication is the fact that cooling might be unnecessary in the presence of sufficient wind if windows can be opened to allow cross ventilation. The effect of reduced wind in the wintertime is unambiguous—decreased infiltration of cold air and reduced convective heat loss both save energy.

While the papers in this chapter do not give a complete picture of the measurements involved in understanding the urban heat island and its effect on energy use, they give an indication of the measurements upon which the theory is based and an indication of the level of understanding of various aspects of the heat island phenomenon. The general reader could profitably skim this chapter—especially the papers of Chow and Brest—to get a feeling for the types of direct measurements used to study the heat island phenomenon. The heat island researcher will find some useful evaluations of measurement techniques and some interesting data, particularly in the papers by Schmugge, Ellefsen, Brest, Heisler and Givoni.

SATELLITE OBSERVATION OF SURFACE TEMPERATURE

T. Schmugge
USDA Hydrology Laboratory

ABSTRACT

Measurements of the upwelling thermal radiation from the earth's surface provide an opportunity to estimate the temperature of the radiating surface. For terrestrial temperatures around 300 K the peak of this radiation is around 10 micrometers, which fortuitously falls in an atmospheric absorption window. The problems of eliminating the residual atmospheric effects and uncertainties in surface emissivity are discussed in this paper. Sources of satellite data in this wavelength area also described along with results from recent studies of urban heat islands using satellite data.

KEYWORDS: atmospheric attenuation, atmospheric absorption, black body radiation, heat islands, remote sensing, surface temperature, urban emissivity, urban environment

SATELLITE OBSERVATION OF SURFACE TEMPERATURE

T. Schmugge
USDA Hydrology Lab

An excellent possibility for observing important aspects of urban heat islands is the use of satellite measurements of land surface temperatures. Using data from the Heat Capacity Mapping Mission satellite (HCMM) Price (1979) observed radiation temperature differences of up to 17 ° C for New York city and greater than 10 ° C for numerous smaller cities in the north east on a clear early June day in 1978. With these satellite data he was not only able to observe the magnitude of difference between the radiant temperatures of the urban areas and those of the surrounding rural areas but also the real extent of the regions of elevated temperatures. Thus for New York city he found an area of 550 km^2 with temperatures at least 9 ° C greater than the surroundings.

These results were based on the measurement of the thermally emitted radiation at 8 to 12 micron (micrometer) wavelengths from the earth's surface which can yield useful estimates of the surface temperature. This radiation which is emitted by any surface with a temperature above absolute zero is described by the Planck Black Body equation:

$$E = C_1 k^3 / (\exp(C_2 k/t) - 1) \qquad (1)$$

where C_1 is 1.191 x 10^{-8} $W/(m^2\ sr\ cm^{-4})$, C_2 is 1.439 cmK and k is the wavenumber (cm^{-1}). This gives the radiation for a perfect emitter or black body with emissivity of one (e = 1). For real surfaces e is less than 1 and in general a function of wavelength. To estimate surface temperatures, radiation at wavelengths around 10 microns (micrometers) is used because:

1) the peak intensity of eq. 1 occurs in this region for terrestrial temperatures (~ 300 K) and

2) the atmosphere is relatively transparent in this region.

These two features are demonstrated in Figure 1 where we have plotted eq. 1 in the wavelength region from 5 to 20 microns for temperatures 280 and 300 K (7 to 27 ° C), i.e., the low range of terrestrial temperatures. At these temperatures the peak of the emission occurs in the 8 to 10 micron range of wavelength. In this figure we have also plotted the atmospheric transmission for cloud free conditions calculated with the Lowtran-6 path radiance model (Kniezys, et al., 1983) for the US standard mid-latitude summer atmosphere assuming the radiometer is at satellite altitude. As can be seen, the atmosphere is also relatively transparent in the 8 to 12 micron range, but that there is still a significant effect, i.e., there is only 60 to 70% transmission with a major dip at about 9.5 microns due to ozone absorption. With the exception of this dip, water vapor is the dominant absorber in the 8 to 12 micron window and is due to what is called the water vapor continuum and not any individual absorption lines. Thus the magnitude of the atmospheric effect will depend on the water vapor content in clear sky conditions. And this unknown or uncertain atmospheric contribution is one of the problems in remote sensing of surface temperature. The filter functions for channels 4 and 5 of the Advanced Very High Resolution Radiometer (AVHRR) on the polar orbiting NOAA series of weather satellites are also plotted. There is a difference in the atmospheric transmission for the two channels with 4 having the higher transmission due to the greater water vapor absorption at the longer wavelengths shown in figure 1. This difference can be used to correct for atmospheric absorption.

The NOAA series of satellites are in sun synchronous orbits at nominal altitudes of 830 km. There are generally two satellites in orbit at all times with one having an ascending (northbound) crossing in the early afternoon and the other in mid-morning. The former then will provide surface temperature observations near their peak. The spatial resolution is 1.1 km at nadir and the sensor swath width is greater than 3000 km providing the possibility of almost daily coverage for the US (Hastings, et al., 1988). In addition to the 2 thermal channels shown in figure 1, the AVHRR has a visible channel (0.58 - 0.68 microns), a near infrared (0.73 - 1.0 microns) and a middle infrared channel (3.6 - 3.9 microns) which responds to both the reflected solar and emitted radiation.

As seen in Figure 1 the atmosphere is only about 70% transparent at these wavelengths which will reduce the magnitude of urban heat islands as observed from satellites. Several approaches have been developed for eliminating atmospheric effects in the estimation of sea surface temperature from space. Here the problem is simpler in that the temperature does not change rapidly with time and a week's worth of data can be used to estimate the surface temperature. The technique used with the AVHRR data from the NOAA series of satellites involves the differential water vapor absorption between channels 4 and 5,the so called split window technique (McClain et al, 1985 and McClain, 1989). However this assumes that the surface emissivity is constant over this spectral band, which, may not be the case for land surfaces (Price, 1984 and Becker, 1987). Price (1984) has developed an algorithm for estimating land surface temperature from the measurements in the two AVHRR bands. He found

$$\begin{aligned} T_s = {} & [T_4 + 3.3*(T_4 - T_5)]*(5.5 - \epsilon_4)/4.5 \\ & - 0.75*T_4*(\epsilon_4 - \epsilon_5) \end{aligned} \tag{2}$$

where T_4, T_5, ϵ_4, and ϵ_5, are the observed temperatures and emissivities in the respective bands. The difficulty arises from the lack of knowledge of emissivities particularly for urban surfaces. For vegetation we expect the emissivity to be close to one with little spectral dependence. However for urban areas Balling and Brazel (1988) estimated emissivities in range from 0.86 to 0.90 based on literature surveys with no spectral dependence.

In a sensitivity study of this problem Wan and Dozier (1989) recently concluded that it would be possible to make the atmospheric and emissivity corrections to surface temperature observations using multiple wavelength data. However it would require non-linear combinations of the channels.

In spite of these problems there have been a couple of recent studies which used satellite observations of surface temperature to study urban heat islands. Balling and Brazel (1988) used AVHRR data to study surface temperature variations around Phoenix during the summer of 1986. The temperature differences were much smaller than those observed by Price (1979) for the cities of the northeast. This is primarily due to the arid nature of the surrounding rural areas around Phoenix. They did observe that the industrial areas were 5 ° C warmer than nearby vacant land.

In a comparison of satellite, ground traverses, and modeling approaches Henry et al. (1989) studied the urban heat island around Gainesville, Florida. The satellite data was from the HCMM sensor as used by Price (1979) in his study. This sensor has a single 10 to 12 micron channel with 600 m resolution and early afternoon and early morning overpass times. These data were corrected for atmospheric effects using nearby radiosounding of the atmosphere. Analysis of 3 passes from November 1978 to March 1979 showed a 5-6 ° C warming of the central business district (CBD) compared to surrounding rural areas for the mid-afternoon passes. The 2 meter air temperature difference measured during an auto traverse of the area was 3 ° C for approximately the same time of year. Again the peak was located in the CBD. They observed a larger heat island in the early morning HCMM data (9 ° C) indicating the CBD cooled more slowly than the surrounding rural areas. From their study Henry et al. (1989) concluded that the satellite thermal infrared data can be effectively used to observe the spatial pattern of urban thermal variations.

CONCLUSIONS

In this paper I have presented a brief summary of the capabilities of satellite sensors for surface temperature observations and through the use several published papers indicate how these remotely sensed data can be used to monitor aspects of urban heat islands. Much more study is needed to quantify the relations between the satellite observations of surface radiant temperature and such factors as air temperature and resulting power usage.

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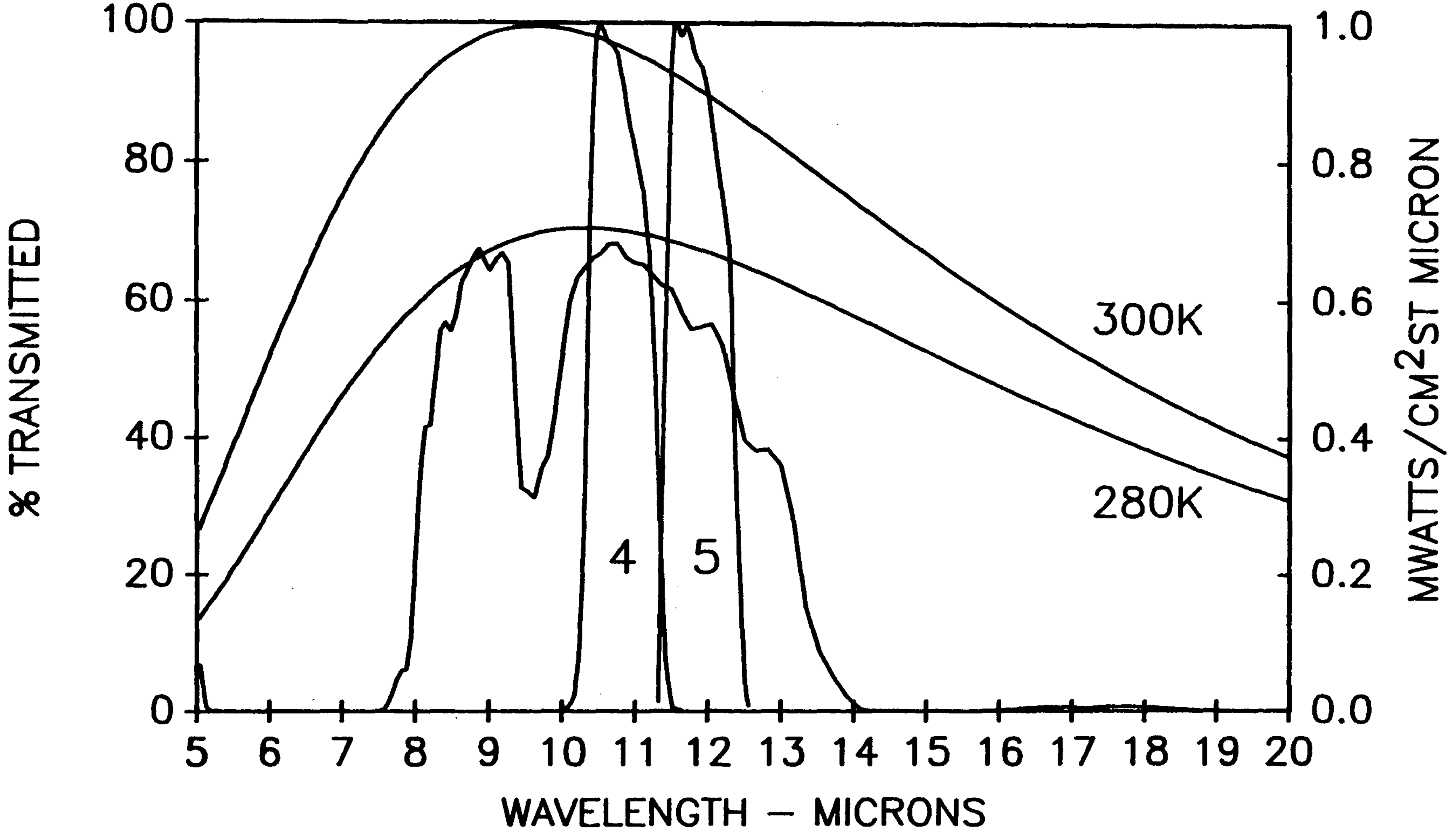

Figure 1. Plot of Planck blackbody radiation (eq. 1) for wavelength region from 5 to 20 micron. The jagged curve between 7 and 14 microns is the estimated atmospheric transmission for a clear mid-latitude summer atmosphere. The two narrow curves are the response functions for the two thermal channels of the AVHRR on the NOAA series of the meteorological satellites.

AIR-SURFACE TEMPERATURE CORRELATIONS

Ilva Ruri Imamura
Institute of Geoscience
University of Tsukuba
Ibaraki, Japan

ABSTRACT

This paper presents preliminary results from a study on the relationship between surface radiative temperature and 1.5-m air temperature at several urban and rural sites in mid-latitude and tropical locations during summer and winter periods. Each of 14 diurnal periods analyzed showed the same pattern: a nighttime period in which both temperatures first cooled and then rose; and a daytime period in which surface temperatures rose an then fell while air temperatures remained approximately constant. The average linear-correlation coefficient for the regressions of the nighttime data was 0.94 excluding one case with snow covered ground.

These results support the finding of Imamura (1986), who has shown that in mid-latitudes urban heat islands based on surface temperatures are larger than the corresponding heat islands based on 1.5-m air temperature during both daytime and nighttime periods during winter and summer seasons. Thus previous urban heat island studies based solely on near surface temperatures have underestimated the magnitude of surface-temperature-based heat islands. This work suggests that it might be possible to develop an empirical equation to predict surface temperatures from air temperatures or vice versa. In order to develop such a relationship it would be necessary to incorporate the effects of meteorological conditions, terrain factors, time of year, and latitude.

KEYWORDS: air temperature, heat islands, measurements, surface temperature

AIR-SURFACE TEMPERATURE CORRELATIONS

Ilva Ruri Imamura
Institute of Geoscience
University of Tsukuba
Ibaraki, Japan

INTRODUCTION

Spatial and temporal variations in mid-latitude urban heat island intensity have been studied using various techniques. Most of these studies determined heat island intensities based on 1.5-m air temperature obtained from automobile traverses (Chandler, 1965; Oke, 1973), on long-term statistical/climatological studies of adjacent urban and rural sites (Ackerman, 1985; Balling and Cerveny, 1987), or on field studies of the urban-canyon energy balance (Oke and Fuggle, 1972; Arnfield, 1976).

Recent heat island studies, however, have utilized surface radiative temperature distributions obtained from thermal-band radiometric observations from satellites or aircraft. These results show large daytime surface heat island intensities, in contrast to the results from the air-temperature studies, which generally show larger nighttime heat islands.

There is a lack of heat island studies in which surface radiative and 1.5-m air temperatures have been observed concurrently. Such studies would help determine the relationship between surface heat island intensity and its more commonly available surrogate (that is, its value at 1.5 m).

The present study presents results from comprehensive urban/rural surface-energy and moisture-balance field projects at both (mid-latitude) Shimozuma Japan during the winter and summer of 1985 and the winter of 1986 and at Campina Grande and Patos in the tropical semiarid region of northweastern Brazil during the 1986 winter dry season (Imamura, 1988a, b). This paper focuses on the relationship between surface radiative and 1.5-m air temperatures at night. The results of a preliminary analysis of the data are presented here.

DATA AND ANALYSIS

Data were collected at Shimozuma, Japan, a mid-latitude city with a population of 35,000 located on the (agricultural) Kanto Plain. Data were also collected at two semiarid tropical Brazilian cities, Campina Grand and Patos. Patos (population 6,500) is located in the center of a semiarid basin surrounded by caatinga vegetation, while Campina Grand (population 250,000) is located in a hilly transition zone between coastal humid and semiarid regions. As neither Shimozuma nor Patos have topographic or coastal influences, they are ideal for urban heat island studies. In addition, the well defined urban edge of Shimozuma is unique among Japanese cities.

During three 24-hour intensive periods (two winter and one summer) at Shimozuma, concurrent surface radiative and 1.5-m air temperatures were measured hourly at four sites (three urban and one rural). Data for a total of 12 cases were thus obtained. Three additional winter data sets were also obtained in Brazil (one from Patos and two from Campina Grande).

For each of the 15 cases, a single plot was prepared showing the 24 hourly surface temperatures values versus the concurrent 1.5-m air temperature values (see, for example, Fig. 1). All but one of the plots revealed a similar pattern, in which the 24-hour period was divided into two sub-periods: a "nighttime period" (from about 1500 LST to about 1000 LST on the following day) and a daytime period (from about 1000 LST until about 1500 LST). The one anomalous case contained data from a snow-covered rural surface.

During the first half of the "nighttime" period (1500 LST until 0700 LST on the following day) both the surface radiative and air temperatures cooled, while during the second half of the nighttime period (0700-1000 LST) both of them warmed. During the "daytime" unstable period, surface temperature first increased while air temperatures remained approximately constant as heat was carried away from the surface by convection. In the final hour of this period, the surface cooled, while the air at 1.5-m again remained approximately constant. Linear regression analyses were carried out for each of the 15 nighttime periods.

RESULTS

The results of the regression analyses are shown in Table I. Discarding the obvious outlier, the snow-covered rural surface (Case 2), the 14 remaining regressions resulted in correlation coefficients ranging from 0.88 to 0.98, with a mean value of 0.94. The standard error of the estimate (between the observed and predicted 1.5-m air temperatures obtained from the surface radiative temperatures) ranged up to 3.07 °C (Fig. 3). The average value of this parameter was 1.3 °C, while its modal value was 1.2 °C.

CONCLUSION

An analysis was carried out of the relationship between surface radiative temperatures and 1.5-m air temperatures at several urban and rural sites in mid-latitude and tropical locations during summer and winter periods. Each of the 15 diurnal periods analyzed showed the same pattern, except for one snow-covered rural site. The typical pattern was as follows: (1) a nighttime period in which both temperatures first cooled and then rose and (2) a daytime period in which surface temperatures rose and then fell while air temperatures remained approximately constant. Air and surface temperatures were shown to be highly correlated during the nighttime periods, with an average correlation of 0.94 neglecting the one snow covered site.

The implication of these results is that it should be possible to predict near-surface air temperatures from observations of radiative surface air temperatures or vice versa.

These results support the finding of Imamura (1986) who showed that mid-latitude surface urban heat islands are larger then their corresponding 1.5-m urban heat islands during both daytime and nighttime periods during the winter and summer seasons. Thus previous urban heat island studies based solely on near-surface air temperatures tend to underestimate surface heat island intensities. This study has indicated that it should be possible to evaluate surface heat island values from concurrent near-surface urban and rural air temperatures.

To utilize this technique for a particular site, it is necessary to first collect sufficient concurrent surface and air temperatures to develop the coefficients for the linear regression equations. After this is done, it should be possible to routinely estimate surface radiative temperatures from standard 1.5-m air temperature observations or vice versa. Development of a more universal predictive equation will require further study, incorporating meteorological factors, surface characteristics, latitude and time of year. Such an effort is currently under way using data from this study and additional data to be collected in each climate zone. Study participants include researchers at the Universities of Tsukuba in Japan and the San Jose State University in California.

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Table I. Regression of 1.5-m air temperatures as a function of surface radiative temperature.

	Site	Type	Surface Cover	Season	M	Y_o	R	E(C)
1	Mid-1	Urban	Asphalt	Winter-85	0.77	-0.31	0.91	1.23
2	Mid-2	Rural	Crop	Winter-85	0.54	4.25	0.28	3.07
3	Mid-1	Urban	Asphalt	Summer-85	0.45	12.80	0.97	0.61
4	Mid-1	Rural	Crop	Summer-85	0.52	10.32	0.92	1.13
5	Mid-1	Urban	Tree	Summer-85	1.02	-0.13	0.91	1.24
6	Mid-1	Urban	Concrete	Winter-86	1.20	2.46	0.92	1.27
7	Mid-1	Rural	Crop	Winter-86	2.00	4.56	0.91	1.56
8	Mid-1	Urban	Concrete	Winter-86	0.53	3.93	0.95	1.02
9	Mid-1	Urban	Grass	Winter-86	1.22	2.34	0.93	1.78
10	Mid-1	Rural	Soil	Winter-86	1.12	2.06	0.88	2.09
11	Mid-2	Urban	Asphalt	Winter-85	0.39	16.24	0.97	0.63
12	Mid-2	Rural	Crop	Winter-85	0.58	9.09	0.93	1.28
13	Trop-1	Rural	Veget.	Winter-86	0.80	1.38	0.95	1.51
14	Trop-2	Rural	Veget.	Winter-86	0.79	0.58	0.98	0.39
15	Trop-2	Rural	Crop	Winter-86	0.69	3.84	0.97	0.78

Key:

Mid-1: Shimozuma City, Japan

Mid-2: Kawagoe City, Japan

Trop-1: Patos City, Brasil

Trop-2: Campina Grande City, Brasil

M: Slope of Gregression Equation $T_a = m\ T_s + Y_o$, where T_a is the 1.5-m air temperature and T_s is the 1.5-m surface.

Y_o: Y-intercept of regression equation $T_a = m\ T_s + Y_o$.

R: Correlation Coefficient

E: Standard Error of Estimate

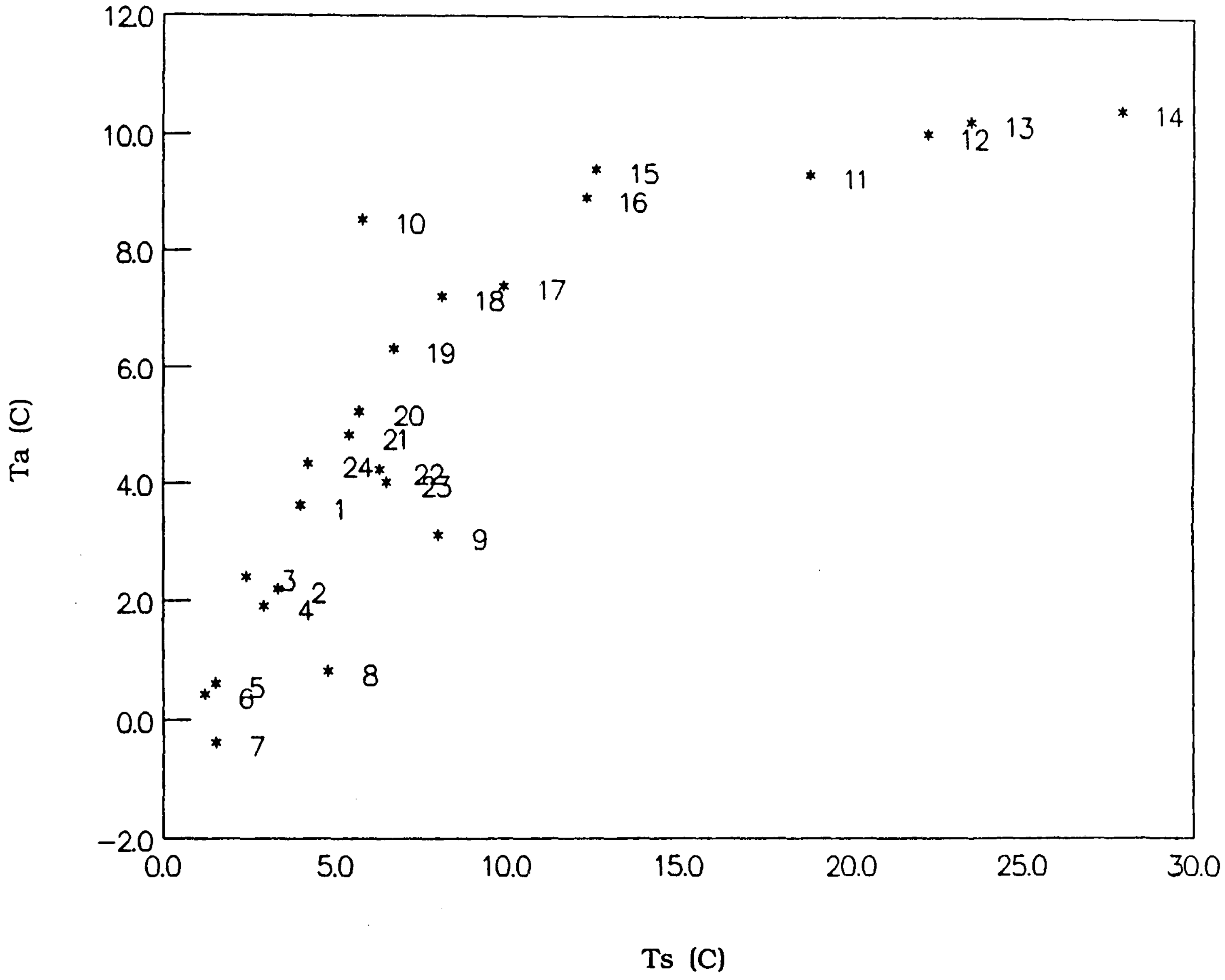

Figure 1. Relationship between hourly (LST) surface radiative temperature Ts (C) and 1.5-m air temperature Ta (C) at a mid-latitude urban site in Shimozuma, Japan, starting at 1000 LST on 11 February 1985 and continuity until 0900 LST on the next day.

THE SHANGHAI URBAN HEAT ISLAND AND ITS FORMATIVE FACTORS*

Chow Shu Djen (Zhou Shuzhen)
East China Normal University

ABSTRACT

The urban heat island of Shanghai is very pronounced. Based on multiple observations, the author describes the diurnal, seasonal, and long-term variations of the urban heat island intensity in Shanghai. The Shanghai heat island develops when the weather condition is steady with clear skies and low wind velocity. Because of the high degree of urbanization, the surface properties of the city are quite different from those of rural areas, characterized by low albedo, less evapotranspiration, more thermal admittance and warmer surface temperatures that release more energy to the atmosphere than do rural surfaces. Due to its greater population density and energy consumption, the amount of anthropogenic heat generated by the city is much higher than the countryside. The Shanghai urban heat island is formed by the combined effects of the above regional synoptic conditions and anthropogenic factors due to urbanization.

KEYWORDS: heat islands, measurements, urban climate

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THE SHANGHAI URBAN HEAT ISLAND AND ITS FORMATIVE FACTORS*

Chow Shu Djen (Zhou Shuzhen)
East China Normal University

INTRODUCTION

Shanghai is the largest and most rapidly growing city in China. The population density, percentage of built-up area and the consumption of energy in the city proper are very high. The urban effects on climate is very remarkable (Chow, 1986).

This paper discusses the Shanghai urban heat island and its formative factors based on: (1) meteorological data obtained by the Shanghai Central Observatory, ten suburban county stations and multiple temporal spot measurements at fixed stations and mobile surveys inside and outside the city; (2) infrared imagery of Shanghai in 1984, 1985 from the Tiros-N/GMS AVHRR* meteorological satellite obtained by the Chinese National Meteorological Bureau and (3) data on coal consumption from the Shanghai Statistic Bureau and Environmental Agency.

This research is not only important to answering the theoretical question of how man's activities affect temperatures, but also provides a scientific basis for urban weather prediction, urban environmental protection, and urban design.

THE URBAN HEAT ISLAND EFFECT IN SHANGHAI

Multiple observations have shown that the urban area is nearly always warmer than its surroundings, especially when the dominant weather conditions are calm and clear. For example, on December 13, 1979 at 8 p.m. (a calm, clear night) the air temperature was 8.5 ° C at the center of downtown while at Jiading, located to the northwest, it was only 2 ° C, indicating an urban heat island intensity of 6.5 ° C (Chow and Chang, 1982). During overcast or foggy days the urban heat island effect isn't obvious. For example, on February 8, 1977 at 8 a.m., when Shanghai was covered by fog, the urban-rural temperature difference ($\Delta T_{u\text{-}r}$) was only 0.2 ° C (Chow and Zheng, 1987). There was no urban heat island on days with strong wind and heavy rain.

Under stable and clear synoptic conditions the diurnal variation of urban heat island intensities in Shanghai is very evident. We find throughout the year that $\Delta T_{u\text{-}r}$ is small during daytime and large during the period from dusk to sunrise. We give an example of our summer measurement on August 9-11, 1959 that showed the heat island

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*AVHRR: Advanced Very High Resolution Radiometer did not exist in the daytime, but developed rapidly in the interval from 3 p.m. to 5 p.m. (Chow and Chang, 1982). The urban heat island intensity remained at 2-4.5 ° C from 6 p.m. to 5 a.m. on the following day (Figure 1).

In Figure 2 we give another example of measurements done on October 2, 1985. Figure 2c shows the networks of air temperature observations at three times (8 a.m., 2 p.m., 8 p.m.). Figure 2b gives the air temperature profiles through seven urban stations from Baoshan County to Xinzhuang. For the same day, we calculate surface temperatures at two times (7:48 a.m., 2:23 p.m.) by analysis of infrared pictures from the Tiros N/GMS meteorological satellite. The profile of surface temperatures from north(N) to south(S) of Shanghai City is shown on Figure 2a. From these figures we can see that, of the three observation times, the highest heat island intensity of air temperature appeared at 8 p.m., while at 2 p.m. the heat island intensity was relatively weak. These results are similar to the summer measurements mentioned earlier. The diurnal variation in the difference between urban and rural surface temperatures (ΔT_B), however is quite different. This difference is an important factor in the formation of urban heat island that will be discussed later.

Seasonal variations in the urban heat island intensity of Shanghai is also very pronounced. From Figure 3 we can see that the urban-rural differences in the monthly mean and minimum temperatures are largest in the late autumn and early winter (October to December) when the cloud amount and wind velocities are at or near their minima. During the spring and summer, the urban heat island intensity becomes weaker as the cloud amounts and wind velocities increase.

A comparison of five-year consecutive annual mean and minimum temperatures over the past 25 years between Shanghai Central (urban), Shanghai County (suburban), and Songjiang (rural) observatories show that the general trends of temperature fluctuations are the same. The reason is that all three observatories are controlled by the same regional climatic factors. However, owing to the influence of urban heat island, the Shanghai Control observatory exhibits greater temperature increases during periods of rising temperatures and smaller decreases during periods of cooling (Chow, 1983). As a result, the difference of temperature between Shanghai urban and its rural areas (ΔT_{ur}) has increased gradually (Table 1).

From Table 1 and Figure 4 we can find additional interesting points. With respect to latitude, Songjiang is in the south (31 ° 00' N); Shanghai County is in the middle (31 ° 07' N) and Shanghai Central, i.e., Longhua, is in the north (31 ° 10' N). During the last 25 years, the annual mean temperature (5-yr. consecutive means) of Longhua was higher than that of Shanghai County and further higher than that of Songjiang. This is because Longhua is located inside, while Shanghai County (i.e., Xinzhuang) and Songjiang are located outside the urban heat island. Moreover, Songjiang is located farther from downtown than Shanghai County. The climatic influence of the city decreases with the distance from the urban areas, and has greater impact than differences in latitude.

The distance between Longhua and Xinzhuang is about 3' latitude (about 6 km.), and shorter than the distance between Xinzhuang and Songjiang (about 13 km.). However, the differences of 5-year consecutive annual mean and minimum temperatures between Longhua and Xinzhuang (columns A and A' of Table 1) were larger than those between Xinzhuang and Songjiang (columns C and C' of Table 1). These are because the former difference is that between inside and outside the urban heat island, while the latter is that between two stations both located outside the urban heat island and hence showing little temperature difference.

With the continued urban development of Shanghai, the urban-rural difference in 5-year consecutive annual mean minimum temperatures (columns A' and B' in Table 1) has been increasing more rapidly than that of annual mean temperatures (columns A and B of Table 1). From Figure 4b, we can see that in the late 1950's, the urban-rural difference in annual mean minimum temperatures was 0.2 - 0.3 ° C, while in 1983-1984, it has reached 0.9-1.0 ° C and increasing faster than that of annual mean temperature (see Figure 4a).

FORMATIVE FACTORS OF THE SHANGHAI HEAT ISLAND

Weather conditions are very important to the formation of the Shanghai urban heat island. Using the meteorological data for 1984, we defined the difference of air temperature at 8 p.m. of every day between Shanghai Central, i.e., Longhua, and Xinzhuang as the heat island intensity $\Delta T_{u\text{-}r.20}$. We then considered the following four factors as independent variables: (1) total direct solar radiation, S (J/cm^2day), (2) mean diurnal wind velocity, $\overline{V}_a$ (m/s), (3) wind velocity at 8 p.m., V_{20} (m/s), and (4) low cloudiness at 8 p.m., N_{20}. All these factors were based on observations at Longhua. We took out the days with precipitation, passage of cold or warm air masses, or fogs, and used the remaining 154 days in a regression analysis. The resultant equation is:

$$\Delta T_{u-r.20} = 1.201 + 0.08375 - 1.146\overline{V}_a - 0.080V_{20} - 0.022N_{20} \qquad [1]$$

This equation has a significance level of 0.05, with a multiple correlation coefficient of 0.68 and a mean square deviation of 0.036 (Chow and Shao, 1987). Equation 1 shows that direct solar radiation has a positive effect on the intensity of the Shanghai urban heat island, but that wind velocity and cloudiness have negative effects on it.

The formation of the urban heat island of Shanghai is also closely related to the differences between the surface properties of urban and rural areas. Due to the high density of buildings with dark roofs and walls, the albedo of the urban area is smaller than that of the countryside. This is clearly shown in picture from the Tiros-N/GMS meteorological satellite (Figure omitted). As a result, the urban area absorbs more solar radiation energy than the suburbs on a clear day.

Due to the reduction in vegetation, heat used in evapotranspiration is sharply reduced in Shanghai proper. Rapid runoff after rainfall essentially eliminates water storage and keeps the urban man-made surfaces dry. In contrast, there are lots of paddy fields in the rural areas. Therefore, on a clear day from sunrise to 2-3 p.m. surface temperatures rise more rapidly in the urban compared to the rural areas (see Fig. 2a).

Since the mean thermal conductivity (K) and capacity (C) of the building materials in the urban surfaces is 3 and 1/3 times larger, the urban areas have a much greater thermal admittance u ($=\sqrt{KC}$) than the rural areas and can store more heat energy during the day (Chow and Chang, 1985). After sunset, urban surface temperatures decrease slower than those of its suburbs. Therefore, the temperatures of urban surfaces are usually higher and give off more energy to its environment by means of long wave radiation and turbulent exchange than do the nearby rural areas. The three factors mentioned above play important roles in the formation of urban heat island.

From analysis of satellite infrared photographs, we found that the surface temperatures of the Shanghai urban areas were much higher than those of its suburbs at 2-3 p.m. (see Figure 2b). The surface temperature (°C) distribution for February 26, 1984 at 3 p.m. shows relatively high temperatures in the city enclosed by isotherms that are highly similar to the pattern of paved areas in Shanghai. However, for the same day an urban heat island was not apparent in the isotherm chart of real measured air temperatures at 2 p.m. (Figure omitted, see Chow and Wu, 1987). Based on the ground observation data the air temperature heat island did not appear until 8 p.m. (Figure 6) and lasted through to 2 a.m. of the next day (Figure omitted). The diurnal variation of wind velocity (V), urban air temperature (T_u), and rural air temperature (T_R) are shown in Figure 7. During the day, especially at 2 p.m., high wind velocities caused significant energy exchanges in the atmosphere in both horizontal and vertical directions, reducing the ΔT_{u-r} between the urban and rural areas (see Figure 7). After sunset, the wind velocity decreases, and the heat exchange weakens. The stored energy in the urban surface is given off continuously and partly compensates for the heat loss to the atmosphere due to long wave radiation. This causes urban air temperatures to fall slower as compared with the rapid temperature decrease in the rural stations (see Figure 7), and results in the formation of an air temperature urban heat island (Chow and Wu, 1987). Moreover, the row upon row of buildings in the city reduces the sky view factor, also contributing to the formation of an urban heat island at night (Oke, 1978).

Another formative factor of urban heat island is that the urban area releases more anthropogenic heat than do its suburbs. According to an investigation of energy consumption of a 500 km^2 area, including both Shanghai city and parts of the nearby four counties conducted by the Environmental Protection Bureau of Shanghai, the 12 districts of the city proper covered 340 km^2, or 68% of the total investigating area, but their coal and fuel oils consumptions accounted for 78.36% and 73.65% of the total (see Table 2). The survey indicated that the annual coal and fuel oil consumption of the urban areas were 36874.6 ton/km^2 and 11533.6 ton/km^2, respectively. This indicates that, for these two factors alone, the average quantity of anthropogenic heat released per-square kilometer in the urban areas is 3.2 times that released in the suburbs. If we consider other sources of anthropogenic heat release, such as the combustion of other fossil fuels, the urban-rural difference of anthropogenic heat release becomes even larger. Besides these, the accompanying emission of CO_2 and plumes also add to the development of an urban heat island.

Over the past 30 years, the increase of coal consumption is very evident (see Figure 8), which must lead to the increase of anthropogenic heat emission. At the same time, the increase in population (Chow, 1983) and the decrease of wind velocity (Chow, 1985) in Shanghai urban area have all contributed to making Shanghai warmer. The progressively increasing urban heat island effect is shown in Table 1 and Figure 4.

CONCLUSION

From the preceding discussion it can be concluded that the urban heat island effect of Shanghai is very pronounced, and caused by both anthropogenic and synoptic factors. Urbanization has resulted in the high density of population and buildings, significant changes in surface properties tending towards low albedo, high thermal admittance, reduced green area, higher surface temperatures, enormous energy consumption and pollutant emission. These anthropogenic factors have produced a remarkable difference between the urban and rural environments. Under conditions of weak atmospheric circulation, i.e., stable weather with clear skies and low wind velocities, such urban-rural differences in air temperature are most evident. The intensity of the Shanghai urban heat island varies with different weather conditions. It is high on calm clear nights and has diurnal and seasonal variations. Due to the rapid development of urbanization, the urban heat intensity has increased gradually, with the increased most obvious in the minimum temperatures.

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Table I. Comparison of air temperature (5-yr. consecutive means) between Shanghai City and its suburbs (1960-1984).

5-yr. consecutive annual mean temperature T(° C)						
Period	I Longhua (urban)	II Xinzhuang (suburban)	III Songjiang (rural)	A I - II	B I - III	C II - III
1960-1964	15.96	15.84	15.80	0.12	0.16	0.04
1965-1969	15.54	15.36	15.24	0.18	0.30	0.06
1970-1974	15.48	15.28	15.26	0.20	0.22	0.02
1975-1979	15.88	15.62	15.88	0.26	0.20	-0.06
1980-1984	15.72	15.26	15.28	0.46	0.44	-0.02

5-yr. consecutive annual minimum temperature T(' ° C)						
Period	I' Longhua (urban)	II' Xinzhuang (suburban)	III' Songjiang (rural)	A' I'-II'	B' I'-III'	C' II'-III'
1960-1964	12.58	12.40	12.40	0.18	0.18	0.00
1965-1969	12.12	11.86	11.74	0.26	0.38	0.12
1970-1974	12.18	11.94	11.76	0.24	0.42	0.18
1975-1979	12.56	12.14	12.10	0.42	0.46	0.04
1980-1984	12.48	11.80	11.72	0.68	0.76	0.08

Table II. The distribution of energy consumption in Shanghai in 1984.

	Urban Area (U)	Rural Area (R)	Total
Investigating area (Km.^{2})	340	160	500
Percentage of coal consumption (%)	78.36	21.64	100
Percentage of fuel oils consumption (%)	73.65	26.35	100
Number of factories, coal consumption $\geq 10^4$Ton/a	72	20	92
Number of factories, coal consumption $\geq 10^3$Ton/a	434	83	517
Coal consumption (Ton/Km^{2}a)	36874.6	21640.0	U/R=1.704
Fuel oils consumption (Ton/Km^{2}a)	11533.6	7648.3	U/R=1.508

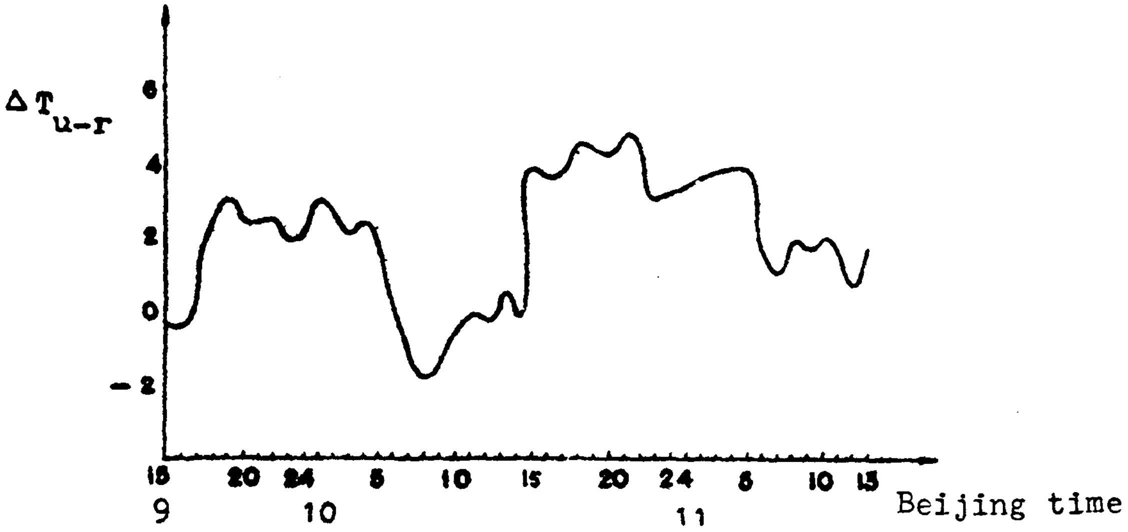


Fig. 1. Diurnal variation of the urban heat island intensity of Shanghai during the period August 9-11, 1959.

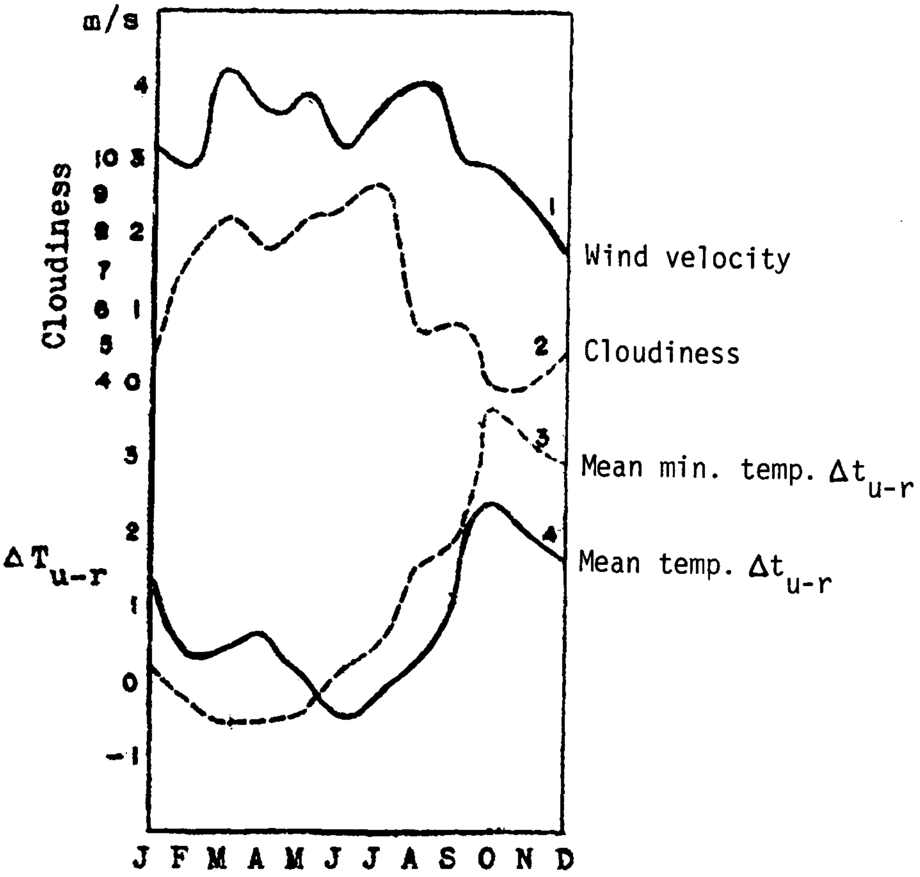
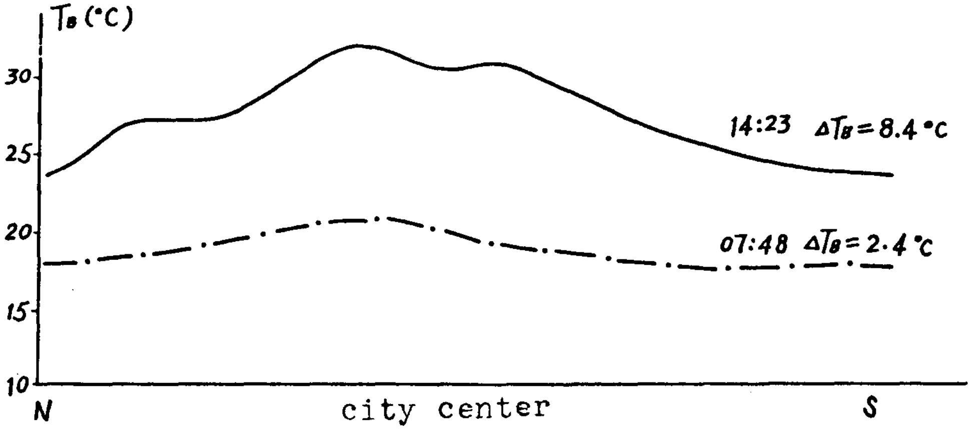
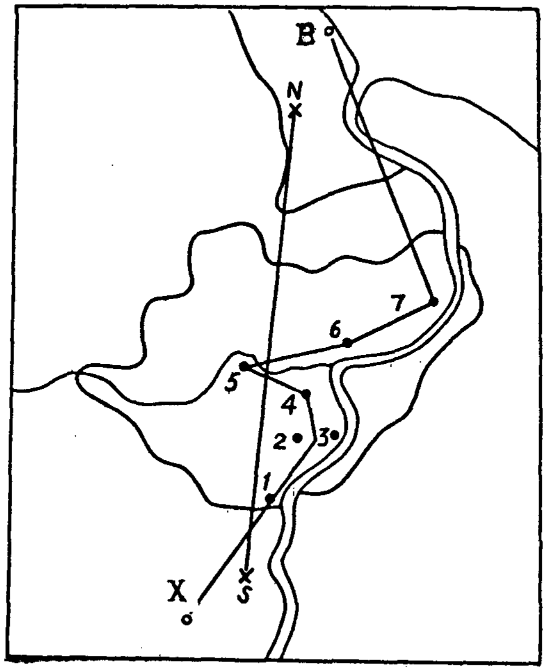


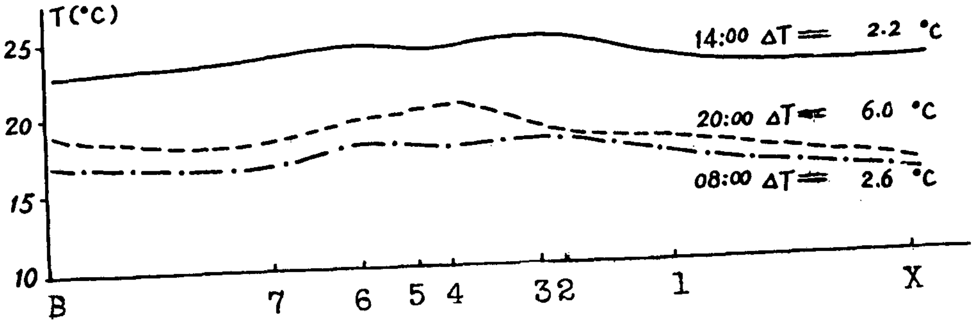
Fig. 3. The annual variations of wind velocity (m/s) (1), cloudiness (2), urban heat island intensities of mean minimum temperature (3), and mean temperature (4).



Δ T_B: urban-rural surface brightness temperature difference
(a) Profile of surface brightness temperature



(c) Networks of observations
N-S: profile line of Figure 2(a)
B-X: profile line of Figure 2(b)
B: Baoshan X: Xinzhuang



Δ T: urban-rural air temperature difference
(b) profile of air temperature

Fig. 2. Profiles of surface brightness temperature and air temperature on October 2, 1985, Shanghai.

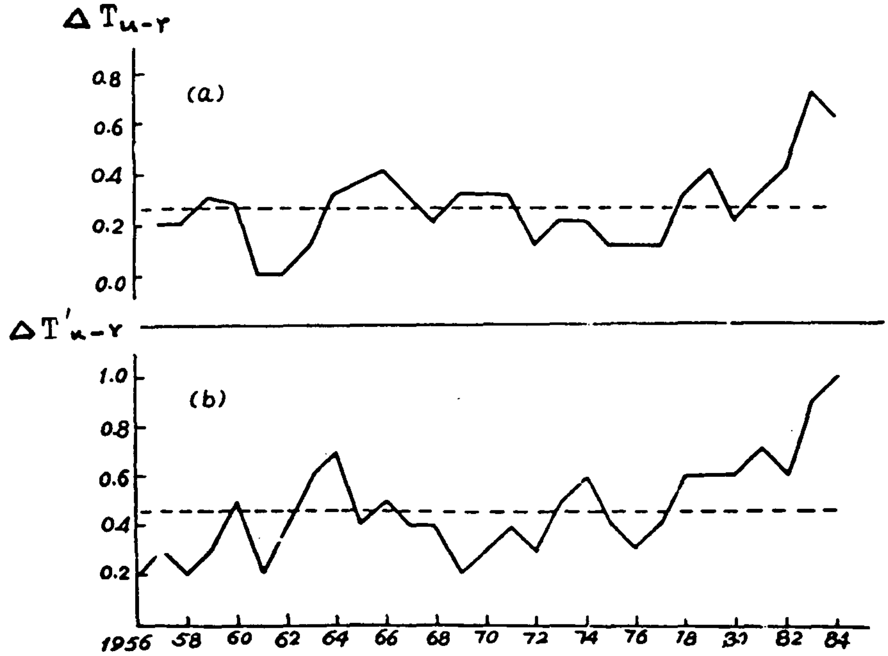


Fig. 4. (a) The evolution of annual temperature difference (Δ Tu-r) between Longhua and Songjiang

(b) The evolution of annual minimum temperature difference (Δ' Tu-r) between Longhua and Songjiang.

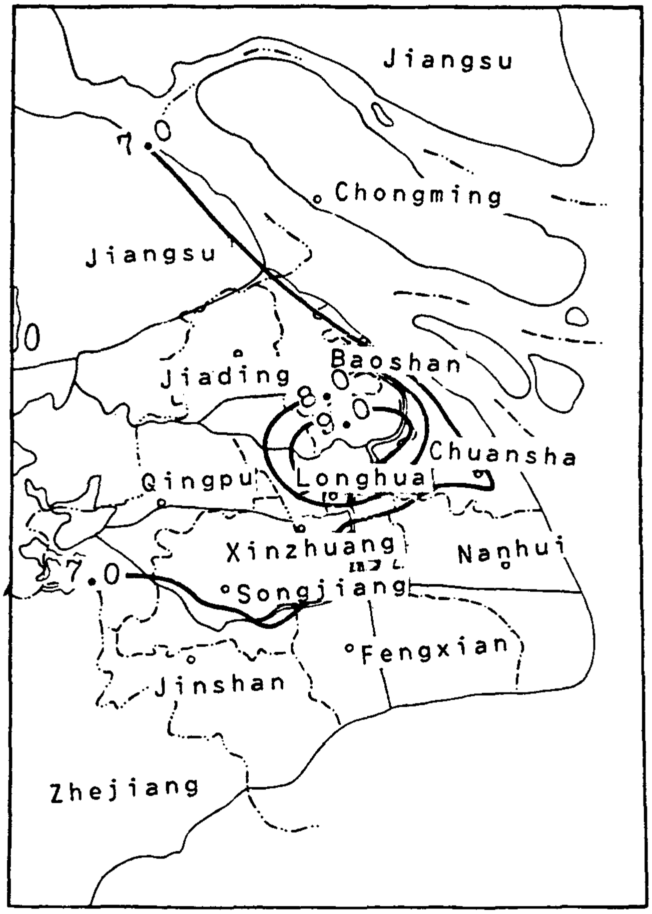


Fig. 5. The distribution of surface temperature (°C), Shanghai, February 26, 1984, 3 p.m.

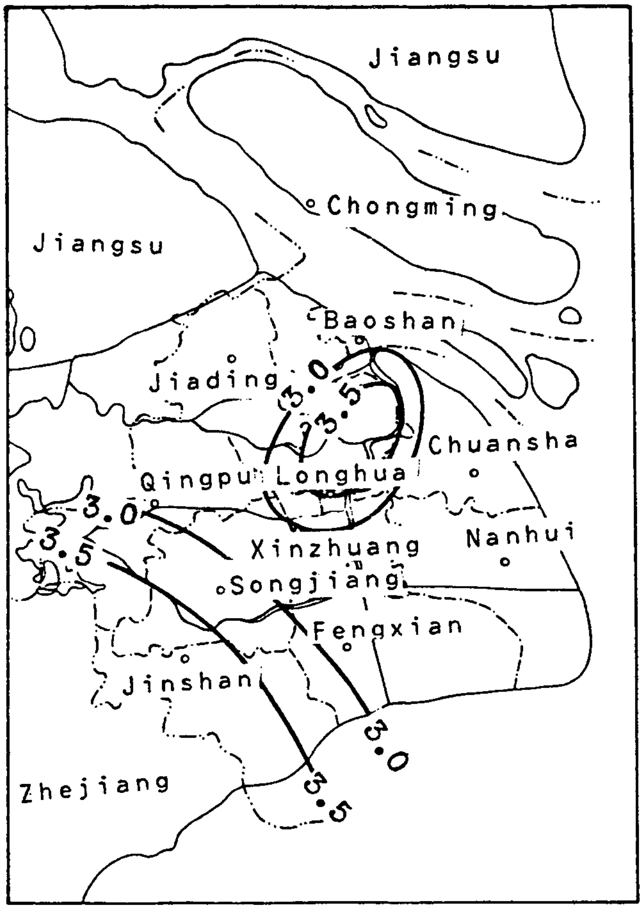


Fig. 6. The distribution of surface air temperature (°C), Shanghai, February 26, 1984, 8 p.m.

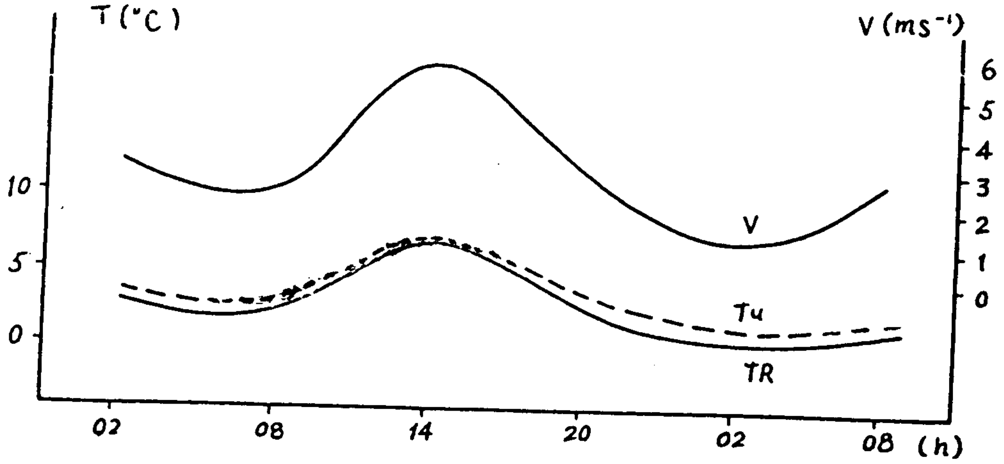


Fig. 7. The diurnal variation of T_u(°C), T_R(°C) and V(m/s), Shanghai, February 26-27, 1984.

T_u: The mean air temperature (°C) of seven urban stations

T_R: The mean air temperature (°C) of ten rural stations.

V: The wind velocity (m/s) of Longhua.

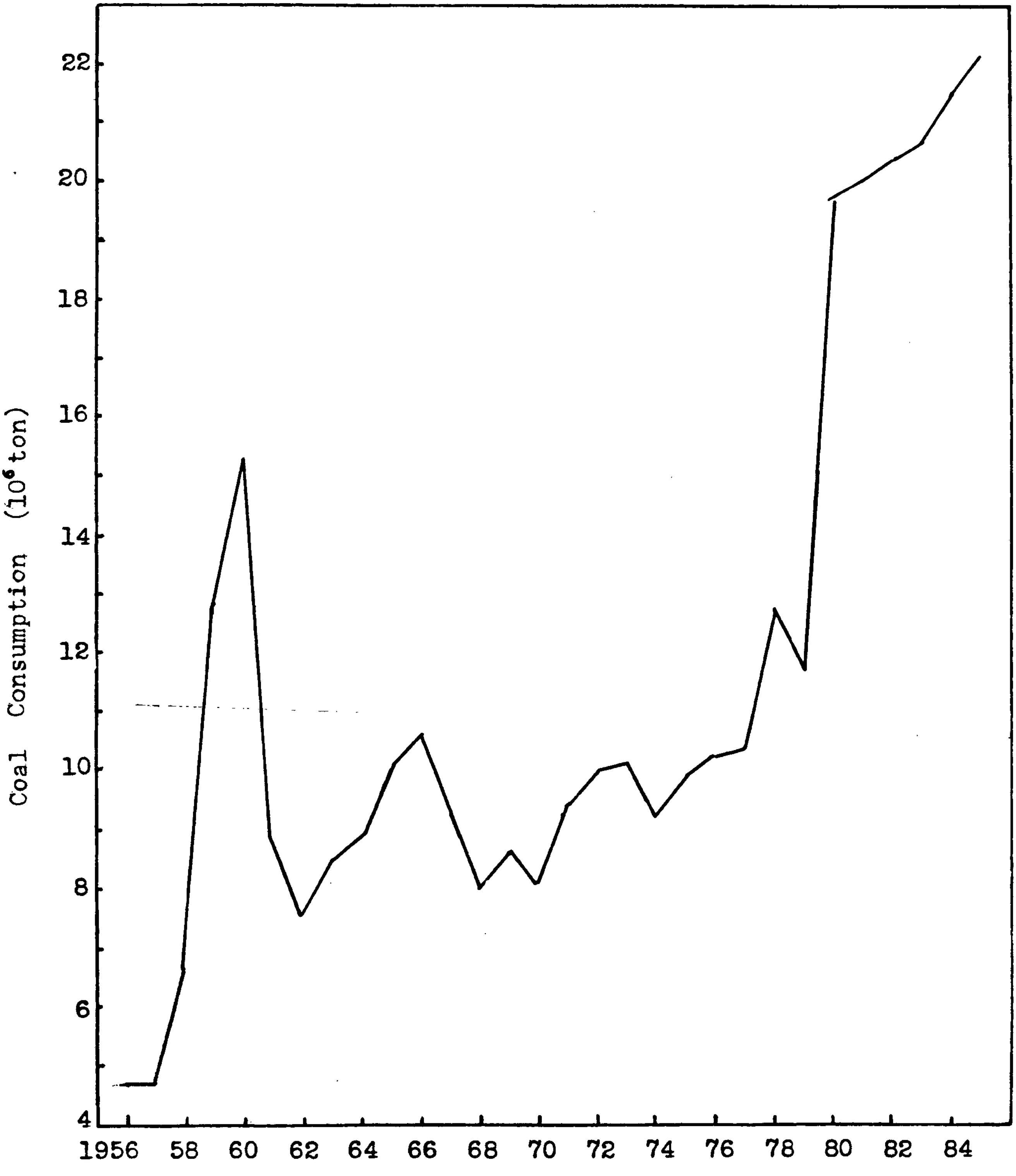


Fig. 8. The evolution of the coal consumption (10 ton) of Shanghai during the recent 30 years (1956-1985).

MEASUREMENT OF SUMMER RESIDENTIAL MICROCLIMATES IN SACRAMENTO, CALIFORNIA

L. Rainer, P. Martien and H. Taha
Applied Science Division
Lawrence Berkeley Laboratory

ABSTRACT

Although the existence of urban heat islands has been known for many years, actual measured microclimate data to quantify this effect has been limited mostly to short time period (1 to 2 day) automobile traverses recording hourly wet and dry bulb temperatures. There have been few simultaneous measurements of microclimates made at multiple sites over long time periods. This long term data is required to validate and improve the numerical models researchers at the Lawrence Berkeley Laboratory (LBL) are developing to quantify the impact of heat islands on cooling-energy loads.

To address this issue we have performed a two month study of the summer urban heat island in Sacramento California. Automatic weather stations which record dry and wet bulb temperature and wind speed and direction where installed in 15 residential locations throughout the city. A total of 1500 hours of half-hourly data were recorded for each site with less than 5% of the data missing or bad.

In this study we have analyzed the microclimatic data for all the locations and the results are characterized according to location, density of tree cover, prevailing wind direction and speed, and cloud cover. In addition, we have prepared hourly temperature contours of the heat island intensity for the city and have parameterized it in terms of the factors previously mentioned. The relationship between the heat island intensity and building cooling-energy loads, and ways of mitigating heat islands suggested by the data are discussed here.

NO PAPER SUBMITTED FOR PROCEEDINGS

REMOTE SENSING OF URBAN TERRAIN ZONES FOR URBAN PLANNING PURPOSES

Richard Ellefsen
Geography Department
San Jose State University

ABSTRACT

High altitude color infrared air photography has been used as the source to identify and map *urban terrain zones* in Sacramento, California. The classification system emphasizes morphological aspects of the urban scene—building heights, density, and materials—rather than traditional land-use classes that are designed to record urban functions.

The urban terrain system consists of such classes as (1) the high density, tall building core area (further subdivided into the traditional Central Business District with its older buildings, and the more recent urban redevelopment area with its glass towers); (2) industrial/storage building zones, one with close-set structures (as along railroad tracks) and another with widely spaced structures, as seen in new industrial park areas at the city's edge; and (3) both close-set and lower density single-family houses in their general settings. Separate thematic maps have been prepared of each of the terrain zone types to aid analysis. Data could be organized into grid cells or polygons or aggregated into any form required by an urban planner or urban climatologist.

The emphasis on form, rather than function, derives from a need in planning to allow for physical aspects of the surface environment (especially those of an urban nature, such as building height and structure spacing) in order to assist a model in identifying air circulation and venturi effects in *urban canyons*. Density and pattern of these morphologically derived zones also serves to help answer questions about the formation of *heat islands*. Study of the interaction between zones are facilitated by such analysis. Also included in the classification process is notation on building material types. Account can thus be made of heat retention and loss.

KEYWORDS: heat islands, land use, remote sensing, urban planning

Remote Sensing of Urban Terrain

Richard Ellefsen

Remote sensing is a useful means of providing some of the data requirement needs of urban environmental scientists engaged in trying to mitigate the effect of urban heat islands. This is especially so considering that remote sensing is at its best providing data on the physical properties of the environment and that this fits precisely the needs of such interests as meteorological modelling of urban areas. Aerial photographs, plus either visual images or digital data from satellites, readily allow identification and areal measurement of ground surface and building materials. Conversely, data collected on the ground for some other purpose — tax assessor's records, for instance — require interpolation to provide the physical information that is directly attainable from remotely sensed data. In short, ground collected data, such as land-use information, are, by definition, *functional* by nature. Needed instead, by urban environmental scientists, is *morphological* information on the physical properties of structures and other urban cultural artifacts.

Remotely sensed information is, in a very straightforward way, physical by defnition. Using either cameras or digital sensors, passive remote sensing systems are set to receive selected bands of the electromagnetic spectrum, mostly in and around the visual segment. Some parts of the spectrum provide physical information on the reflectance properties of certain areas of interest e.g., rooftops, while others are better suited (infrared, for instance) to supplying data on vegetation. In all instances, remotely sensed information is directly physical in character and is accordingly especially well suited to supporting physical studies of the urban environment.

Such physical information is readily usable by modellers to account for the intra-city differences of the lower boundary condition of the atmosphere. For instance, total building surface as well as building material in an industrial district differs significantly from conditions occurring in a tract of well spaced suburban houses. Studies prescribing tree planting locations can readily use remote sensing derived inventories on the present occurrence of street and yard trees plus the targeting of areas for further plantings. Large scale aerial photographs of urban areas have also been suggested as useful to urban hydrologists concerned with the quality of runoff from impervious urban surfaces leading, perhaps, to its recycling (northern California could well profit in 1989 from such measures).

The use of systematic, low oblique photographs to inventory wall and roof materials in support of urban acid precipitation studies in Baltimore, Cincinnati, and Los Angeles was demonstrated by the author. Further work is necessary to serve the goals of the National Acid Precipitation Assessment Program (NAPAP), especially in the US Northeast.

Available remotely sensed images and other data

Numerous basic texts and manuals are but a part of the voluminous literature detailing types of remote sensors and their specialized uses. Those systems most useful to the urban scientists in this workshop fall into the two major classes of air photographs and digital/visual data acquired from satellites. This is not to ignore such obvious tools as aircraft carried multi-channel scanners and arrays to measure surface temperatures.

Air photographs can be simply divided into oblique and vertical and these, in turn, to basic families of scale (and thus resolution and detail, although this also varies with film, filtration, focal length, and quality of lenses, plus various degrees of sophistication of camera mounting and handling). Oblique photography is given special attention later.

Vertical air photographs of urban areas that are readily available to anyone can be placed in a few basic classes. At very large scales are collections of photographs acquired by city governments for a variety of daily purposes such as tax assessment, public works, and city planning. These photographs are in the public domain and all municipalities make some provision for individuals to buy copies; some cities have simple systems, complete with public offices and browse files and maps, while some offer awkward arrangements, sometimes through contracted blue print firms. A likely place to begin an inquiry is the local public works department, or the planning department. The product sold to the public is usually a blue-line (or black-line) paper *Diazo* print made (at same size) from a reproducible black and white transparency (usually in quite a large format, like 18 by 24 inches); cost to the customer is usually only the charge for the print plus a service, about $3.00 is common. Scales are compatible with those used in city government and are usually expressed in terms of inches to feet, rather than the common representative fraction used in scientific circles. Thus, photographs are usually available at a scale of one inch equals 100 feet (1:1200) and at one inch equals 500 feet (1:6,000). Both are large enough to see, and measure, such features as individual single-family houses.

At the next level of commonly available urban air photographs are those at scales of around 1:20,000; these result from flying a 12 inch lens aerial mapping camera at an altitude of 20,000 feet (well above local airport traffic). These photographs are collected, catalogued and made available to the public through the National Cartographic Information Center, operated by the U.S. Geological Survey with browse files and order information available at their public centers (fortunately, for San Francisco Bay Area residents the nearest office is at the U.S.G.S. office at 345 Middlefield Road, Menlo Park).

Yet smaller scale photographs are taken by NASA for their principal investigators and these products become available for interested scientists. The photos are usually in the form of color infrared 9 by 9 inch transparencies with a scale of 1:65,000. Flown from an altitude of 65,000 feet with a U-2 or ER-2 reconnaissance aircraft and with fine resolution lenses, the pictures have both a fine level of detail and virtually no distortion. The scale is small enough to allow the capturing of large parts of cities on a single frame (for instance, Sacramento from the river to Folsom is included on a single frame). Spatial patterns are readily apparent at this scale. Again, the source is local: the High Altitude Program of NASA is operated out of Ames Research Center, Moffett Field. Arrangements to visit the facility and use the pictures can be made.

Pictures created from digitally collected data obtained by satellites are also easily available and form a valuable source of information to the urban scientist. The coarsest resolution of these is from the Multispectral Scanner Subsystem (MSS) aboard Landsat which provides digital data and "pictures" at a spatial resolution of 80 meters (each *pixel* is an aggregate of digital data at points along a gray scale with a measurement of nominally 60 by 80 meters). More recent Landsat satellites have flown the *Thematic Mapper* with its resolution of 30 meters (plus more spectral information). Most recently, the French have been marketing pictorial and digital data from their satellite *SPOT* (systeme probatoire pour la observation de la terre) with its capacity to offer data at a 10 meter resolution level. Photographs from this system (see Figure 1 of Phoenix) offer a level of resolution that approaches the quality of poorer aerial photographs. The obvious big advantage to such images is their availability for any city in the world, even commonly "denied" ones. Individual scientists can become licensees and can order data to be acquired over specified target areas. Cost is high, however, and an individual needing such a product might well consider either available air photographs, or contracting for tailored scanning or photographic services.

Intraurban differentiation: Urban Terrain Zones

Needed for the treating of urban physical phenomena (to be compatible with physically based data) is a system for identifying and classifying the distinctly different subdivisions (regions) of the city based on *physical* not *functional* characteristics. The commonly used land-use maps, census tracts, and tax assessor's records serve purposes that are economic or meet government record keeping needs. They are essential for commerce, planning, and governance but, as a result are awkward in studies of the physical urban environment for they make no attempt to account for physical properties.

The system proposed here, the delimitation and use of *Urban Terrain Zones,* is one based on full consideration of the physical properties of the urban landscape. The system, developed by the author for the Defense Department and tested in both domestic and foreign cities, takes into account several conditions of the buildings found within each zone. Characteristics of the buildings are: age, density, height, and type of construction. The relative location of the zone within the city is noted and only then is function (land use) considered. The two major subdivisions of the system indicate whether the buildings are attached to each other or are apart (detached). Further distinction among the detached buildings is then made of the degree of separation (close-set as opposed to open-set structures). Attached buildings are found in the city where land values are so high that developers feel the necessity to use as much as possible of the lot on which the building stands. Obviously, this condition obtains in downtown areas and along older (pre-automobile) arterial streets. An

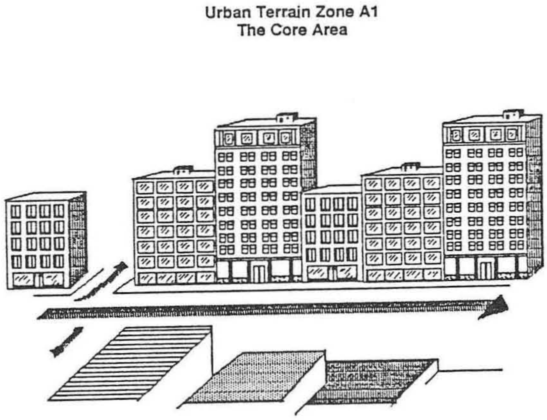
Figure 1. This black and white copy of a full color enhanced SPOT image of a segment of central Phoenix reveals only a part of the spatial information provided. Delimitation of urban terrain zones could easily be accomplished through photo interpretation of the original.

exception to the notion of attached in downtown areas is seen in administrative/cultural units (as a Civic Center) where master planning for the whole parcel can be practiced and where image matches practicality. A recent exception to the rule is the practice of separating new high-rise office towers by "breathing" space around; architects have responded by designing buildings whose facades and proportions are meant to be viewed from all sides.

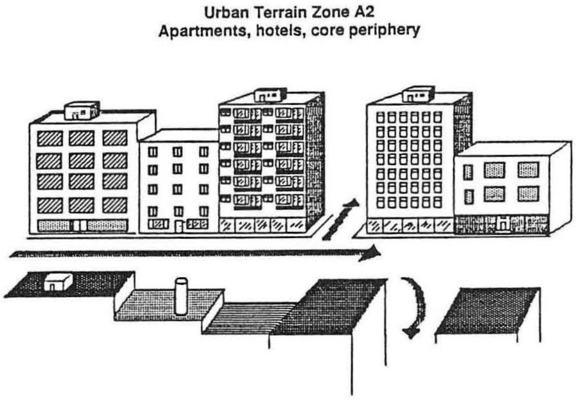
The following text and illustrations explain the zones:

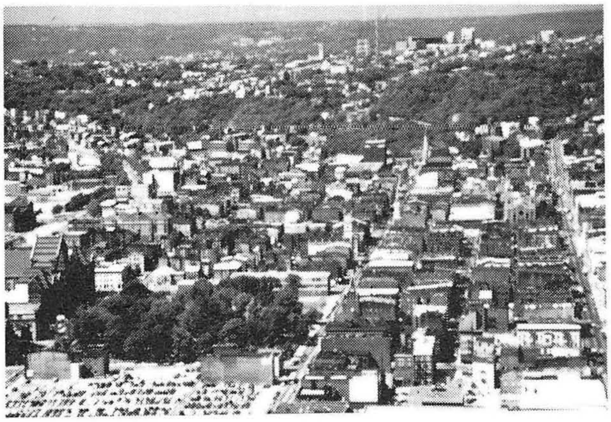
Attached building urban terrain zones

Zone A1: The Core Area. This zone is the old downtown and consists largely of offices and stores. Construction is mainly either pre-twentieth century brick or framed heavy-clad, erected during the period from about 1890 to 1941.

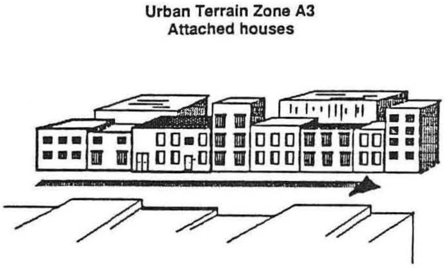


Zone A2: Apartments, hotels, core periphery. Buildings in this zone are attached, reflecting the extension of high land values outward from the core but with a lower level of intensity. Buildings are again either mass constructed brick or framed, heavy-clad.

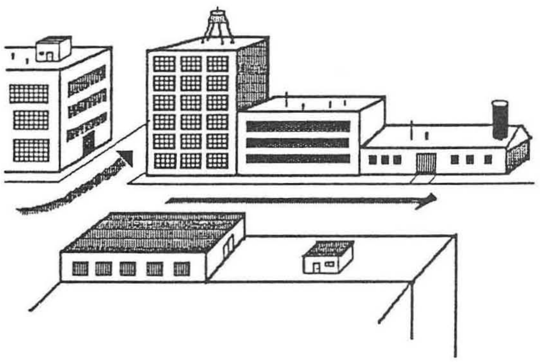




Zone A3: Attached houses. These are the typical "row houses" seen in many eastern cities, in Europe, and in a few other locales, such as San Francisco. Eastern examples are made of brick; western are usually wooden construction.

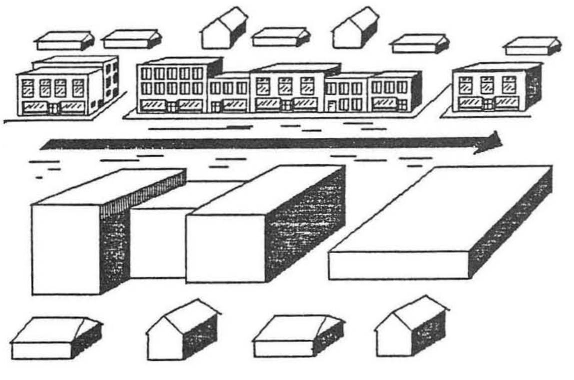


Zone A4: Attached buildings, industrial/storage. In virtually all cities of any appreciable size and developed in the last century, an area of factories is found near the core area (some have been removed in extensive urban redevelopment projects and replaced by modern facilities, such as sports stadia, parks, or monuments). Again, buildings are either brick construction or framed, heavy clad. This is the first of three morphological variations of the function industrial/storage.

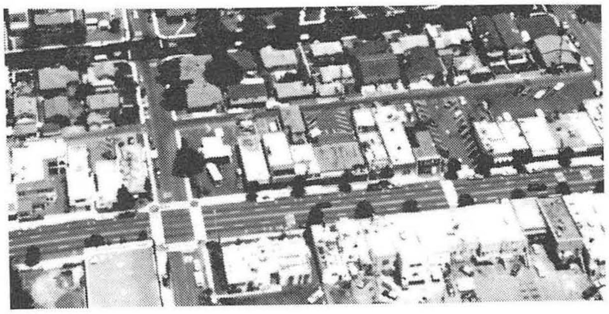


Urban Terrain Zone A4
Attached buildings, industrial/storage

Zone A5: Old commercial ribbons. High land values, expressing high accessibility, have resulted in the placing of attached buildings along arterials extending outward from city core areas. Much lower land values immediately behind these commercial units permit the customary amount of open space around detached houses. Commercial buildings facing the street are often older, brick structures; houses behind reflect the dominant residential construction form, either mass or framed.

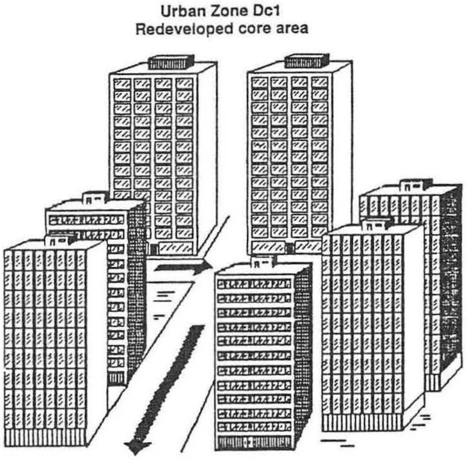


Urban Terrain Zone A5
Old commercial ribbons

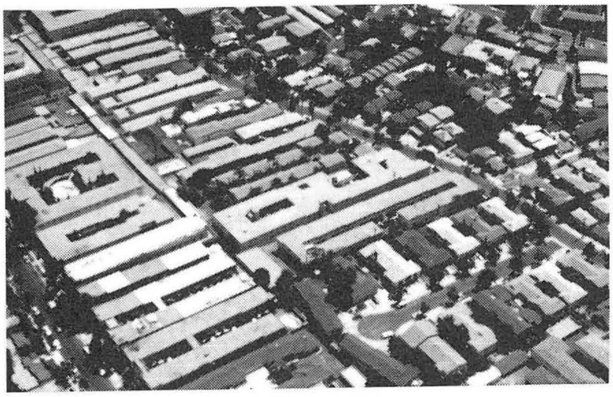


Detached, close-set building urban terrain zones

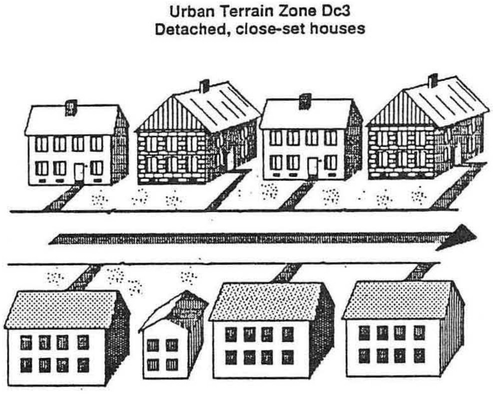
Zone Dc1: Redeveloped core area. Urban redevelopment and urban renewal projects in downtown areas built in recent years have come to exceed the original core and have imparted imposing skylines of modern structures to major cities everywhere, both domestic and foreign. The buildings, usually free-standing, are modern in style and form of construction being framed, light-clad; cladding varies according to fashion and ranges from all glass to polished thin granite veneer.



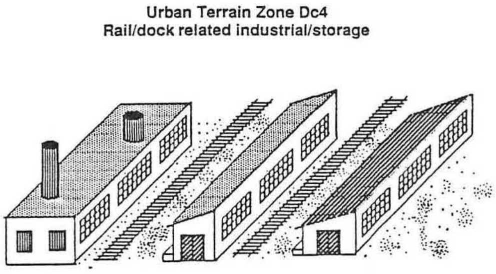
Zone Dc2: Apartments, close-set. Lower land values away from the core allow for some space between apartment buildings even though they are found on ordinary streets. Construction type is usually in keeping with the methods of the area.



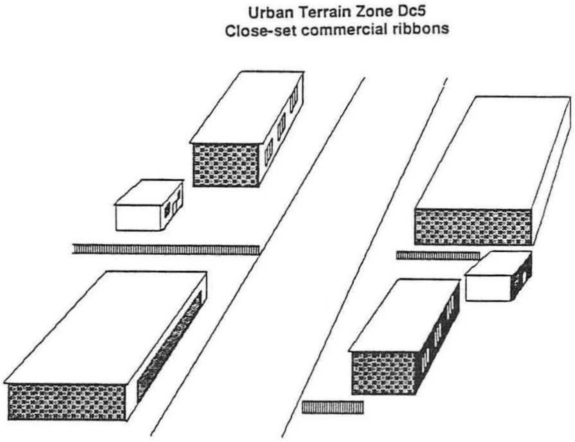
Zone Dc3: Detached, close-set houses. This class, curiously, reflects relatively high land values both in the pre-automobile days and today in such modern housing tract developments as those in California where even though the units are, at the moment, remote from city center they occupy high-value land. The high cost of providing urban services is another reason for high densities.



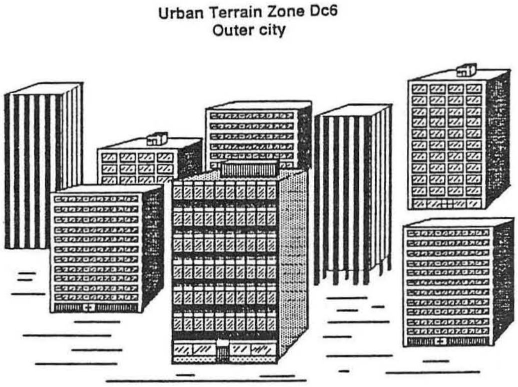
Zone Dc4: Rail/dock related industrial/storage. Buildings in this class show a clear adjustment to their siting. Being served by linear transportation lines, the buildings often have little space between them (often only enough for a railroad siding). Several construction modes are seen including mass construction forms of brick and concrete and framed structures, especially those clad with corrugated steel.



Zone Dc5: Close-set commercial ribbons. Commercial businesses in this class sit along major arterials but exhibit patterns that suggest evolution toward the provision of off-street parking; some older structures are remnants of attached structures along arterials while some newer ones have responded to modern planning regulations. Construction type is mixed, ranging from brick and concrete to wood framing (usually clad in stucco in California).

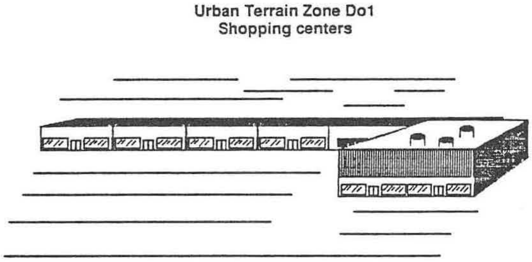


Zone Dc6: Outer city. These areas are fully planned units of shopping, offices, hotels, and often apartments resembling fully created downtowns but placed at some point of high accessibility in suburbia (as at a major highway interchange) or, increasingly, at airports (the development around LAX in Los Angeles offers a fine example). Construction type is obviously recent and therefore of the framed, light-clad variety.

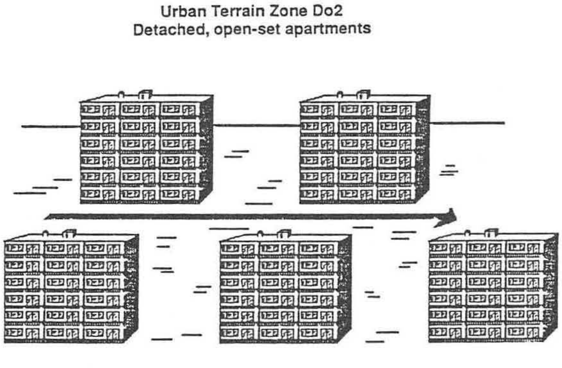


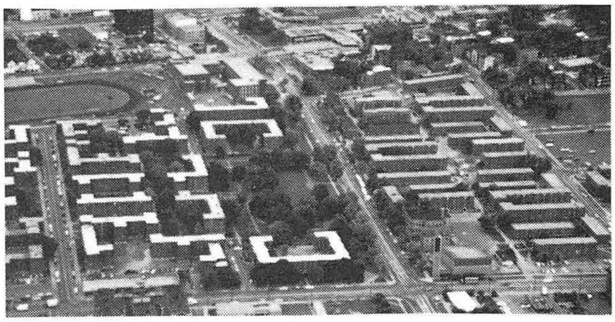
Detached, open-set building urban terrain zones.

Zone Do1: Shopping centers. Where the space required for automobiles exceeds that of the footprint of the building(s) the separation of structures clearly is open-set. Interest in studies of the urban environment might shift from structure to the nature of the impervious surface of the parking lot. Structures are modern, sometimes framed construction and sometimes mass, either concrete poured in place or "tilt-up" or concrete building block.

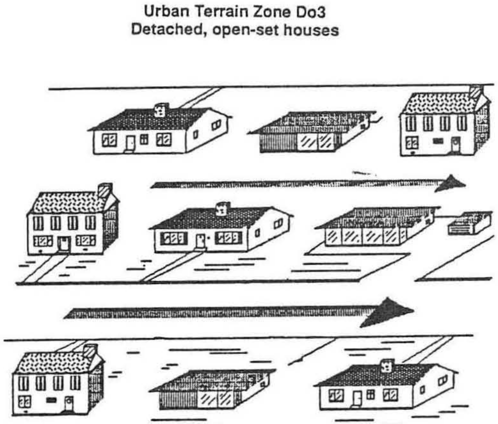


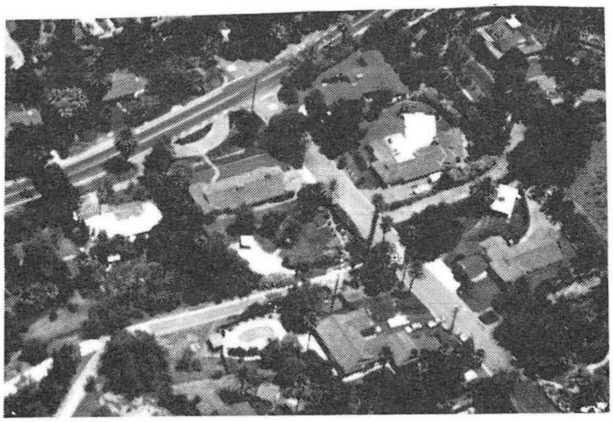
Zone Do2: Detached, open-set apartments. Developments of this kind usually show ample evidence of being planned on a fairly large parcel of land. Buildings are frequently multi-story, usually of the same design throughout the development, and separated by some distance from one another by parking lots, landscaping, and activity areas. Construction is frequently of a framed type.



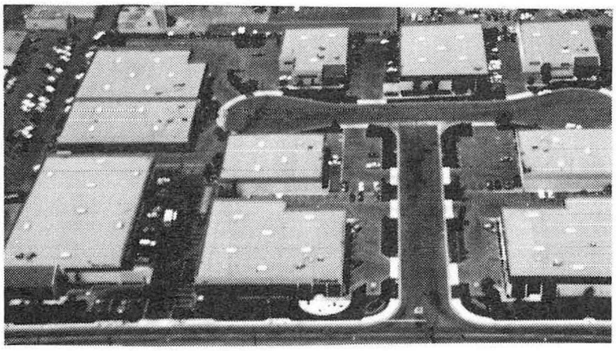


Zone Do3: Detached, open-set houses. Houses in these areas are commonly of high enough value to pay for the luxury of abundant space around them; lots are often an acre or more in size. Interestingly, dependent of course on the climatic situation, these areas are frequently sites of large numbers of urban trees; planting, however, is usually more for esthetic than pragmatic purposes.

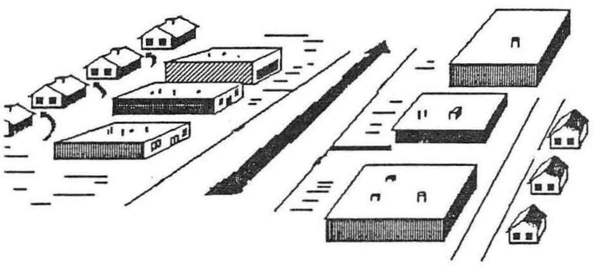




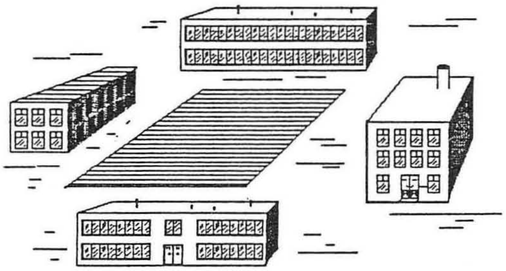
Zone Do4: Detached buildings, industrial/storage. These zones are modern in style with ample space around the structures designated for employee parking, storage of raw materials or products, and even landscaping (plantings of trees in berms is almost a cliche). Often found in "industrial parks (estates)," they are usually quite uniformly spaced one from another. Construction form is also modern, often mass "tilt-up."

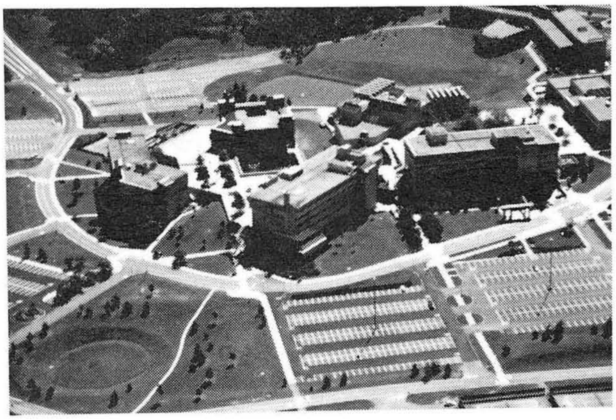


Zone Do5: Detached buildings, new commercial ribbons. This phenomenon is found along major, usually very wide, commercial arteries. Buildings are commonly in units of several stores served by a combined parking lot in the front (some are landscaped, a few have trees). Construction is varied; some are framed, some mass.


Urban Terrain Zone Do5
Detached buildings, new commercial ribbons

Zone Do6: Administrative/cultural. These areas definitely show the result of planning and erecting a number of structures in accordance with a master plan; a university campus is a good example. Structures are usually well separated from each other. Construction varies with the age of the facility; older institutions will often have old and new forms.


Urban Terrain Zone Do6
Administrative/cultural



The Enviro-pod camera system

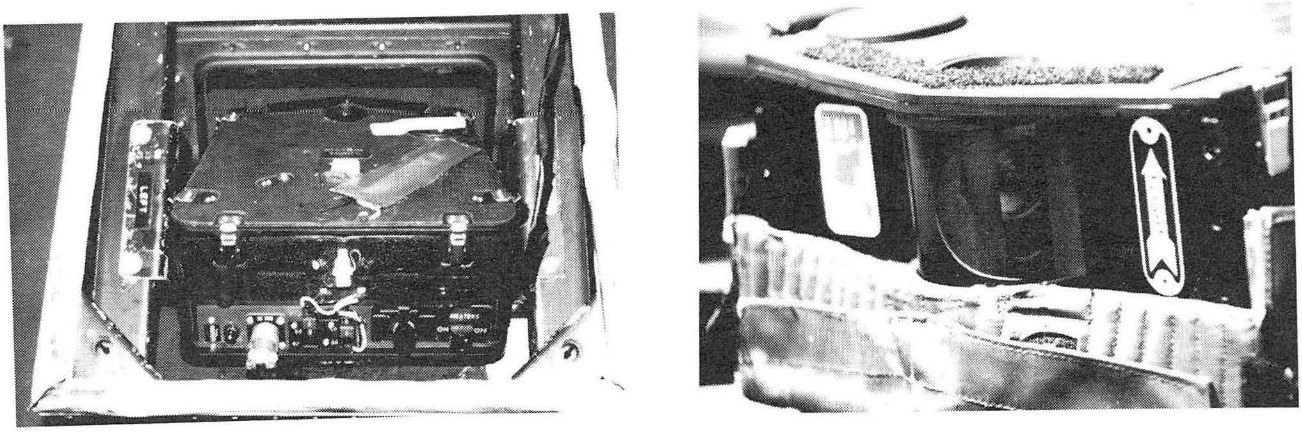
While acquiring vertical photographs with sufficient sidelap to obtain coverage of broad areas and with enough overlap to allow viewing them stereoscopically is common, oblique photographs of urban areas have been largely of the "one-off" variety, a publicity shot of a commercial firm, a news program photo, etc. Acquisition and use of **systemic** areal coverage of oblique photographs would seem to be especially useful to urban scientists. One obvious advantage, over vertical images, is the ability to see the sides of buildings, as well as the roof. Yet another is the ability to see profiles of urban trees, not just their crowns. Identification of at least groups of species of trees would seem possible. In the same vein, some information on *soffets* of buildings (those areas under porch roofs, balconies, and the like) can be obtained from oblique photos.

Research was conducted in 1987 and 1988 by the author in the acquisition and use of an oblique camera system, the **Enviro-pod**, in studies of Baltimore, Cincinnati, and the Los Angeles area (the South Coast Air Basin); the studies involved making inventories of wall and roof building materials in support of acid precipitation damage studies.

System and mission specifications

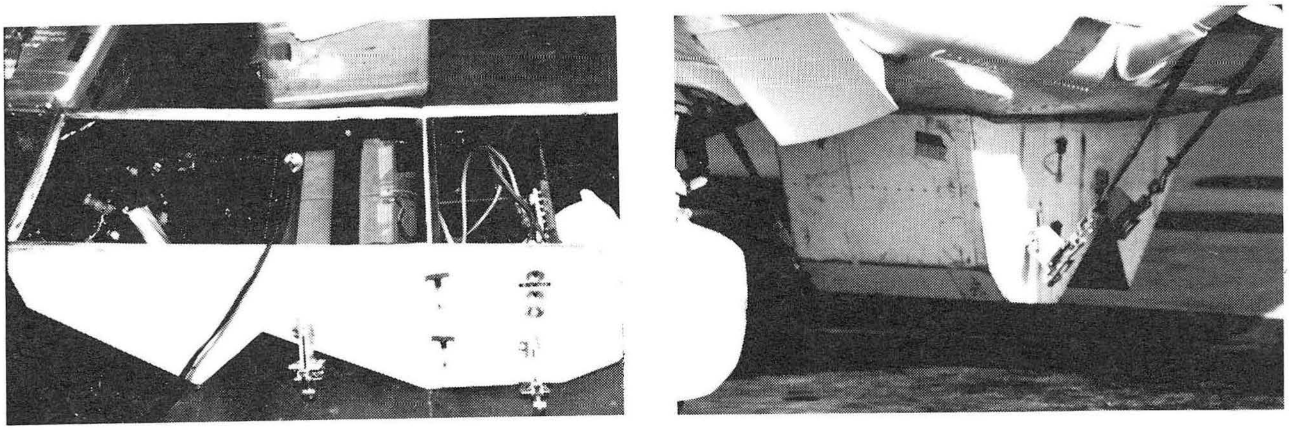
The Enviro-pod camera system is composed of a pair of US Air Force reconnaissance K85A cameras, one mounted at a 45° angle and the other vertically in a metal capsule designed to be attached to the bottom of the fuselage of a Cessna high-wing aircraft (either a 172 or a 182); the intent was for broad, easy usage with aircraft that are universally common. The cameras, are of the "panning" type (with a rotating lens), and they expose 70 mm film in 200 mm wide strips on 200 foot long rolls; film used was full natural color and processed as transparencies; alternative films are, of course, available. The camera's shutter is controlled with an intervalometer from inside the aircraft. The pod prior to attachment, the camera, and the system as attached to the aircraft are seen in Figure 2.

Flight lines, demarcated on maps, were 1.5 kilometers apart. Flying at the FAA approved minimum flying altitude of 1,000 feet and with the standard 80 mm lens attached this distance allowed for sufficient side lap. At a flying speed of 90 knots the intervalometer was set to provide full



a. The oblique camera in its bay

b. The camera's rotating lens



c. The Enviro-pod

c. Mounted on a Cessna 182

Figure 2. The panels show the Enviro-pod camera system, its cameras, and how it is mounted on the fuselage of an aircraft.

coverage (and little overlap) at an interval of 6.5 seconds. The Baltimore study was a pilot effort with only one 200 foot roll being exposed over test sites in the center of the city. In Cincinnati, the entire contiguously built-up area was covered (including parts of adjacent Kentucky). For the Los Angeles area, a total of 30 sites (averaging 4.6 km^2 each) was covered. In all cases, pictures were obtained along flight lines vectoring in all four cardinal directions, viz., W-E, E-W, N-S, and S-N, thus providing the interpreter with views of front, back, and sides of buildings; building materials on the front are commonly different from those at the rear. Figure 3 is an example of an Enviro-pod picture of one of the Los Angeles area sites.

Interpretation

Interpreters were able to determine and to measure quite discrete levels of building material. Wall materials were: concrete block, brick, concrete, stucco, tile, terra cotta, stone, aluminum, steel, wood, glass, and plastic. Where applicable, notation was made as to whether the material was painted or bare. Roof materials recorded were composition, wood, metal, plastic, and concrete. The height and material of fences was also noted. Account was made of such mechanical features as vents, antennae, and air conditioners. As the studies were conducted for different agencies, the lists were not uniform.

Applicability of Enviro-pod photographs to urban heat island mitigation studies

Several possible applications and advantages of the Enviro-pod system deserve consideration of its use in urban heat island studies. One is the use of the pictures to prepare a very fine scale delineation of the urban terrain zones of a city; such a map, coupled with specific data about the physical character of its buildings, streets, and non-built-upon spaces could be very useful to meteorological modelers. Lessons learned from inventorying building and roof materials could be employed to derive potentially valuable information on reflectivity, shadows, venturi effects between buildings, and texture of walls and roofs to be used in the modeling process. Vegetation details, although not considered in the acid precipitation building materials inventory work, show readily in the photographs and could be employed in

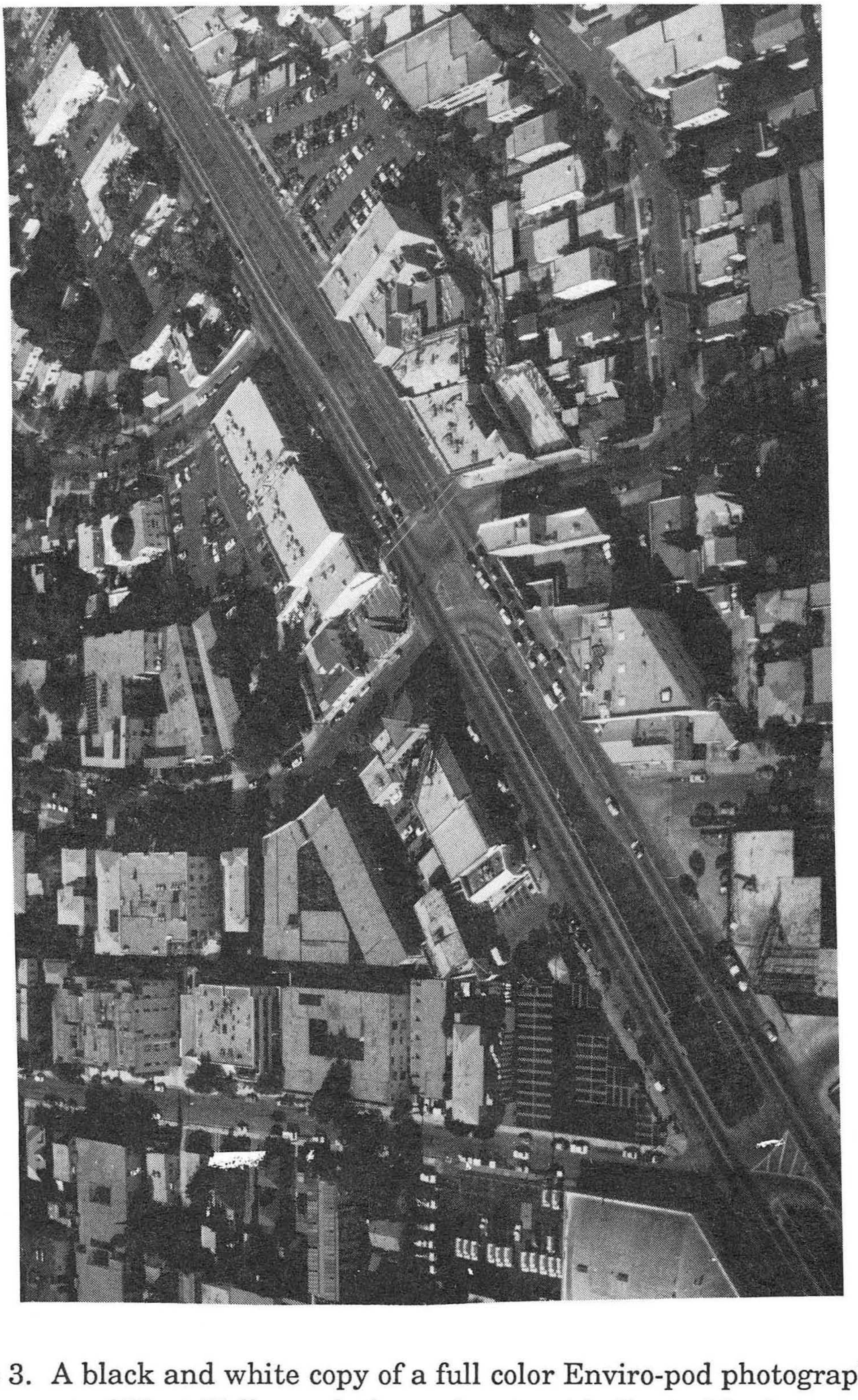


Figure 3. A black and white copy of a full color Enviro-pod photograph. The site is a part of West Hollywood; the major street is Santa Monica Boulevard. Note the detail of the roof features. Building height can be determined by counting stories.

a variety of ways. In short, the quality of these high resolution, low altitude oblique photographs is very high thus providing almost as much detail as can be obtained by actually being on the ground. Sometimes the amount of information is greater, for as with the case of buildings with flat roofs and parapets, the roof surface or even its fixtures cannot be seen from the ground. The ability to examine areas clinically within the confines of a well equipped laboratory offers considerably more efficiency than going into the field and facing the friction of city streets, anxious homeowners, and unfriendly dogs.

The Enviro-pod system was developed by and is maintained by the Environmental Protection Agency. The units have been used mainly to monitor specific pollution sources and until now have not been thought of as a means to provide systematic coverage of urban areas. A sufficient number of the systems is available so that credentialed researchers could probably borrow and use them for projects. Principal costs would be film, development, aircraft, and services of a pilot. Given good flying conditions, a city the size of Cincinnati can be completely covered in a few flying days (limiting the flying time to the best light conditions). The resulting data base would provide a mine of information to be used by researchers for a long time.

Richard Ellefsen, Ph.D. is a Professor of Urban Geography at San Jose State University

SEASONAL ALBEDO OF AN URBAN/RURAL LANDSCAPE FROM SATELLITE OBSERVATIONS

Christopher L. Brest
NASA Goddard Institute for Space Studies

ABSTRACT

Cities exhibit different temperature, humidity, and wind characteristics than those of surrounding rural environs. The best known of these urban/rural climatic differences is the urban heat island: the higher temperatures that most cities exhibit in comparison to their outlying areas.

Despite the well-documented existence of the urban heat island there exists no definitive understanding of its causes. A variety of explanation have been offered including: the addition of heat to the atmosphere by industrial and residential combustion; a blanketing effect of atmospheric pollution; reduced evaporation and plant transpiration; building and paving materials having large heat capacities and conductivities; buildings acting to retard windspeed; and varying albedo.

This lack of a definitive understanding partially results from the focus of many previous studies of urban climate modification which measured the magnitude of the effect (e.g., higher temperature) but failed to quantify the causes of these observed effects. The local microclimate is a result of the interaction between available energy and the surface configuration at the earth-atmosphere interface. Considering its importance as a component of the energy budget, it is surprising to note that only a small number of urban climate studies explore the albedo component of the urban energy budget. Furthermore, little has been done to investigate urban/rural differences. Therefore, this comprehensive investigation was specifically designed to measure the spatial and seasonal dynamics of surface albedo in a metropolitan area. It investigates surface reflectance and albedo in a heterogeneous urban/rural landscape to measure its magnitude, assess urban/rural differences, and ascertain its seasonal variability.

The spatial distribution and seasonal variation of surface resistance and albedo in the Hartford, Connecticut metropolitan area was studied using 27 calibrated Landsat observations acquired between 1972 and 1979. The satellite data was calibrated, to remove atmospheric effects, by a target calibration procedure using 22 urban targets (building rooftops and parking lots) whose reflectance has been measured by a

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KEYWORDS: albedo, atmospheric attenuation, blackbody radiation, reflectance, remote sensing, satellite, urban emissivity, urban environment, urban trees.

radiometer. Landsat bands 4 and 7, representing the visible and near infrared portions of the spectrum, are calibrated using linear regression analysis to relate the field-measured surface reflectance of the target to its satellite observed radiance. The resulting equations are used to predict surface reflectance from satellite observed radiance.

The visible and near infrared reflectance are combined into a measure of albedo by the use of weighted average schemes which incorporate the spectral reflectivity of the surface of interest and the spectral distribution of solar radiation. Three schemes are employed: one for vegetated surfaces; one for non-vegetated surfaces; and one for snow-covered surfaces.

Results are presented according to 14 land cover categories adapted from the U.S. Geological Survey Land use/land cover classification system. Categories include urban, suburban, tree vegetation, and non-tree vegetation land covers.

The spatial distribution of albedo (for both snow-free and snow-cover observations) is examined using means, coefficients of variation, and statistical tests to ascertain significant albedo differences among categories. Urban/rural and snow-cover/snow-free differences of albedo are presented.

The seasonal analysis (for 23 snow-free observations) is conducted by fitting periodic curves to the data to derive a one-year cycle of reflectance. Mean monthly values of reflectance and albedo area calculated from the periodic curves.

In order to quantitatively evaluate the effect of albedo on climate, and in particular the higher air temperatures associated with urban heat islands, a comprehensive modeling analysis of the interface energy budget is necessary. Such an analysis is beyond the objectives of this research; however, some implications of albedo differences for selected categories are briefly discussed using simple examples of blackbody surface radiant temperature calculations.

In addition to demonstrating the capability of satellite observations to measure surface reflectance in a complex landscape, this research establishes: the dependence of albedo on land cover, the lower albedo of urban areas, the spectral nature of surface reflectance, and the seasonality of albedo.

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INTRODUCTION

Considering the importance of albedo as a component of the energy budget, it is surprising to note the small number of urban climate studies that explore surface albedo. The comprehensive data set reported here is the result of an investigation specifically designed to analyze surface reflectance and albedo in an urban/rural landscape and produce data suitable for energy budget analysis.

The urban area is a mosaic of surfaces. Remote sensing analysis, using image-formatted, digital data from optical scanning equipment carried onboard aircraft or satellite platforms, provides an excellent means to study surface properties. Only in remotely sensed data are the necessary areal integration and the canopy structure of the surface incorporated into the measurement. Further, the use of satellite-borne remote sensing equipment, with repetitive coverage of a given site, allows multi-temporal investigation. Although remote sensing techniques are well suited to study surface albedo, there are two considerations which must be addressed: first, the calibration of the data to remove atmospheric effects; second, derivation of broadband albedo from narrowband observations.

Based on careful visual selection, 27 Landsat scenes, acquired between 1972 and 1978, of the Hartford, Conn. region were identified as suitable for analysis. They cover eleven months of the year and are from Landsats 1, 2, and 3. The observations were acquired under clear, dry, cloud free atmospheric conditions.

Only results for snow-free conditions are presented here. For information about snow-cover reflectances, or more details on the results presented here, see Brest (1987) and Brest and Goward (1987).

METHOD

Because the atmosphere functions as an interfering medium due to spectrally selective absorption, scattering, and re-radiation, the satellite observed radiance must be calibrated before it can be used as a measure of surface reflectance. This was accomplished by using a target calibration procedure. A calibration target is defined as one distinct surface area, either a building rooftop or a paved surface area (i.e., a parking lot). The choice of urban surfaces, whose reflectivity is stable both seasonally and over the long-term, avoids problems inherent in the use of natural targets: changes in surface conditions due to phenological cycles, soil moisture variations, or stress conditions. A multi-channel radiometer was used to measure spectral reflectance of 22 targets distributed throughout the region. These targets cover a range of reflectance from 3 to 50%. Two of the radiometer bands approximate Bands 4 and 7 (respectively .5-.6 and .8-1 μm) of the Landsat multispectral scanners.

The calibration procedure is a least-squares linear regression of the target's satellite-observed radiance data (in units of counts: 0-127 for band 4 and 0-63 for band 7) and field-measured reflectance data (in units of percent: 0-100%). Because of the spectrally selective modification by the atmosphere, each band is calibrated individually. Correlation coefficients range from .94 to .99 (mean = .98). All correlation coefficients are significant at the 95% level. The standard error of estimate ranges from 1.5-2.9% and 2.4-4.0% for Bands 4 and 7, respectively.

The calibrated data for Landsat bands 4 and 7 represent reflectance in the visible and near infrared portions of the solar spectrum. Derivation of an accurate measure of albedo from narrow band reflectance measurements must include the following three factors: 1) the spectral reflectance of the surface of interest; 2) the wavelength location of the narrow bands; and 3) the spectral distribution of the irradiance. The reflectivity of a surface is wavelength dependent, with few natural surfaces being uniform reflectors across the portion of the electromagnetic spectrum of interest here. However, an albedo measurement can be constructed from these observations if the spectral reflectivity of the surface and spectral distribution of solar radiation are known. The technique is to divide a spectral reflectance curve into segments of uniform bandwidth, each segment being represented by a narrow band measurement. An accurate broadband albedo is constructed from these narrow band measurements by calculating a weighted average. The weighting factors for each band are the proportion of solar radiation incident at the earth's surface in each segment of reflectance. Two formulas are derived, one for vegetation and one for non-vegetation.

A simplified spectral reflectance curve for a hypothetical vegetated surface is shown in Figure 1a. Green vegetation displays, to first order, three distinct segments of spectral reflectance: low in the visible, high in the near infrared, and medium in the mid infrared. These segments are defined by characteristics common to all green, living vegetation: a sharp increase in reflectance immediately beyond a chlorophyll absorption band (.68 μm), and a decline in reflectance due to a water absorption band centered at 1.4 μm. The location of the midpoint of the sharp rise in reflectance between the visible and near infrared is .725 μm. Because there is no Landsat band in the mid infrared, an estimate of mid infrared reflectance was derived based on the measured near infrared reflectance. After examination of spectral reflectance curves of vegetation a value of mid infrared reflectance equal to half of the near infrared reflectance was selected. The proportions of radiation incident at the surface are .526, .362, and .112 for the visible (.3-.725 μm), near infrared (.725-1.4 μm), and mid infrared (1.4-4.0 μm), respectively.

Non-vegetated surfaces have a more uniform spectral response (Figure 1b) and a simpler two-part weighted-average formula was used; the near and mid infrared segment were combined and the solar irradiance is proportioned into two segments, again using .725 μm as the cutoff. A surface was classified as either vegetation or non-vegetation based on whether the ratio of Band 7 to Band 4 calibrated reflectance exceeded a selected threshold value. The albedo calculation is shown schematically in Figure 2.

RESULTS

Results are presented using a land use/land cover classification based on one developed by the United States Geological Survey. Thirteen land cover categories are defined: City Downtown (CDWN), High Density Residential (HDR), City Outlying (COUT), Medium Density Residential (MDR), Low Density Residential (LDR), Park Forested (PFOR), Forest Deciduous (FDEC), Forest Evergreen (FEVG), Wetland Forested (WFOR), Wetland Non-forested (WNF), Agriculture (AG), Rangeland (RANG), and Park Non-forested (PNF). To facilitate discussion, the land categories are discussed in four groups: urban, suburban, tree vegetation, and non-tree vegetation.

The satellite data are treated as if they were acquired during a one year period, and periodic curves, representing a one year cycle of reflectance, are derived for each land cover category. A second order Fourier series was selected to produce the periodic curves of generalized seasonal reflectance. These curves represent the cyclical trend of surface albedo, in the absence of snow, over the course of a year. Curves for visible reflectance, near infrared reflectance, and albedo, for each land cover category, are derived separately, resulting in a total of 39 seasonal reflectance curves. The curves and data points are plotted for each category (Figures 3 through 6).

The seasonal albedo curves for city downtown and high density residential (Figures 3a and 3b) are almost identical, although they arise from dissimilar curves of visible and near infrared reflectance. Both categories have relatively flat albedo curves, with seasonal amplitudes of 2-3%.

The albedo curve for city outlying (Figure 3c) has a similar shape and amplitude to city downtown and high density residential but is offset by about 3%. Although close in value to the albedo of medium density residential and only 1% less than that of low density residential at its peak, the visible and near infrared reflectance curves are very different from those of medium and low density residential (Figures 4a and 4b). The city outlying albedo is governed by the reflectance of inorganic surface construction materials which are relatively bright in the visible and only slightly brighter in the near infrared bands. The visible curve for medium density residential has a slight dip, and the near infrared curve has a significant peak, during the summer season, both indicative of the presence of photosynthetically active vegetation.

The seasonal curves of albedo for the five categories discussed thus far are relatively flat. They do, however, display a gradation of amplitude: low density residential is more peaked than medium density residential, which in turn is more peaked than the three urban categories.

For the vegetation certain patterns are common to almost all categories. The visible reflectance decreases and the near infrared reflectance has a significant peak during the summer season when the vegetation cover is most extensive. These are both characteristics indicative of the presence of photosynthetically active vegetation: low visible reflectance associated with chlorophyll absorption and the rise in near infrared reflectance due to the cellular structure of vegetation leaves.

Albedo curves for the tree categories (Figures 5a through 5d) indicate spectral and temporal similarities in the reflectance behavior of these types. A strong peak occurs in summer, associated with the peaking of the near infrared reflectance, only partially offset by the lower visible reflectance.

Wetland nonforest (Figure 6a) has the largest amplitude of any land cover category for both the near infrared and albedo, values of 30% and 11% respectively, based on monthly averages. This is due to the spring minimums, attributed to flooding due to the proximity of the sites to the Connecticut River.

The seasonal curve for agriculture (Figure 6b) displays two interesting characteristics: a spring minimum and a peak in late summer. The former results from the bare soil response following spring plowing, while the latter is due to a later peaking of cultivated crops relative to natural vegetation. This pattern is indicative of a difference in maturation processes between crops and natural vegetation cover.

Range (Figure 6c) displays a strong seasonal trend, similar in magnitude to the tree categories, while park nonforest (Figure 6d) displays an unusual seasonal pattern (for a vegetation category). Both the visible and near infrared band reflectance of park nonforest have a relatively small amplitude, approximately 3 and 5%, and the resulting albedo curve is virtually constant throughout the year. The reasons for this unique seasonal pattern of reflectance are not clear.

The seasonal reflectance curves can be grouped to examine similarities and differences among categories. Figure 7a displays the albedo curves for the urban and suburban categories. Two sets of curves, of similar seasonal trend but different magnitude, are evident. The lower set is for city downtown and high density residential, and the upper set of curves is for city outlying, medium density residential and low density residential. The difference between the sets of curves demonstrates two points: 1) the higher albedo of suburban areas due to greater vegetation cover; 2) the difference between city outlying and the other two urban categories, attributed not to vegetation cover, but to the lower reflectance of the city proper due to multiple reflections within the urban canopy. Thus two factors responsible for the urban/rural albedo differences can be noted: the higher albedo of categories with significant vegetation cover; and the lowering of albedo due to the vertical canopy structure of the urban areas.

The seasonal reflectance curves for the tree categories are displayed in Figure 7b. The similarities of band by band reflectances for all four categories are indicative of the common vegetation component and similar canopy structure in all of these categories.

Figure 7c displays the reflectance curves for two dissimilar categories: vegetated (forest deciduous) and non-vegetated (city downtown). Note the increasing differences in band reflectance from winter to mid-summer. The non-vegetated category is relatively stable throughout the year, while the vegetated category curves increase sharply in the summer in the near infrared band, and decrease sharply in the visible band. Visible reflectances, which were virtually identical in February, reach a maximum difference of 6% in July. The near infrared reflectance for the vegetation category ranges from 14% in winter to 38% in summer, generating differences between the two categories of 4% in winter to 24% in summer. The resulting albedo differences range from 1% in winter to 7% in summer.

Daily reflectance values were calculated from the Fourier coefficients for the seasonal curves and averaged for twelve 30 day intervals to obtain monthly means. These monthly means, summarizing the information portrayed in Figure 3 through Figure 6, quantify the seasonal dynamics of surface reflectance and albedo.

The mean monthly visible reflectances are shown in Table 1. Many of the vegetation categories have their lowest monthly mean of visible reflectance in July. The three urban categories have values from 8-12%, with slightly higher values in summertime. The two suburban categories generally have values intermediate between the urban and the vegetation groups. The tree vegetation categories have the lowest values of visible reflectance. Nontree vegetation categories have slightly higher visible reflectances than tree categories. All categories of the suburban, tree, and nontree groups have lower visible reflectance in the summertime, in contrast to the urban group which peaks in the summer.

The near infrared reflectance is shown in Table 2. All land categories display a maximum near infrared reflectance in July. As in the visible reflectances, there is a distinction between the urban categories and the other land surface categories. Summertime values of 14-18% are noted for the urban categories, compared to 27-31% for suburban, and 32-41% for the two vegetation groups.

The mean monthly values of albedo are presented in Table 3. This table summarizes both the seasonal and spatial aspects of surface albedo. All categories have maximum mean monthly albedo during summertime. Albedo differences between land cover categories are evident, from the low values for man-made surfaces e.g., city downtown (maximum monthly mean of 11.7%), to the high values for a grassy surface e.g., park nonforest (approximately 20% year round).

Urban/rural albedo differences for a few selected categories are shown in Table 4. All values are positive indicating that city downtown has a lower albedo year round than any of the categories listed. Simple blackbody radiant temperature calculations suggest that these albedo differences are significant, although a comprehensive energy budget analysis is necessary before any definitive statement can be made regarding the role of albedo in the formation of the urban heat island.

CONCLUSIONS

In the heterogeneous urban/rural landscape a range of albedo values associated with the nature of the surface is observed. Two characteristics of the surface appear most important in determining albedo: presence of vegetation and canopy structure. Vegetation surfaces generally have higher albedos (driven by high near infrared reflectance) than most urban surface materials and exhibit a characteristic seasonal pattern of reflectance, associated with phenology.. Canopy structure is important due to interactions within the canopy, which alter albedo values in comparison to those observed from simple flat surfaces of the same material.

The spectral nature of reflectance is evident in the contrasting reflectance patterns observed in the visible and near infrared for many land cover categories (particularly vegetation). The large differences in band reflectance preclude simple estimation of albedo based on a limited spectral sample without consideration of the spectral reflectivity of the surface of interest.

The seasonal reflectance curves delineate the temporal dynamics of surface albedo. The amplitude of these curves is largest for vegetation categories, although even the urban categories display some seasonal variation. As a group, the greatest amplitude of monthly mean albedo is exhibited by the tree vegetation categories, 6-8%. The urban categories display maximum January-July differences 2-3%. Medium density and low density residential have values of 3-4%. A diversity of differences is exhibited by the nontree vegetation group with values ranging from less than 1% to over 10%. The intra-category seasonal variation is, in many cases, comparable to the inter-category differences.

The mean monthly reflectance and albedo values presented here represent the most comprehensive data set of its kind. Use of this data in urban climate energy budget analysis will allow for: 1) a determination of the role played by albedo (if any) in formation of the urban heat island; and 2) the improvement of urban climate models by providing accurate and comprehensive data.

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Table 1. Mean Monthly Visible Reflectance (%)

	CDW	HDR	COUT	MDR	LDR	PFOR	FDEC	FEVG	WFOR	WNF	AG	RANG	PNF
JAN	8.1	7.9	10.5	8.8	8.2	8.3	7.7	6.9	8.2	7.7	11.1	8.2	10.1
FEB	8.2	7.8	10.5	8.8	8.2	9.0	8.0	6.9	8.1	7.2	10.6	8.2	10.2
MAR	8.5	7.8	10.7	8.5	7.7	8.9	7.6	6.5	7.3	6.4	9.4	7.6	9.7
APR	8.9	7.8	11.1	8.0	6.9	7.6	6.4	5.8	5.9	5.6	8.0	6.6	8.7
MAY	9.4	8.0	11.5	7.5	6.0	5.5	4.9	5.0	4.6	5.2	6.9	5.5	7.7
JUNE	9.6	8.1	11.9	7.0	5.4	3.8	3.6	4.3	3.7	5.0	6.2	4.7	6.9
JULY	9.6	8.1	11.9	6.8	5.1	3.2	3.2	4.0	3.5	5.0	6.0	4.4	6.5
AUG	9.4	8.0	11.7	6.7	5.1	3.6	3.6	4.0	3.9	5.1	6.1	4.5	6.6
SEPT	9.0	7.8	11.4	6.9	5.5	4.6	4.4	4.4	4.6	5.5	6.6	5.0	7.0
OCT	8.7	7.8	11.0	7.3	6.1	5.6	5.3	5.1	5.6	6.1	7.6	5.8	7.7
NOV	8.4	7.9	10.8	7.9	6.9	6.3	6.1	5.8	6.6	6.9	9.1	6.7	8.5
DEC	8.2	7.9	10.7	8.4	7.6	7.1	6.9	6.4	7.6	7.6	10.4	7.6	9.4

Table 2. Mean Monthly Near Infrared Reflectance (%)

	CDW	HDR	COUT	MDR	LDR	PFOR	FDEC	FEVG	WFOR	WNF	AG	RANG	PNF
JAN	9.0	9.6	12.9	17.7	16.5	14.9	13.7	12.4	11.0	10.2	20.7	16.1	35.1
FEB	9.7	10.0	13.2	18.2	17.4	16.7	15.0	13.5	11.1	8.7	19.5	17.1	34.9
MAR	11.0	11.2	14.1	19.9	19.9	20.7	18.8	16.9	13.8	10.3	20.2	20.4	35.7
APR	12.5	12.9	15.4	22.4	23.7	26.3	24.9	22.4	19.8	17.1	23.2	26.2	37.2
MAY	13.8	14.5	16.7	25.0	27.6	32.0	31.7	28.5	27.7	27.4	27.9	32.9	38.8
JUNE	14.5	15.6	17.7	27.0	30.4	35.9	36.9	32.9	34.1	36.6	32.5	38.1	40.0
JULY	14.5	15.9	17.9	27.4	30.9	36.7	38.3	34.0	36.2	39.7	34.9	39.3	40.5
AUG	13.8	15.3	17.4	26.4	29.1	34.0	35.4	31.6	33.2	35.6	34.6	36.1	40.3
SEPT	12.6	14.1	16.3	24.4	25.8	29.0	29.7	26.7	27.1	27.3	32.0	30.1	39.7
OCT	11.3	12.5	15.1	22.0	22.2	23.4	23.4	21.3	20.7	19.7	28.8	24.0	38.7
NOV	10.0	11.1	13.9	19.9	19.1	18.6	18.3	16.7	15.9	15.0	25.8	19.4	37.5
DEC	9.2	10.0	13.1	18.4	17.2	15.7	15.0	13.7	12.9	12.6	23.2	16.9	36.3

Table 3. Mean Monthly Albedo (%)

	CDW	HDR	COUT	MDR	LDR	PFOR	FDEC	FEVG	WFOR	WNF	AG	RANG	PNF
JAN	8.5	8.7	11.6	12.4	11.4	10.8	10.0	9.0	9.4	8.7	15.0	11.2	20.0
FEB	8.9	8.9	11.8	12.6	11.8	12.1	10.8	9.5	9.3	7.8	14.3	11.6	20.0
MAR	9.6	9.3	12.3	13.0	12.6	13.7	12.2	10.7	10.0	8.0	13.8	12.7	20.0
APR	10.5	10.0	13.0	13.7	13.7	15.2	14.0	12.5	11.7	10.3	14.2	14.5	20.1
MAY	11.2	10.8	13.7	14.5	14.8	16.4	16.0	14.6	14.1	14.2	15.4	16.7	20.3
JUNE	11.7	11.3	14.3	15.0	15.5	17.0	17.4	16.0	16.2	17.9	16.9	18.4	20.3
JULY	11.7	11.4	14.4	15.0	15.6	16.9	17.7	16.3	16.9	19.2	17.7	18.7	20.3
AUG	11.2	11.0	14.1	14.6	14.8	16.1	16.7	15.3	15.9	17.5	17.6	17.5	20.3
SEPT	10.6	10.5	13.4	13.8	13.7	14.5	14.7	13.5	13.7	14.3	16.9	15.2	20.3
OCT	9.8	9.8	12.7	13.1	12.5	12.7	12.6	11.6	11.6	11.5	16.1	13.1	20.2
NOV	9.1	9.3	12.2	12.6	11.7	11.1	10.9	10.1	10.3	10.1	15.8	11.7	20.2
DEC	8.6	8.9	11.8	12.4	11.4	10.4	10.0	9.3	9.7	9.6	15.6	11.1	20.1

Table 4. Difference in mean monthly albedo between city downtown and selected categories

	LDR	FDEC	FEVG	AG	PNF
JAN	2.9	1.5	0.5	6.5	11.5
FEB	2.9	1.9	0.6	5.4	11.1
MAR	3.0	2.6	1.1	4.2	10.4
APR	3.2	3.5	2.0	3.7	9.6
MAY	3.6	4.8	3.4	4.2	9.1
JUNE	3.8	5.7	4.3	5.2	8.6
JULY	3.9	6.0	4.6	6.0	8.6
AUG	3.6	5.5	4.1	6.4	9.1
SEPT	3.1	4.1	2.9	6.3	9.7
OCT	2.7	2.8	1.8	6.3	10.4
NOV	2.6	1.8	1.0	6.7	11.1
DEC	2.8	1.4	0.7	7.0	11.5

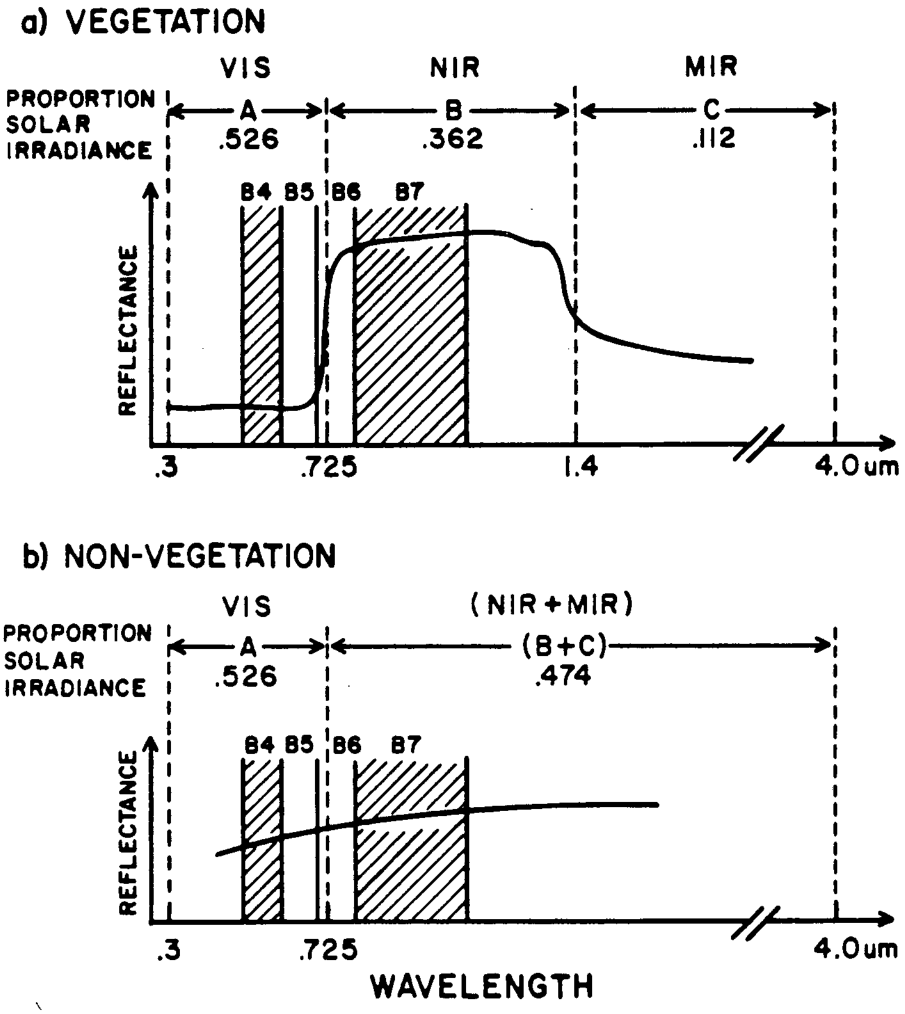


Figure 1. Simplified spectral reflectance curves for (a) vegetation and (b) non-vegetation surfaces, showing location of Landsat bands and proportional weighting factors.

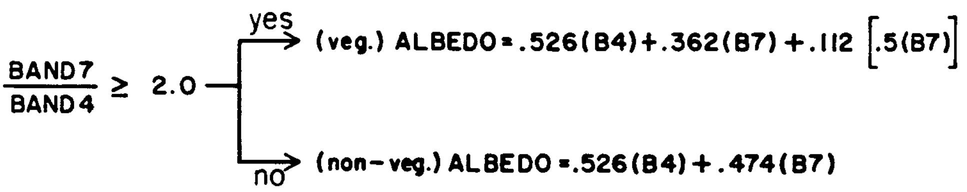
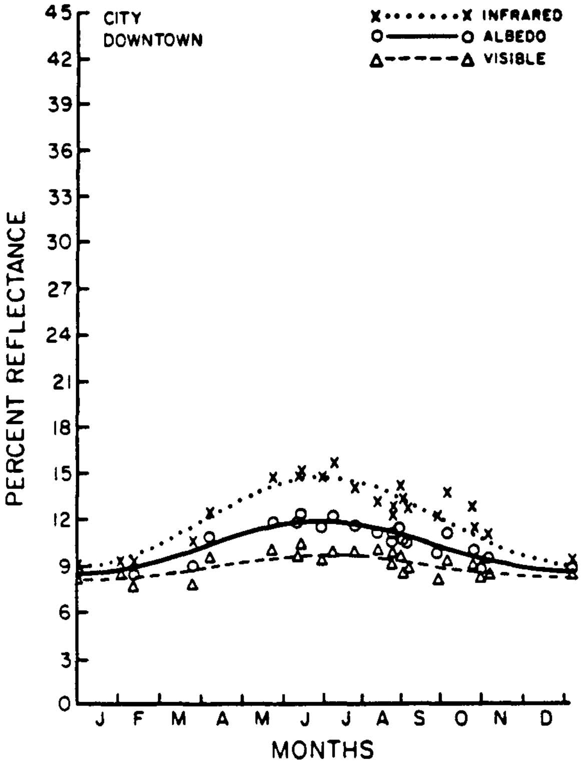
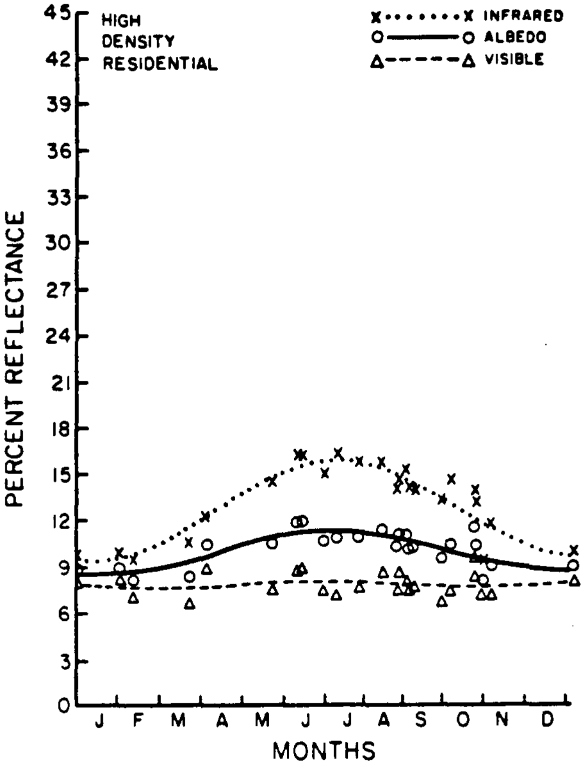


Figure 2. Schematic of albedo calculation for a vegetation and non-vegetation surface.





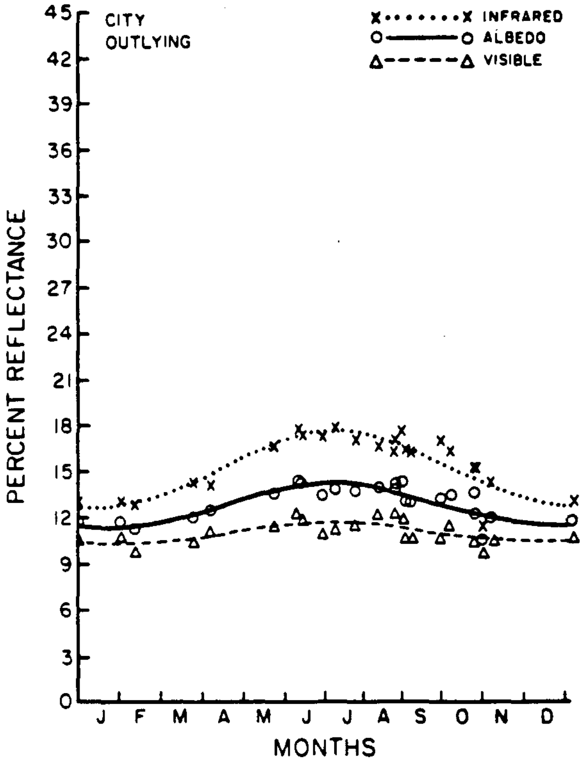


Figure 3. Data points and seasonal reflectance and albedo curves for urban land cover categories: a) city downtown, b) high density residential, and c) city outlying.

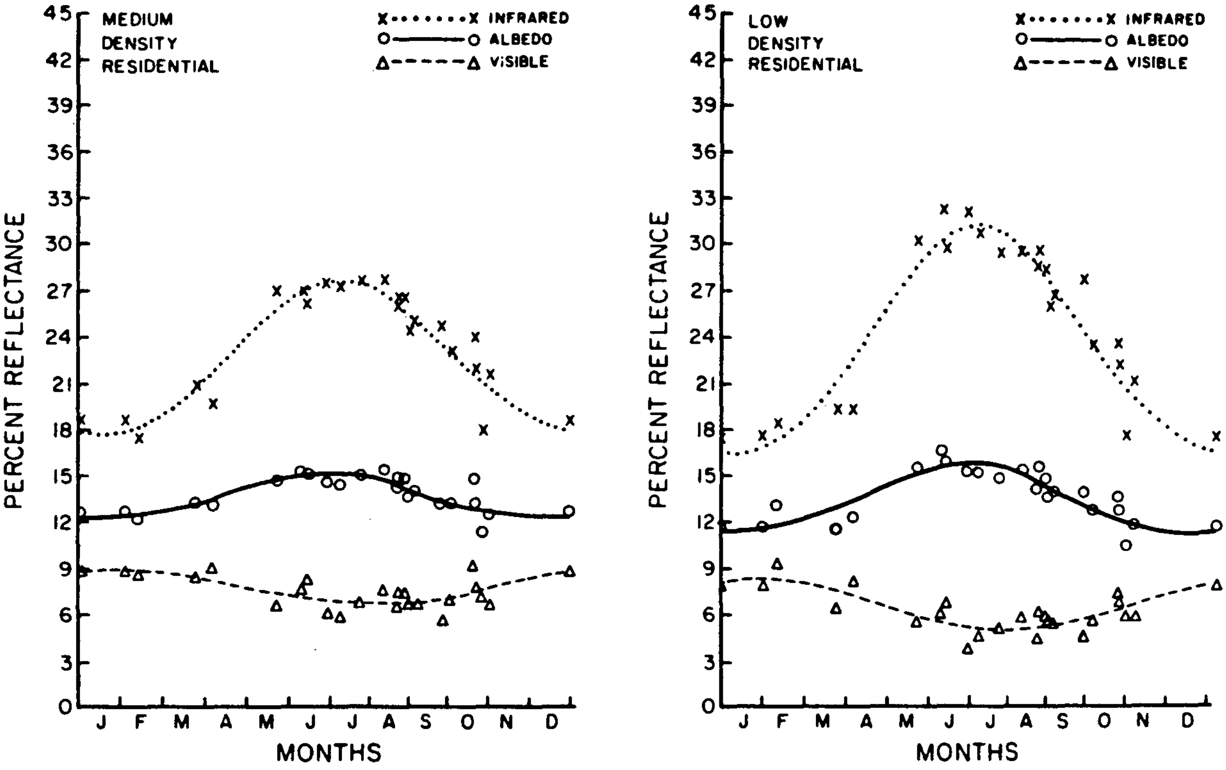


Figure 4. Data points and seasonal reflectance and albedo curves for suburban land cover categories: a) medium density residential and b) low density residential.

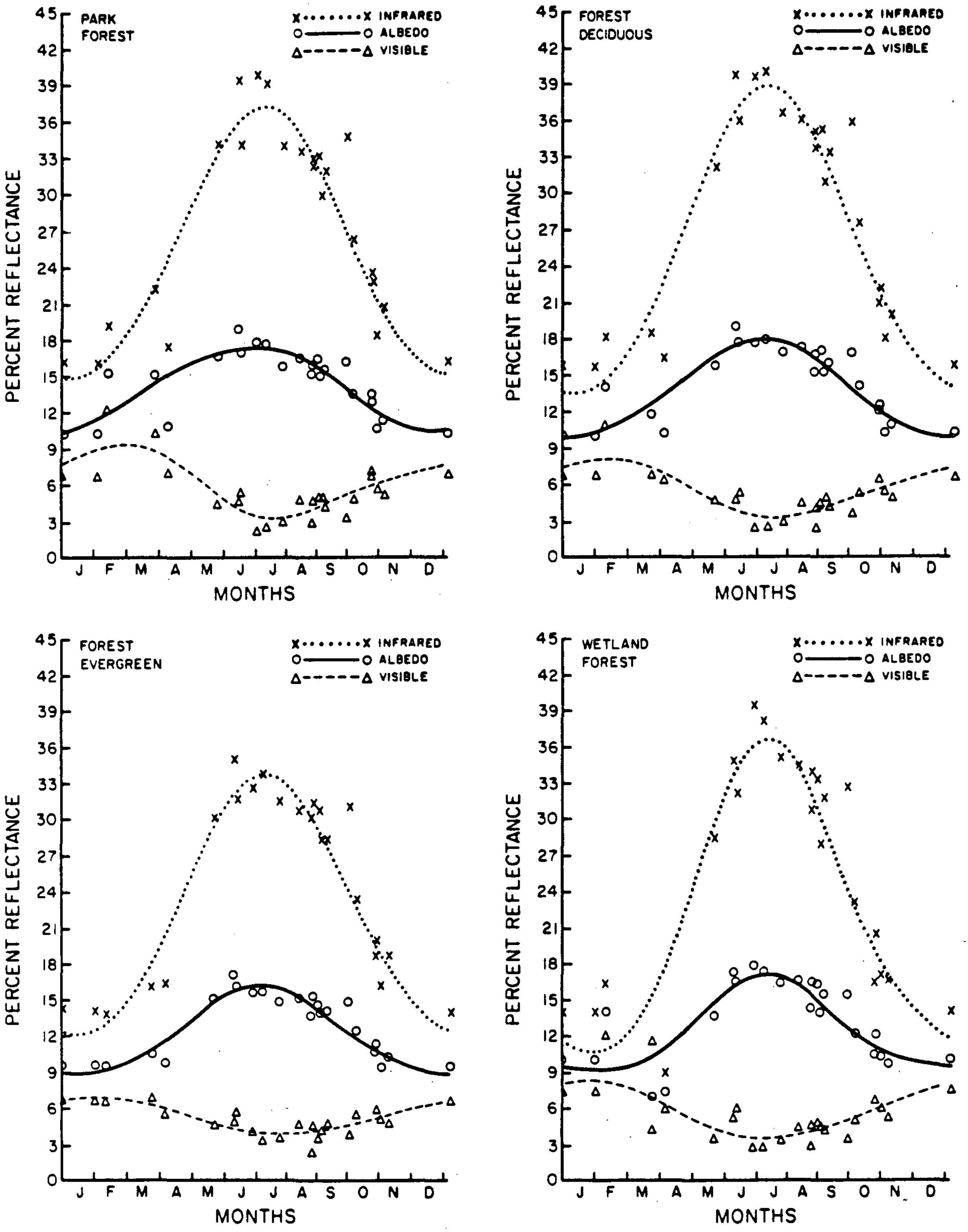


Figure 5. Data points and seasonal reflectance and albedo curves for tree vegetation land cover categories: a) park forest, b) forest deciduous, c) forest evergreen, and d) wetland forest.

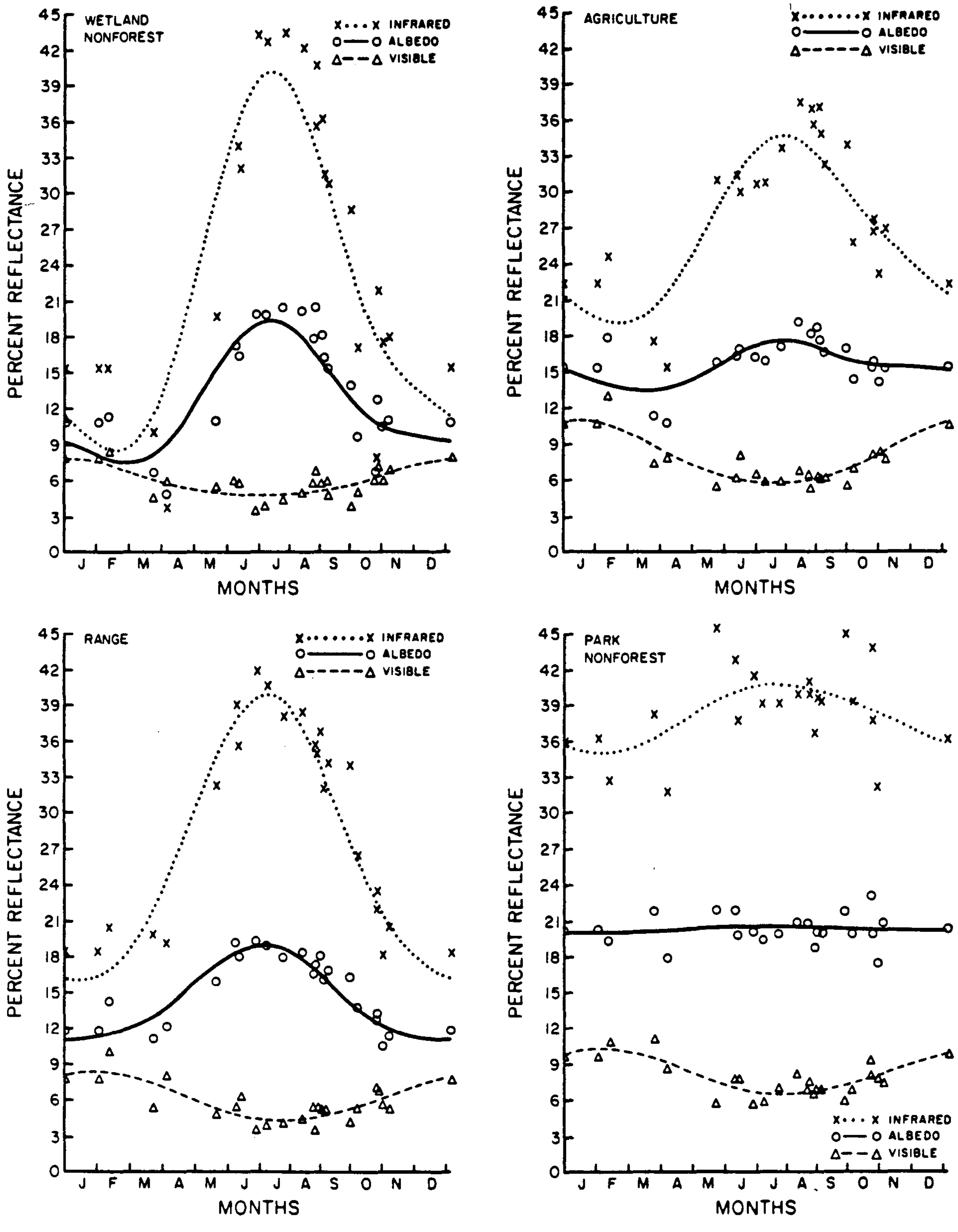


Figure 6. Data points and seasonal reflectance and albedo curves for non-tree vegetation land cover categories: a) wetland nonforest, b) agriculture, c) range, and d) park nonforest.

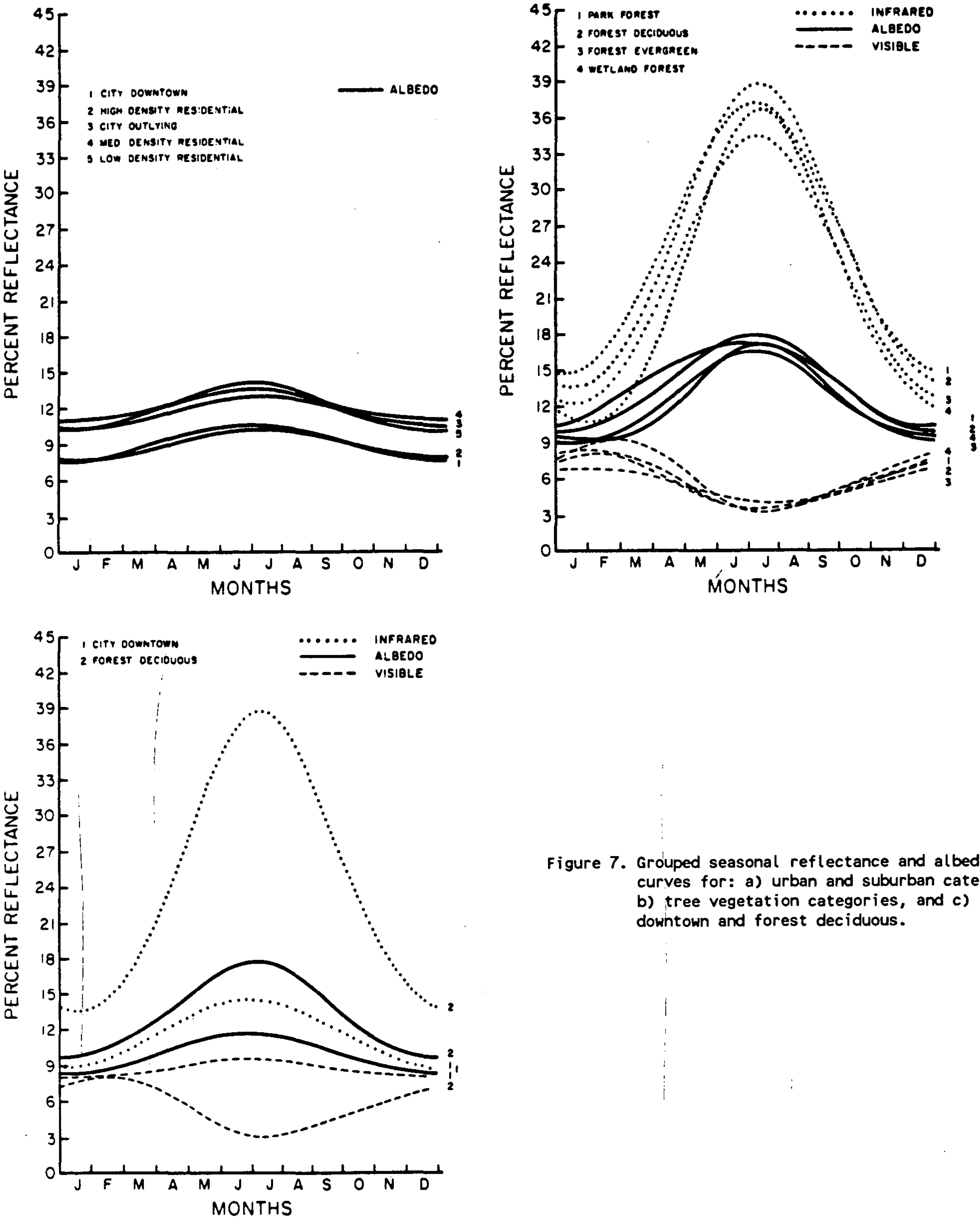


Figure 7. Grouped seasonal reflectance and albedo curves for: a) urban and suburban categories, b) tree vegetation categories, and c) city downtown and forest deciduous.

MEAN WINDSPEED BELOW BUILDING HEIGHT IN RESIDENTIAL NEIGHBORHOODS

Gordon M. Heisler
USDA Forest Service
Northeastern Forest Experiment Station

ABSTRACT

Many factors that influence summer heat islands, such as building and vegetation density and general morphology, also influence mean windspeed. Therefore, in considering moderation of heat islands by practices such as manipulating urban vegetation, it is important to consider the implications for wind flow. Windspeed within residential neighborhoods influences a host of environmental factors important to the human species, including outdoor thermal and mechanical comfort of people, air pollution, and energy use for heating and cooling buildings. There is little available knowledge of the absolute or relative effects of trees and buildings on wind at or below building roof height or of how to model these effects.

In this study, a first step was taken towards developing the relationship between tree and building morphology and wind reductions by measuring mean windspeed at the 2-m height in neighborhoods of single-family houses. Building densities ranged between 6 and 12% of the land area and tree cover densities were between 0 and 77%. Measurements were made with an array of cup anemometers at points either 1/2 or 1 building height from the houses of interest. Windspeeds at the same height at a local airport served as the reference windspeed, U_o. Empirical models were derived to predict the effect of trees on windspeed separately from the effect of buildings. The models were based on tree and building geometry derived from map measurements, aerial photos, and fisheye photos from wind-measuring points.

With reference windspeeds between 1.6 ms^{-1} and 3.7 ms^{-1}, windspeeds (U_b^n) measured near houses in a neighborhood with no trees were reduced an average of 29% compared to U_o. Part of these reductions were caused by the close proximity of the measuring points to the houses of interest. When approach windspeeds (U_a^n) toward these houses were estimated by modifying U_b^n by relationships determined from data collected at a single house in the open, the reduction in U_a^n was about 22%. In a neighborhood with 23% tree density, reductions in U_a^n by both trees and buildings averaged 38% in winter and 52% in summer, with respective apparent reductions by trees of 14% and 29%. With 77% tree density, comparable total U_a^n reductions averaged 65% and 70% and U_a^n reductions by trees were 42% and 46%.

KEYWORDS: buildings, residential, shading, trees, urban environment, wind-shielding

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Gordon M. Heisler
USDA Forest Service
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INTRODUCTION

Any broad policy of vegetation management or landscape design to modify an urban heat island as expressed in air temperature will also effect other variables: wind, solar irradiance, long-wave radiation transfer, and humidity. The most important and largest effects on variables important to human well-being will be the effects on wind and solar radiation. The potential effects of trees on these variables is large—up to about 90% in densely treed areas. The important effects will be those below the top of the "canopy." (Here the quotes signify that both buildings and trees are included in the canopy layers.)

The effect of trees on windspeed in residential neighborhoods is important because windspeed is one of the factors that influence energy use for heating and cooling buildings (for example, DeWalle and Heisler, 1988; McPherson et al., 1988). Windspeed also influences other environmental conditions such as comfort of people outdoors and dispersion of air pollutants.

Even though residential neighborhoods usually have few of the traditional windbreaks that consist of rows of closely-spaced dense trees, the total effect of trees distributed as individuals may affect windspeed substantially in all seasons. The aggregate of these individual trees in urban and residential areas is often referred to as the "urban forest".

Most of the studies of tree effects on energy use in buildings have considered individual buildings with relatively simple tree arrangements. However, most single-family homes, of which there are over 60 million in the U.S., are located in developments on relatively small lots, and their microclimate is influenced by components of the urban forest throughout the development.

Determining the urban forest effect on wind is a complex problem because trees and buildings are generally interspersed in irregular patterns making it difficult to separate effects of buildings from effects of trees. The wind measurements and numerical modeling of wind flow that have been done for dense continuous forests and orchards would seem to have little relevance in the complex suburban situation. Wind tunnel models have been used to evaluate tree effects on pressure coefficients of residences (e.g. Mattingly et al., 1979), but only for relatively simple configurations of trees and buildings.

In the literature, there are few or perhaps no reports of measurements of aggregate tree effects on windspeed below house height in residential neighborhoods. McGinn (1983) measured windspeeds with an anemometer in the open and another in one of several neighborhoods in turn, but his measurements were only in summer and for points close to house height.

As part of a study of tree effects on energy use for heating and cooling houses, we measured mean windspeeds at the 2-m height in four neighborhoods of single-family houses. Measurements were made near houses that had no tall hedges or tree rows nearby. Tree cover in the neighborhoods ranged from negligible to quite dense. Wind at a local airport served as a reference. Statistical models were derived to predict the effect of trees on windspeed separately from the effect of buildings. This paper briefly summarizes the study. A detailed report to the primary sponsor is available (Heisler, 1989).

METHODS

Residential Area Sampling Points

One goal of this study was to provide information on wind reductions by trees throughout neighborhoods so that tree influences on building energy use could be simulated. Tree effects on windspeeds would intuitively differ with height, and in particular, effects below building height would differ from those above. In energy analysis programs, input required for wind is hourly mean windspeed at one reference height, such as ceiling height (Sherman and Modera, 1984). In this study, the 2-m height was chosen for wind measurements with the assumption that windspeed at 2-m is representative of flow around the house, or at least that 2 m is sufficiently close to "ceiling height." As a practical matter for this study, instruments were placed temporarily around houses within neighborhoods on each of 14 measuring days. The need for fast set-up time would have precluded placing anemometers at a much greater height.

Another goal in this study was to develop data to model energy use in specific sample houses. Therefore, measurements near houses rather than in a vacant lot away from houses were needed. If the requirement for evaluating flow around particular houses had not been present, measurements in vacant lots might have sufficed. Again as a practical matter, however, few such sites were present in the neighborhoods we studied.

If we wish to evaluate wind flow approaching house A in a neighborhood, it is often not possible to place anemometers sufficiently far from house A to avoid its influence on the measurement. Even in the upwind direction, windspeed may be reduced up to 5 or even more heights from an obstacle (Heisler and DeWalle, 1988). At sides and corners (relative to wind flow), windspeed may be greater than approach speed. Therefore, before selection of measurement points around houses in the residential areas, measurements of windspeed around an isolated single representative building were made to develop a correction for the effect of the sample building itself.

Single-Building Measurements

The goal of the single-building measurements was to establish a relationship between local windspeed (U_b^s) (see NOMENCLATURE) at points near the isolated building and the approach windspeed (U_a^s) measured outside of the influence of the building, 10 building heights upwind. The near-building windspeed, U_b^s, was measured at 24 points at distance, $D = 1/2$, 1, or 2 h (h = building height) from the sides, corners, and ends of the building. The points were designated as position types 1 through 9 (Figure 1). For each wind observation, the wind/corner angle, C, of the average wind direction from a line to the corners of the building (Figure 1) was evaluated.

Regression equations were developed to predict relative windspeed, $R = U_b^s/U_a^s$, as a function of C and D, $R = f(C,D)$. These relationships were used to obtain predicted approach windspeeds (U_a^n), at houses in the residential neighborhoods, as $U_a^n = U_b^n$ / (predicted R), where U_b^n was the measured windspeed in the neighborhood. In Figure 2, the relationship $R = f(C,D)$ is shown for the distance $D = 1$ h. In analyzing measurements in the neighborhoods, we used only data with C positive.

Wind Measurements in Neighborhoods

Measurements were made at a total of 15 houses in four neighborhoods with different tree densities that can be used to categorize the neighborhoods approximately as: no trees, low-tree-density, medium-tree-density, and high-tree-density. Tall fences or hedges were not part of the study, and only houses without these features were selected for sampling.

Wind measurements in neighborhoods were made on 7 days in winter and 7 days in summer. At each of 4 to 7 houses that were included in the measurements on a particular day, measurements were made at up to four positions that were analogous to one of the position types at the individual building (Fig. 1).

The neighborhoods were up to 8 km apart and up to 5 km from the reference site. Elevations in the neighborhoods differed by as much as 72 m from the reference site elevation. Slopes in the neighborhoods were up to 8%, which is generally small relative to the degree of slopes that have been shown to significantly influence windspeed near the ground (Rutter, 1968).

For wind measurements in the neighborhoods, we used up to 15 Stewart[1], 4-cup, contact anemometers, which are relatively inexpensive but rugged instruments. They are not the most sensitive available, but they were matched and calibrated against sensitive Thornthwaite-type cup anemometers before the measurements. In the neighborhoods, anemometers were used with individual specially-designed counters that total

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[1] Mention of a commercial or proprietary product does not constitute endorsement by the USDA or the Forest Service.

wind run over each hour. They had to be visited sometime during the following hour for manual recording of the wind run.

Concurrently with measurements in the neighborhoods, a reference mean windspeed (U_o), vector wind direction (θ), standard deviation of direction, and net all-wave radiation were measured at the local airport. A data logger measured these values at 3-sec. intervals and output hourly averages. An anemometer and wind vane system provided θ. Counts from a Stewart anemometer were logged to obtain U_o. Turner atmospheric stability class (T) was estimated according to Turner (1961) from calculated solar elevation and airport observations of cloud cover and height.

We made measurements in neighborhoods only in daytime periods and avoided measurements during significant precipitation or extreme cold. Hence, the measurements reported here are not totally representative of a year's wind climate.

Building and Tree Morphology Measurements

Morphological characteristics of the buildings in the upwind and downwind directions from neighborhood wind measuring points were evaluated from maps that showed the location and height of each house, using a procedure similar to that previously used for central city buildings (Heisler and Grant, 1987). For each measurement hour, building characteristics at each neighborhood wind point were determined along three lines—through average wind direction θ, and 15 ° to each side of it. The three values of each measured building characteristic were then combined to yield averages, maximums, minimums, or largest difference between the three values of the characteristic for that hour. The characteristics included: distance in building heights to the nearest upwind and downwind building; upwind building average heights and densities over 0 to 300 ft (91 m) and 300 ft to 1000-ft (305-m) distances; and density times average height, which formed an index of building volume.

Tree characteristics were evaluated similarly to building characteristics, but with photographs rather than maps. At each wind-measuring point, a 180-degree fisheye slide photo was taken to evaluate the vertical angle subtended (V_a) by and the density (V_d) of tree crowns visible from the wind points. This was done by projecting each slide onto a polar grid so that vertical angles and densities could be estimated as averages over 15-degree segments. Separate photos were taken for summer and winter. The percentage of tree-crown cover in the 0- to 300-ft and 300- to 1000-ft distances in the upwind direction from the center of each sample house was estimated by a dot-grid method from aerial photos. Average tree height was derived from field data.

RESULTS

Building and Tree Morphology

Averages of building descriptors generally characterize the house morphology within each neighborhood. There were some differences (Table 1). The low-tree-density neighborhood had the highest building density with 12% of the land area covered by buildings. The large value of nearest downwind building distance in that neighborhood occurred because one house was on the edge of the development.

Table 1. Averages of building descriptors by neighborhood tree density group. Density is average percent of land covered by building as determined from maps and averaged over upwind directions from each wind point. The building volume index has units of ft because it was derived from density (nondimensional) and building height (ft).

Tree-density group	Bldgs. 1000 ft upwind			Nearest building distance	
	Density	Ht.	Volume index	Upwind	Downwind
		ft	ft	bldg.	heights
No trees	.06	12	1.0	25	22
Low	.12	12	1.5	17	128
Medium	.09	16	1.7	18	15
High	.10	14	1.5	19	20

Averages of tree descriptors (Table 2) indicate general differences in trees in the neighborhoods. Although cover indicates the fraction of ground covered by tree crowns without including a crown density factor that would differ with the season, cover (and height) within a density grouping differs slightly from summer to winter because wind direction θ differed and the data are averaged over θ during measurements. Tree volume index is derived from tree cover and height.

Table 2. Averages of tree descriptors by neighborhood tree density group.

Tree-density group	Season	Trees 1000 ft upwind cover	Ht.	volume index	Fisheye view Density V_d	Angle V_a
			ft	ft		Deg.
Low	S	.24	29	7	.86	27
	W	.24	25	6	.40	23
Medium	S	.67	47	31	.85	47
	W	.68	44	30	.53	50
High	S	.77	56	43	.83	76
	W	.77	60	46	.49	54

Tree cover and height are generally correlated. Average tree-crown density (V_d) in the three groupings is similar. Average winter density ranged from 47% to 62% of summer density. The dominance of tree cover in these neighborhoods is indicated by the fact that trees cover about twice the area that buildings cover even in the low-tree-density neighborhood.

Wind Reductions by Neighborhood

An initial impression of tree influences on windspeeds is shown by scatter plots of all data as approach windspeed in the neighborhoods, U_a^n, plotted against airport windspeed, U_o, by tree density groups in winter (Fig. 3) and summer (Fig. 4). The values of neighborhood U_a^n in Figures 3 and 4 are calculated as neighborhood $U_a^n = U_b^n$ /(predicted R) as described earlier, where U_b^n is windspeed measured at a neighborhood sample building. Predicted R had a mean of 0.89 and ranged from 0.37 to 1.11. Mean values by neighborhood of U_b^n and calculated U_a^n differed by up to 4%.

Higher windspeeds in neighborhoods than at the reference site in the open may be anticipated for some points at building corners or where channeling occurs in neighborhoods with little vegetation. However, below 1.6 ms-1 some unreasonably large increases in U_b^n and U_a^n over U_o were present, and all data with U_o less than 1.6 ms^{-1} (3.5 mph) were deleted. This is justified partly on the basis of simultaneous wind measurements at two open sites about 5 km apart that showed good correlation in both speed and direction at higher windspeeds but low correlation below 1.6 ms^{-1}. The lack of correlation is expected because wind directions tend to be much more variable below 1.6

ms^{-1} than at higher windspeeds (Fig. 5). Also, anemometers are less accurate during periods of very low windspeed when the wind may be slower than their threshold speed part of the time. Anemometers at airport weather stations, from which weather data for energy analysis is generally obtained, usually have threshold speeds in excess of 1 ms^{-1}.

The overall effect of trees and buildings on windspeed in the different neighborhoods is indicated by averages of approach windspeed reduction, $\Delta U = (U_o - U_a^n)/U_o$, over neighborhood and season as in Figure 6. Here, summer and winter data for the no-trees neighborhood are combined. This implies that building effects are the same in the two seasons, which is contrary to the expectation of smaller reductions by obstacles with more unstable atmospheric stability classes (Heisler and DeWalle, 1988; Rutter, 1968), which were generally present in summer. In fact, although when summer and winter data were combined, atmospheric stability class varied from class 1, extremely unstable, to class 4, neutral, the effect of T on ΔU in the neighborhood with no trees was not statistically significant.

Regression analysis of tree and building effects on wind reduction

The buildings in the neighborhood with no trees reduced U_a^n by an average of 0.22 (Fig. 6). To determine whether this was representative of the reductions by buildings in the other neighborhoods, that is, to separate building and tree effects on windspeed reductions, the data for all neighborhoods were combined; and wind reduction, Δ U, was regressed on building and vegetation variables. The building and vegetation variables were transformed to physically meaningful nonlinear forms and used as interactions to yield many potential independent variables (see Heisler, 1989). In stepwise regression analysis, a large number of both building and tree variables entered as significant along with standard deviation of windspeeds in the open and net allwave radiation there. For all observations with $U_o > 1.6$ ms^{-1}, the coefficient of determination, R^2, reached 0.73. For the less scattered reductions in the data with $U_o > 3$ ms^{-1}, R^2 was 0.82 (Heisler, 1989). Most of the residuals (observed-predicted values) in these analyses were less than 20 percentage points, although some were as high as 40 percentage points, indicating something less than complete success in predicting percentage wind reductions at individual points for a particular hour.

With tree variables set to the values they would have with no trees, the mean predicted building effects on ΔU in the neighborhoods with trees ranged from .21 to .24 (Table 3). This is close to the value of 0.22 for the neighborhood with no trees (Fig. 6). The predicted building effects in the different neighborhoods in Table 3 are generally proportional to the building volume index in Table 1.

The apparent tree reductions ranged up to 0.46 for the high-density neighborhood in summer. Except in the low-density neighborhood, apparent wind reductions by trees

Table 3. Average reductions in U_a^n by buildings and trees in the neighborhoods with trees, as evaluated by regression models. The different neighborhoods are indicated by the tree-density group.

Tree-density group	By buildings	By trees Summer	Winter
Low	.24	.28	.14
Medium	.21	.39	.37
High	.24	.46	.41

in summer were not much greater than in winter. The difference between summer and winter tree density (V_d) was greatest in the low-density neighborhood (Table 2), and this is at least partly responsible for the larger differences between summer and winter in wind reductions by trees. The generally small differences between summer and winter tree effects might be related to generally more thermally unstable atmospheric conditions during the summer days than during the winter days, but Turner atmospheric stability class did not appear as a statistically significant independent variable in regressions for ΔU.

Windspeeds were much less closely correlated with any of our building morphology indicators than with our tree morphology. When ΔU was regressed on individual independent variables, the largest coefficient of determination, R^2, for a building variable was 0.15 for the building volume index. Tree cover was the single tree variable most closely related to ΔU, with an R^2 of 0.62. Our tree morphology indicators probably described tree morphology better than the building morphology indicators described building morphology. However, the higher correlation of tree morphology indicators with wind reduction is evidently caused primarily by a greater magnitude and range of influence of trees on windspeed in these neighborhoods.

There was a general trend of increasing percentage wind reductions with increasing U_o up to about $U_o = 3$ ms^{-1}. With U_o reference windspeeds between 3.1 and 5.4 ms^{-1}, total reductions in U_a^n by both houses and trees in the four neighborhoods averaged between 4 and 12 percentage points higher than when reference windspeeds were between 1.6 and 3.1 ms^{-1}. During daytime periods, higher reductions at higher speeds might occur because the higher windspeeds cause a more neutral thermal stratification in the lower atmosphere resulting in larger percentage reductions in mean windspeed by obstacles. However, this logical explanation is contradicted by the statistically nonsignificant effect of Turner stability class on ΔU. Turner class provides an indicator of thermal stratification.

A comparison can be made between our summer ΔU averages and the measurements of McGinn (1983). His "suburban canopy density" is a sum of fractional land area covered by trees times their height plus fractional area covered by buildings times their height. This produces an index that is approximately equivalent to our volume index for buildings plus the crown volume index for trees. McGinn's "density" ranged from 2.0 with no trees to 31.5 in an orchard. Our equivalent building plus tree-crown volume index ranged from about 1.0 to 44. McGinn (Fig. 7) extrapolated greater reductions than ours at high density. However, his high density case was an orchard with higher coverage of land area by tree crowns than is likely to ever be found in a residential neighborhood, while tree height was only about 35 ft (10.7 m), not as tall as trees generally present in a residential neighborhood with very dense tree cover. The short tree height resulted in a rather small density index given the cover percentage.

Wind reductions plotted versus the sum of building and tree densities in the neighborhoods in this study along with the data of McGinn (Figure 8) seems to yield a little less scatter in the data than in Figure 7 where height is included. The curve is fit to our summer means.

APPLICATIONS

A goal of this study was to provide a means of extrapolating wind reductions by trees and buildings to other neighborhoods. The map- and photo-derivation of building and vegetation morphology as reported here and in more detail in the final report (Heisler, 1989) along with the prediction equations for reduction in U_a^n (ΔU) in that report could be used to obtain approximate results in neighborhoods with not too different building density. In extrapolating, one method would be to select at least one "wind point" on each side of the building and then evaluate building and tree morphology over all wind direction sectors. Wind reduction over a year would then be modeled by selecting the hourly wind direction from a year's TMY or TRY data. By calculating C values, the ΔU values from any points with positive C (i.e., on the upwind side of the building) could be averaged.

For the purpose of modeling energy use in the buildings in this study, wind reductions for each season will be taken to be the seasonal average reductions from the tree density group in which the house is located. In the transition months of April and October, the summer and winter reductions will be averaged.

For approximate estimates of wind reduction below building height in neighborhoods of less than about 25% building density, values might be extrapolated from Figure 7 or 8. The points for summer wind reductions differ from the curve in Figure 8 by a maximum of 12 percentage points.

RECOMMENDED FUTURE RELATED WORK

The work on this study suggests the need for many additional kinds of measurements and studies. Just a few of these include:

1. Continuous measurements of windspeed reductions in residential neighborhoods over periods long enough to sample all atmospheric stability conditions and higher windspeeds in all seasons. A relatively small number of points would suffice.
2. Measurements in developments around houses with large masses of on-site trees, such as dense rows of conifers, to evaluate the effect of on-site trees in the turbulent air of a rough suburban surface.
3. Measurements to evaluate mean windspeeds at different heights in neighborhoods with trees.
4. Concurrently with wind measurements in 1 to 3, measurements of air temperature and humidity.
5. Simplified methods of modeling solar radiation and validation of existing models.
6. Improved methods of extrapolating weather data between separated sites in the presence of topographic variation.
7. The influence of trees and buildings on turbulent wind fluctuations within the canopy layer is also of interest, although current energy analysis programs do not include turbulence as an input.

CONCLUSIONS

A striking result of this study is the apparently large potential of the aggregate urban forest to reduce mean wind speeds in residential neighborhoods of single-family houses. Where houses reduced windspeed about 24%, trees in mostly scattered arrangements reduced windspeed up to an additional 46%. Even in neighborhoods where most of the large trees were deciduous, reductions of windspeed by trees in winter averaged 50 to 90% of reductions in summer. Wind reductions during nighttime periods may, on average, be larger than those reported here, which were all made in daytime periods. Prediction equations from regressions of wind reductions on descriptors of building and tree morphology explained up to 82% of the variability in wind reduction at points in residential neighborhoods.

The measurements reported here are preliminary to planned measurements to include a wider range of stability conditions, to evaluate the effect of dense windbreak rows within developments, and to evaluate windspeeds at other heights above ground.

ACKNOWLEDGMENTS

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NOMENCLATURE

C	horizontal angle at a wind-measuring point between wind direction and a line through the corner of the building.
D	horizontal distance from a building in units of h.
h	building height in ft.
R	relative windspeed U_b^s/U_a^s.
T	Turner atmospheric stability class.
U_a	approach windspeed toward a building but outside of its influence.
U_b	windspeed near a building within range of its influence.
U_o	mean windspeed at open control site.
U^n	windspeed within neighborhoods.
U^s	mean horizontal windspeed in single building measurements.
ΔU	reduction in windspeed in neighborhoods $= (U_o-U_a^n)/U_o$
V_d	density of tree crowns from wind points.
V_s	subtended angle of tree crowns from wind points.
θ	wind direction azimuth.

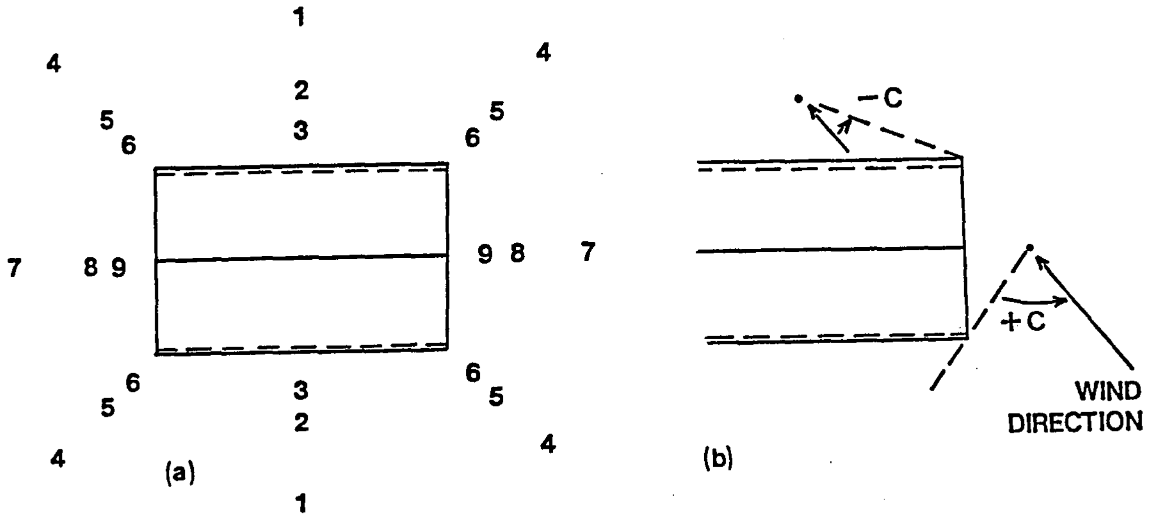

Figure 1. Plan views of isolated building indicating (a) position types (b) wind/corner angle (C).

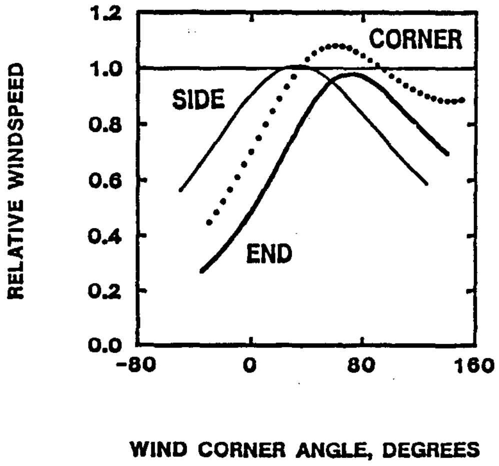

Figure 2. Relative windspeed at sides, ends, and corners of isolated building at a horizontal distance of 1 building height. The wind corner angle (C) is defined in Figure 1. The ends of the curves represent wind direction perpendicular to the sides or ends or parallel to the bisector of the corner, either toward the building (+C) or over it (−C).

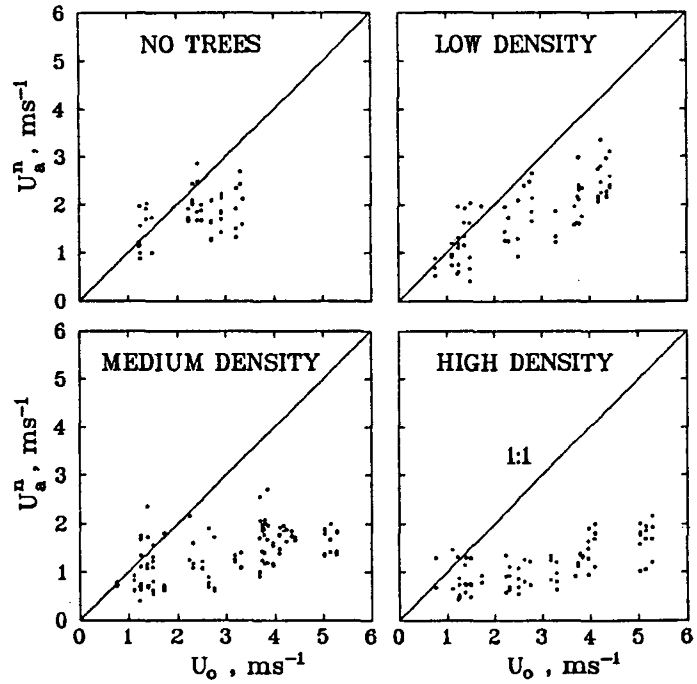

Figure 3. Approach windspeed toward houses (U_a^n) in winter versus reference windspeed (U_o) by tree density.

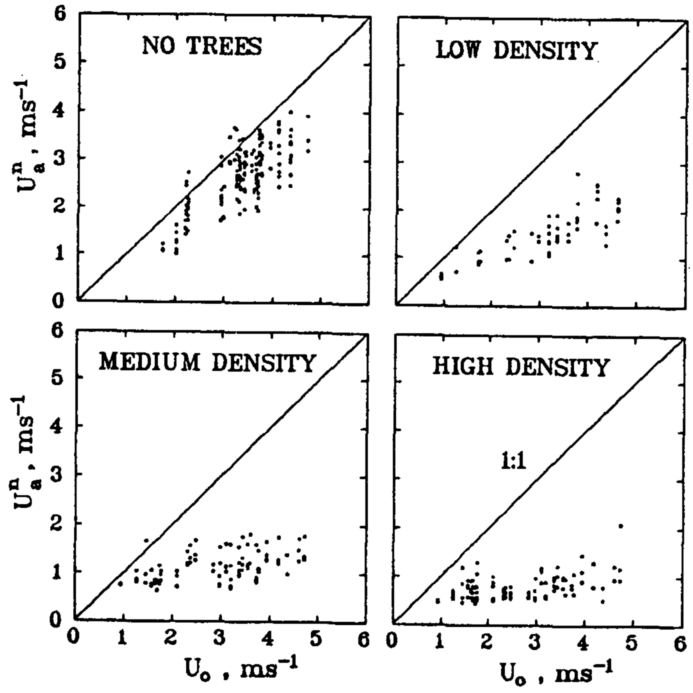

Figure 4. Approach windspeed (U_a^n) in summer versus reference windspeed (U_o) by tree density.

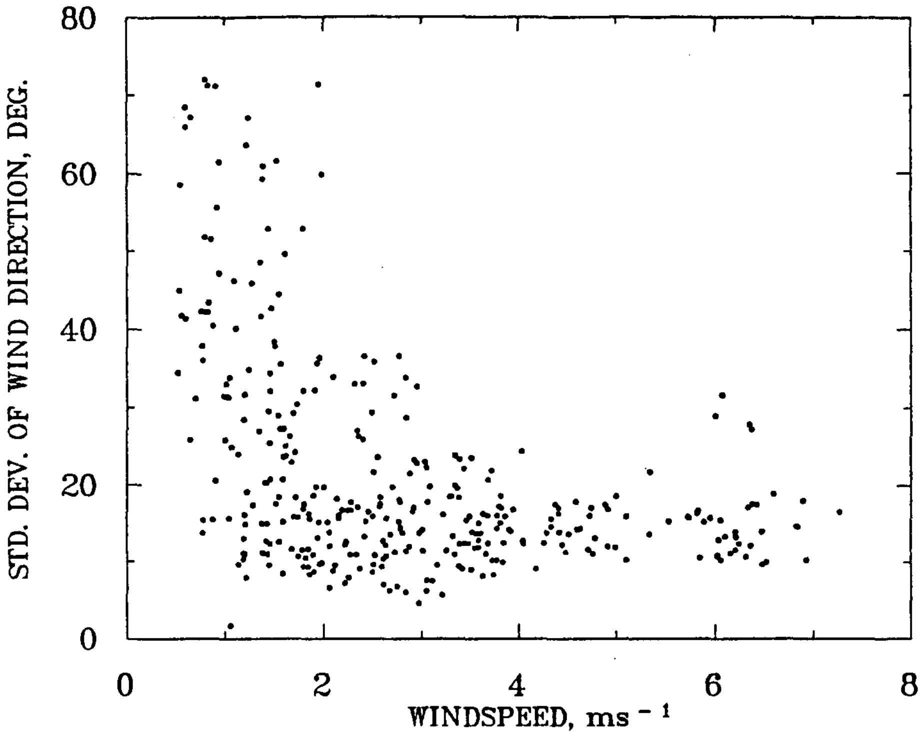

Figure 5. Standard deviation of wind direction at the 2-m height in an open area. Each point represents a one hour period.

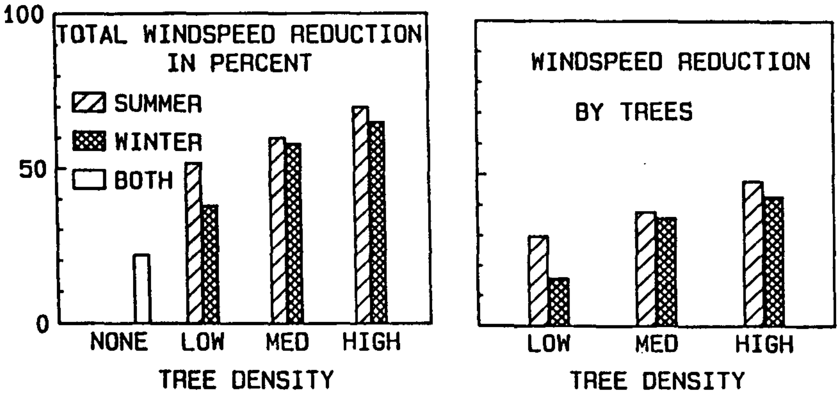

Figure 6. Mean total windspeed reductions and apparent reductions by trees shown by tree density for all data with $U_o > 1.6$ ms^{-1}.

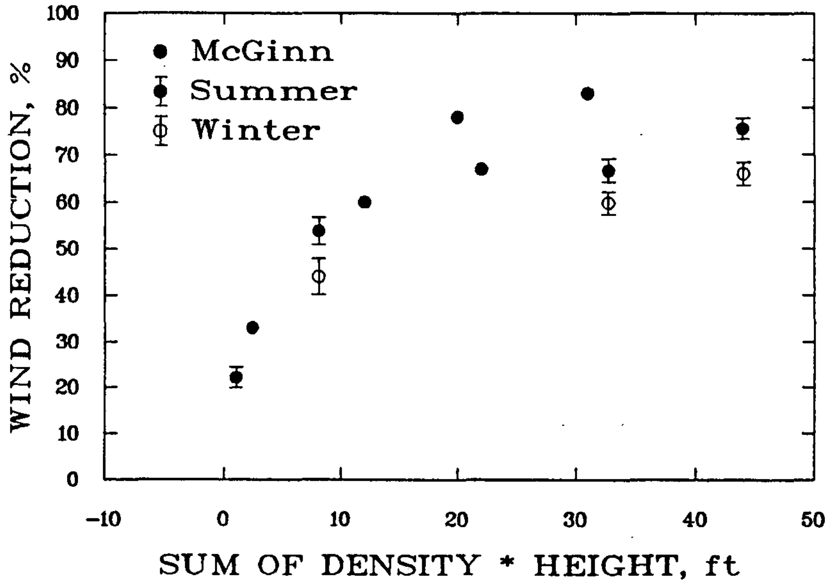

Figure 7. Wind reduction in residential neighborhoods versus the sum of area density x average height for buildings and trees from McGinn (1978) for summer and the measurements in this study for summer and winter. The error bars indicate 95% confidence limits about the means.

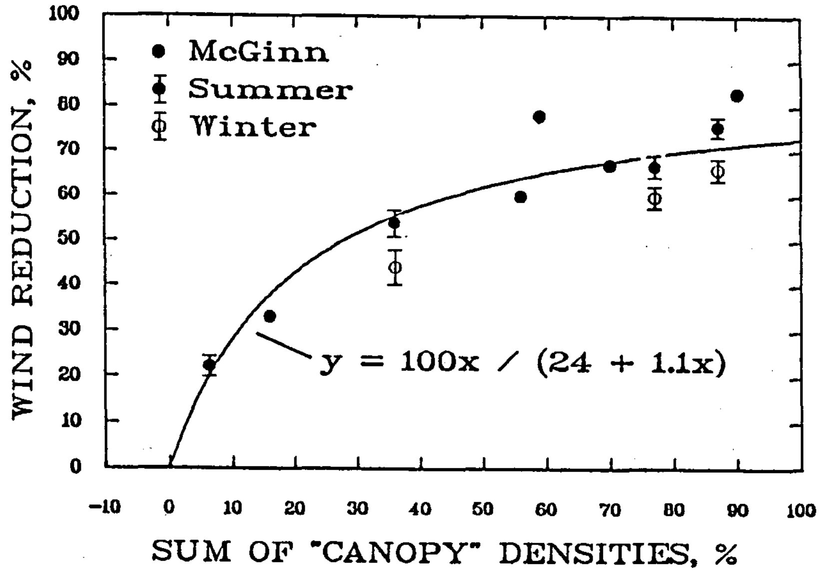

Figure 8. Wind reductions in residential neighborhoods versus the sum of area density of buildings and trees from McGinn (1978) for summer and the average neighborhood values from this study for summer and winter. The error bars indicate 95% confidence limits about the means.

URBAN WIND PROFILE AS A FACTOR AFFECTING URBAN VENTILATION AND VEHICULAR AIR POLLUTION CONCENTRATION AT STREET LEVEL

B. Givoni
Graduate School of Architecture & Urban Planning
University of California, Los Angeles

ABSTRACT

In a built-up area there are great variations in the wind speed around and between buildings. Extensive wind-tunnel research was carried out by Givoni (1968), Givoni and Paciuk (1972), and Paciuk (1975) on the effects of building height and spacing between buildings on the wind speed between the buildings. The modeled heights of the buildings were scaled to represent 12, 24 and 36 meters; the height-to-width ratios varied from 1:3 to 3:1. An arrangement of buildings of uniform height served as a base case to which higher buildings were later added for studying the effect of highrise buildings interspaced among rows of lower buildings. The effect of building height and spacing on urban wind speed, as obtained from the measurements in the above wind tunnel studies, was expressed mathematically by regression analysis.

The ventilation condition in the urban space as a whole, and in particular along streets with high vehicular traffic, has a significant impact on the concentration of air pollutants at the street level. The higher the speed and turbulence of the wind at street level, the greater is the mixing of the highly polluted low level air with cleaner air flowing above the urban canopy.

This study has demonstrated that by using different urban-design configurations, especially the location of highrise buildings with respect to wind direction, it is possible to change the urban wind speed near street level by as much as a factor of 5. Higher mixing, turbulence, and air speed in regions with high vehicular traffic can thus significantly reduce the concentration of pollutants.

KEYWORDS: urban design, urban climatology, urban ventilation, urban pollution

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INTRODUCTION

The conditions of ventilation in the urban space as a whole, and in particular in streets with high vehicular traffic, have significant impact on the concentration of air pollutants at the street level. The higher the wind speed and turbulence at street level the greater is the mixing of the more polluted, street-level air with cleaner air flowing above the urban canopy.

The street-level air velocity and turbulence conditions depend, on one hand, on the regional wind speed, which is a climatological factor but, on the other hand, they are greatly affected by urban-design features. In particular, specific design details of the buildings and the streets—such as the height of the buildings relative to one another, and the orientation of the individual buildings and the streets with respect to the wind—may greatly affect the actual urban wind speed and turbulence at the street level, and hence the concentration of the air pollutants.

Extensive windtunnel research was carried out by Givoni (1968), Givoni and Paciuk (1972), and Paciuk (1975) on the effects of building height and spacing on wind speed in the streets between the buildings, when the buildings are arranged perpendicular to the wind direction. The wind speed was expressed as the percent of the "reference" wind at the same height but well in front of the first line of buildings. In these studies the urban wind, and the reference wind were measured at a "modeled" height equivalent to a height of 5 meters above the street level. It should be noted that this reference is not the "free" wind at a height of 10 meters above ground that is measured at most meteorological stations. This particular choice of a reference, at the same height at which the urban wind was measured, enabled direct calculation of the effect of the buildings on the ratio of the urban speed to the undisturbed wind speed at the same height.

The modeled heights of the buildings were scaled to represent 12, 24 and 36 meters. The width of the spaces between the buildings (streets) were also scaled to 12, 24 and 36 meters, changing the buildings height-to-width ratios from 1:3 to 3:1. An arrangement of buildings of uniform height served as a base case to which higher buildings were later added for studying the effect of highrise buildings interspaced between rows of lower buildings.

EFFECTS OF BUILDING HEIGHT AND STREET WIDTH WITH UNIFORM BUILDINGS

In the above studies it was found that when an urban neighborhood consists of long rows of buildings of uniform height, arranged perpendicular to the direction of the wind, the building height and spacing has only a small, although not insignificant, effect on the speed of the wind currents in the streets. This is due to the fact that the first rows of buildings divert the approaching wind current upwards, and the rest of the buildings behind are left in the "wind shadow" of the buildings standing upwind of them. The small effect of building height and spacing which still exists in this configuration is expressed quantitatively later in this paper.

A significantly higher wind speed was observed in the "first" street (between the first and the second row of buildings), and to a lesser degree in the "second" street. This pattern was observed in all the combinations of height of buildings and the width of the space between them. After the second street, the relative speed gradually stabilized, giving only small differences between the different spaces.

From observation of the flow pattern it seems that when wind blowing over an open space encounters an abrupt resistance, in the form of a series of long buildings perpendicular to wind direction, the highest suction is formed above, and immediately behind, the first line of buildings. This suction generates turbulent air flow in the streets between the buildings, apparently in proportion to the pressure differences. The initial "agitation" increases with the height of the buildings (h), resulting in a higher suction over them.

The higher wind speed, generated by the initial turbulence "agitation" over the first lines of buildings, declines gradually toward a uniform wind speed in the spaces between the buildings. The rate of decline in wind speed seems to depend on the distance into the built-up area (D - the total length of buildings and open spaces between them) and on the width of the spaces between buildings (W). The analysis of the data suggested that the ratio D/W is the main factor which determines the rate of drop in air velocity toward an asymptotic value of about 10% of the "free" wind speed.

The effects of building height and spacing, as obtained from the measurements in the above wind tunnel studies, were expressed mathematically by regression analysis. The regression equation developed for the wind speed in the streets between rows of buildings of uniform height, perpendicular to the wind direction, is (Paciuk, 1975):

$$V_{r(u.h)} = 10 + (66\,(1-e^{-0.08h}))e^{-0.18(D/W)} \qquad (1)$$

Where:

$V_{r(u.h)}$ = relative wind speed (percent of speed at the same height in front of first row of buildings)

D = distance traveled by the wind inside the city (meters) = $n\,(b+W) - 0.5\,W$

b= length of the buildings along direction of wind (meter)

n = serial number of the street (downwind)

h = height of the buildings (meters)

W = width of the street (meters)

Figure 1 shows the correlation between the measured relative wind speed and that computed by Eq. 1. The solid line represents one-to-one correlation and the dashed line represents the regression.

This formula predicts that the wind speed in a street, in an urban configuration of long buildings of uniform height and streets perpendicular to the wind, decreases gradually toward an asymptotic level of 10%, with increasing "depth" into the city (D). Wider spacing (streets) between the buildings (W) with given height of buildings (h), or lower buildings with a given spacing, tend to increase the wind speed in the streets.

WIND SPEEDS AROUND HIGH RISE BUILDINGS LOCATED AMONG LOWER BUILDINGS

Individual buildings rising high above those around them create strong air currents around them. This phenomenon is due to the fact that a highrise building is exposed to the main wind current that flows above the "general" level of the urban canopy, which is stronger than the air flow through the urban canopy itself.

Against the facade of a highrise building which faces the wind, a high air pressure pocket is formed, which causes a strong downward current. This mixes the air layers near the ground between the lower buildings with the air flowing above the urban canopy. The direction and quantitative effect of the high rise buildings on the urban wind field depends greatly upon their specific location within the urban fabric.

Quantitative Effects of Highrise Buildings on Air Speeds Around Them

In a series of comprehensive experimental studies with models in a wind tunnel, Givoni and Paciuk investigated the quantitative effect of highrise buildings, interspersed among lower buildings, on the air speed in the streets around them. Different arrangements of the highrise buildings were tested.

In the first experimental series (Givoni and Paciuk, 1972) models of nine highrise buildings were placed with different configurations over five rows of uniform-height buildings, 36 meters high, with spaces of 12 meters between the buildings. Figure 2 shows the relative air speeds in the four "streets" lined by buildings of uniform height, either without any high buildings, or with nine high buildings interspaced in different configurations among the lower buildings. In one configuration the high buildings formed a "wind break" upwind of the lower buildings. In other configuration the high buildings were dispersed throughout the whole "neighborhood." It can be seen that even without the "wind break" the overall configuration of long buildings perpendicular to the wind direction inhibits air flow between the buildings. The wall of highrise buildings upwind further lowered the wind speeds between the row buildings.

The average relative speed in the configuration with uniform buildings was 26% of the wind speed at the same height, far in front of the first row. A "wall" of high buildings upwind & reduced the average speed to 15%, demonstrating the potential use of high buildings for "sheltering" a neighborhood, but at the same time reducing the potential for dilution of vehicular air pollutants.

The nine "towers" were later dispersed among the rows of long buildings with two different configurations, producing various "spots" of high and of low pressure. Smoke tracing has demonstrated that downward flow formed in front of the high buildings while in the streets, lined by the row buildings, the flow was mainly parallel to the buildings, away from the points of high pressure and toward the points of low pressure. The highest speeds were measured in front of the high buildings and the lowest speeds at points behind and between two towers. The average wind speeds in the two configurations with dispersed towers were 60% and 52%. Thus with the different configurations of highrise buildings, from one protected from the wind to those enhancing the wind speed in the streets, a range from 15% to 60% of the unobstructed wind at the same height above the ground was achieved. Spot measurements at individual points had a much larger range.

In a second expanded experimental series (Paciuk, 1975), the effect of high towers was measured in an arrangement of nine rows of uniform height buildings perpendicular to the wind. Nine "towers" were placed, in different configurations, over the row buildings. The effect of the towers was measured with different heights to spacing ratios of the row buildings. The modeled height of the towers was 36, 48 and 60 meters above the level of the lower row buildings (Figure 3).

It has been found that when the towers were "dispersed" throughout the "neighborhood" they always significantly increased the air speed in the "streets". The absolute and relative effects, however, depended mainly on the height to spacing ratio of the row buildings. As the whole "urban area" with nine rows was deeper, the average wind speeds were lower than in the first series with only five rows of buildings.

By regression analysis of the data on relative speeds, obtained with different arrangement of the tower buildings, it was possible to develop a general formula, estimating the relative wind speed at any point in the streets as a function of its distances from the centers of pressure (in front of the towers) and centers of suction (behind them).

The independent (urban design) factors in the formula are the height of the row buildings (h), the spacing between them (W), the height of the towers (H), and the distance between towers in the same street (d_p+d_s). This general formula (Paciuk, 1975) incorporates also the special formula given above for buildings of uniform height and the configuration of the towers ($V_{r(u.h)}$)

$$V_{r(t)} = V_{r(u.h)} + K(dV_r)$$

Where:

$V_{r(t)}$ = relative speed in an urban configuration with towers

$V_{r(u.h)}$ = relative speed in a configuration of rows of uniform height (without towers), as given by equation 1.

$$K = 1.18\ (1-e^{-0.8H/W})$$

$$dV_r = 48e^{-0.16dp} + 30\ (1-d_s/(d_p + d_s))$$

dV_r = increase in speed by the towers

d_p = distance of the point from the pressure center

d_s = distance of the point from the suction center

This equation expresses the observation that increased distance from the pressure center reduces the speed, and that the existence of a suction center on the other side increases the speed. Figure 4 shows the correlation between the measured data (in the two series) and the computed relative speeds, in the various configurations of the different experimental studies. The solid line represents one to one correlation and the dashed line the regression.

EFFECT OF HIGH RISE BUILDINGS ON VEHICULAR AIR POLLUTION

The studies of Givoni and Paciuk summarized above have shown that it is possible to manipulate to a great extent the wind speed and direction in the streets by specific placements of high buildings. An increase of the street level wind speed and turbulence increases the mixing of the pollutants emitted by vehicles, with clean air from above, thus reducing the street level concentration of the pollutants. This was demonstrated in the study of Georgii (1970) and is shown in Figure 5.

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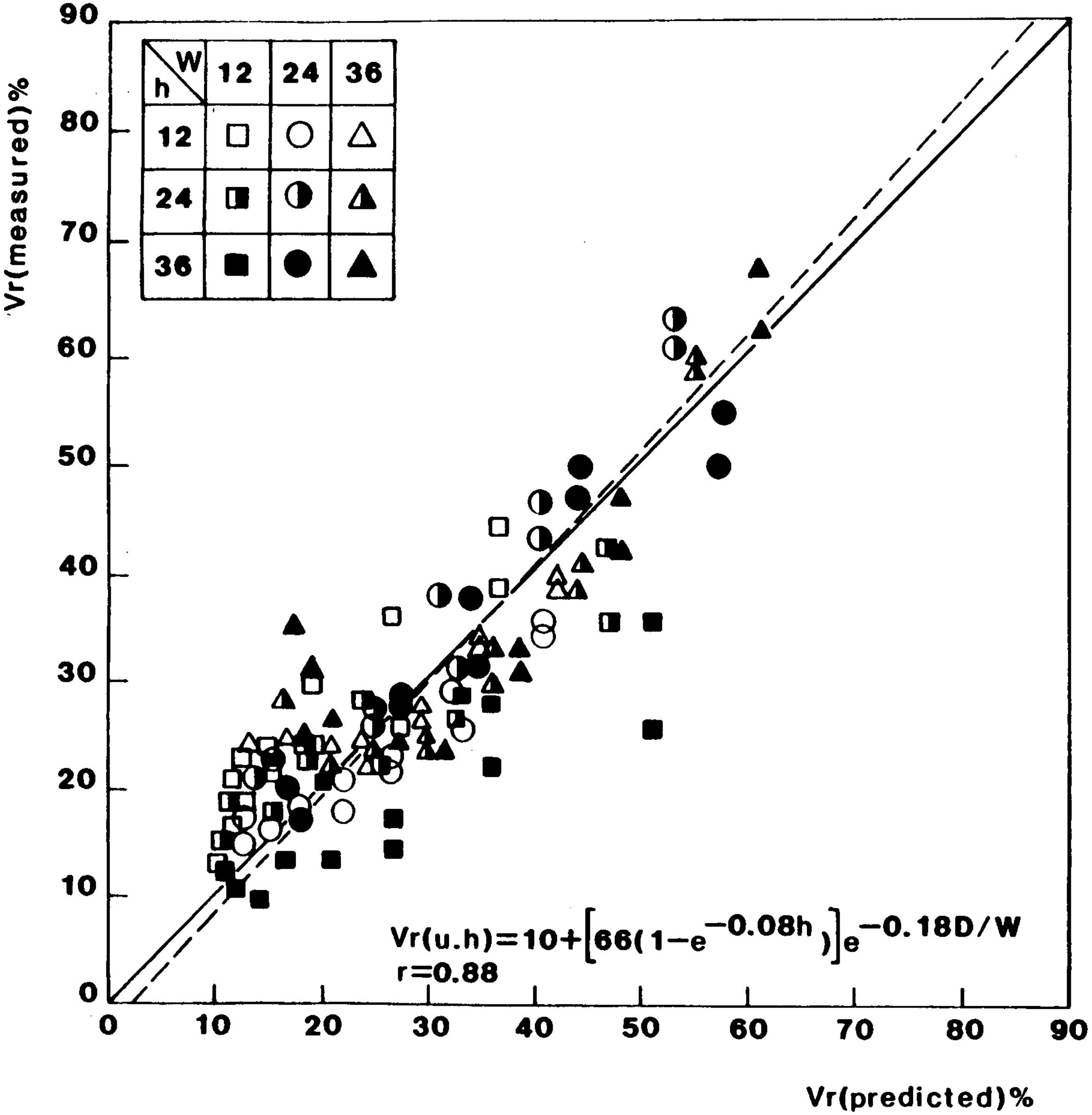
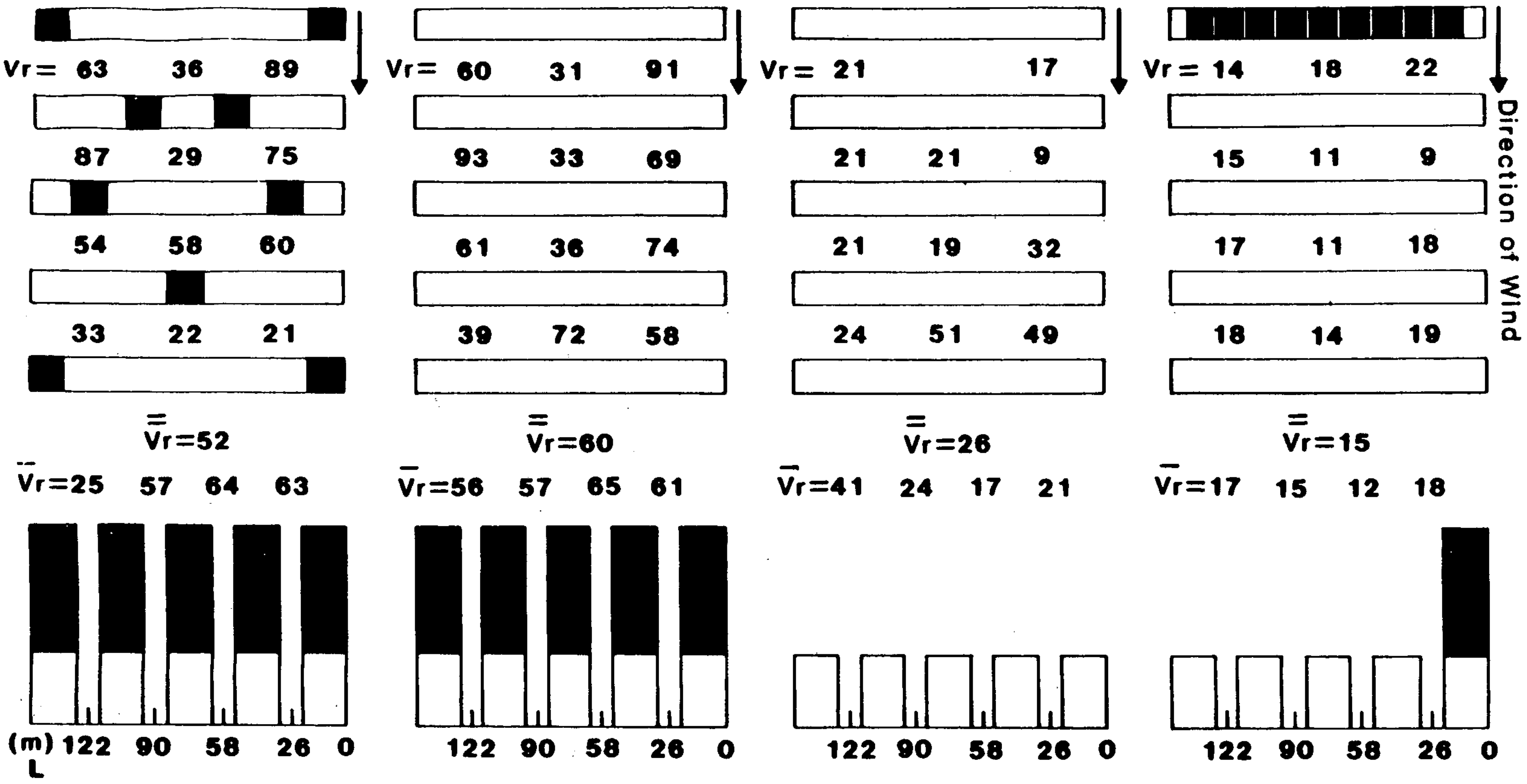


Figure 1: Measured and Computed Wind Speeds in Urban Configuration of buildings of the Same Height.



Vr: at point of measurement.

$\bar{V}r$: average in-between rows.

$\bar{\bar{V}}r$: grand-average.

Figure 2: Distribution of Wind Speeds in Urban Configuration with 4 Streets Without and With Highrise Buildings.

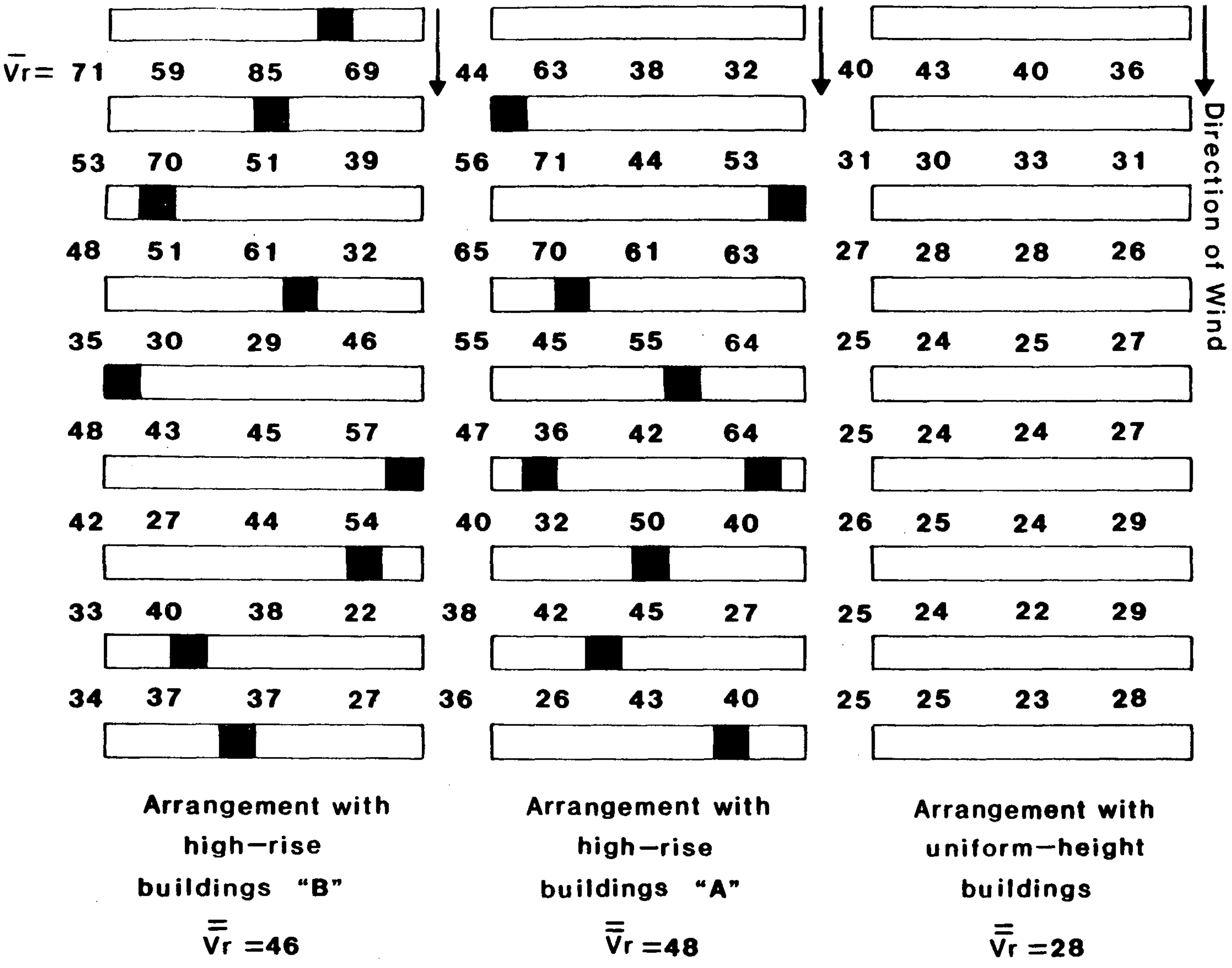


Figure 3: Distribution of Wind Speeds in Urban Configurations with 9 Streets Without and With Highrise Buildings.

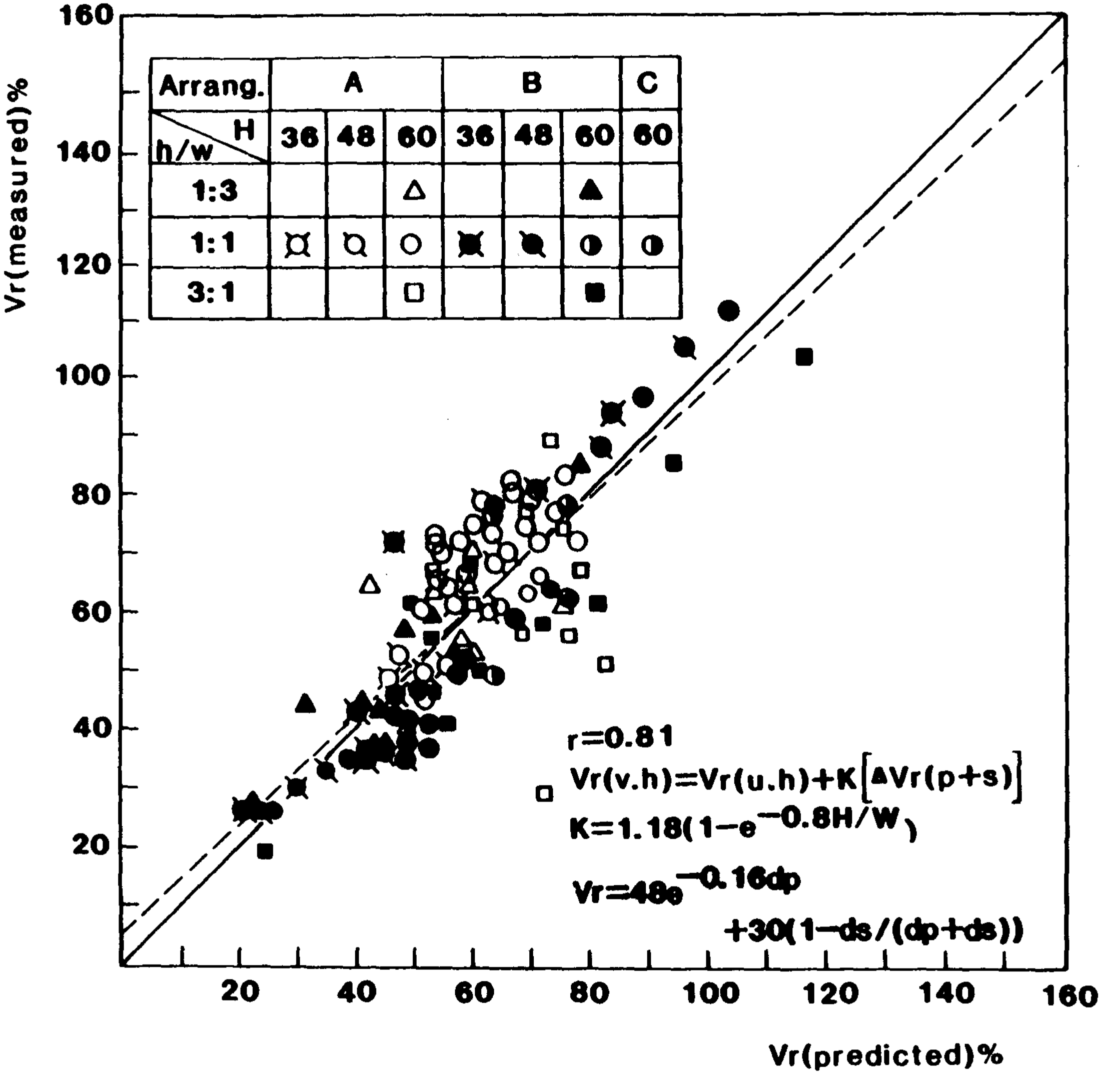


Figure 4: Measured and Competed Wind Speeds in Urban Configurations With and Without Highrise Buildings.

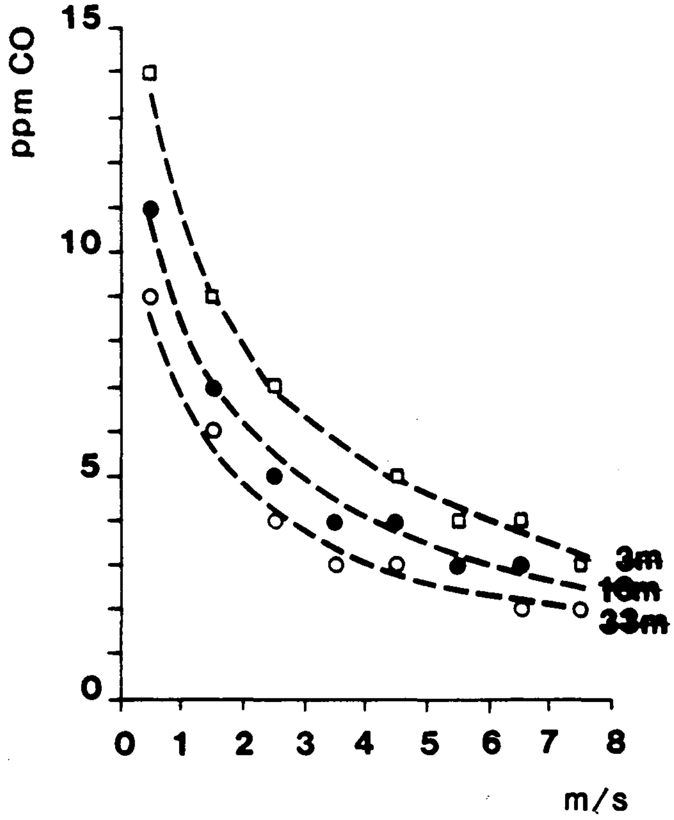


Figure 5: Air Pollution (CO) Concentrations in a Street as Functions of The Wind Speed (m/s) and Height above the Pavement (From Georgii, 1970).

CHAPTER 5

Policy Design and Implementation of Heat Island Mitigation

Chapter 5

POLICY DESIGN AND IMPLEMENTATION OF HEAT ISLAND MITIGATION MEASURES (Editors' Summary)

We are yet to quantify to what extent large-scale heat islands can be reduced by changes in characteristics of the urban surface (e.g., reflectivity and vegetation cover), and hence to accurately estimate the energy savings and air quality improvements that could be derived therefrom. Certain aspects of the problem, however, are sufficiently clear to warrant immediate implementation of heat island mitigation programs at some level. We can estimate with a fair degree of certainty the impact of whitening roofs and planting trees next to houses in warm climates. Microclimate cooling in the vicinity of the modification is significant and can yield cooling-energy reductions at low cost. In fact, these reductions are likely to be cost-competitive with the lowest-cost energy-efficiency methods.

Less well understood is the potential for trees and white surfaces to significantly cool the urban environment at the mesoscale (city-wide). Proposals to cool cities by increasing transpiration through large-scale afforestation must consider the water constraints of arid areas and the already high humidities of moist areas. Proposals to increase albedos city-wide must consider subsequent alteration of "whitened" surfaces, for example, particulate deposition, detritus, and bleaching, and the relative merits of lightening different parts of the urban surface (for example, the deep canyon geometry of city streets in the urban center makes walls much less efficient net reflectors than roofs, which are likely to receive fewer back reflections from adjacent surfaces). Despite these potential obstacles, the possibility of wide-spread benefits—energy reduction, smog reduction, increased thermal comfort, carbon sequestering, and a generally improved urban environment—justify investigating these issues at the larger scale. On the other hand, previous dramatic failures in urban afforestation programs in particular, such as in Mexico City in the 1970s (see Beatty, this chapter), urge the need for careful planning. Research on the performance and survival rate of trees in the urban environment, coordinated with smaller scale urban afforestation programs, can be used to determine if larger investments are warranted. A similar argument can be made for field research on white surfaces.

An example of the type of research that can tell us how to optimize tree planting programs is given by **Clark** *et al.* This type of study can help us better understand tree function in the urban environment, and therefore the potential of trees to alter that environment. The authors studied the development of sweet gum trees in three contrasting parts of the urban environment: the park, the urban canyon (defined by two facing rows of buildings and the street in between), and the plaza (any large, open paved area such as a parking lot). The study found a similar vigorous response of the trees to the park and canyon environments, but found decrease in size and vigor in plaza trees. The authors assert that heat island mitigation and tree survival will be maximized by the clustered planting of trees in "refugia", but offer no direct evidence for this assertion. This question requires more research. Depending on the function of particular species, dispersed trees might have a greater impact on the local atmosphere than clustered trees, although the trees themselves are likely to have higher survival probability if planted in clusters. For example, clustered trees will increase the humidity within the canopy reducing per-tree transpiration rates, whereas individual trees are likely to maintain higher rates since moisture transpired from their leaves is mixed into a larger volume of drier air. Furthermore, the energy benefits to be derived from dispersed planting—a few trees next to each house to modify the microclimate of individual buildings—are likely to be significantly greater than if trees are planted in park-like clusters away from buildings. These questions merit further research.

In addition to the Clark paper, this chapter presents four others that raise issues relevant to the policy, design, and implementation of tree planting programs. **Akbari** *et al.* in Chapter 1 also raise policy issues of heat island mitigation and should be reviewed by interested readers. Unfortunately, there are no papers directed specifically at implementation of programs to increase urban albedo, because of the shortage of research on, and lack of prior experience with, such programs. This area is ripe for further research. Regarding the design and implementation of programs to enlarge the urban forest, the most important issues raised are the need to focus on tree survival, not merely tree planting, and the related need to incorporate the human community into the program design and implementation process.

As mentioned in the introduction to Chapter 1, any decision to adopt, or not adopt, a policy to mitigate urban heat islands ought to consider all of the benefits and costs of the measure(s) adopted, not merely those directly related to energy use. **Moll** makes an informal assessment of some of the more important, non-energy-related benefits of urban trees such as ecological and psychological benefits and increased property values. He also describes some attempts at assigning economic values to these benefits. It should be noted that, although increased property value is relatively easy to quantify, this measure fails to capture many of the more important ecological and environmental benefits of urban trees. More research of such economic benefits—and of costs such as side-walk damage and limbs falling on houses, cars, and telephone lines—will be needed to make a meaningful cost-benefit analysis of urban forests.

Lipkis and Lipkis describe in some detail the tree-planting program of the Los Angeles-based, non-profit organization TreePeople that succeeded in getting one million trees planted in Los Angeles before the 1984 Olympics. The group succeeded, with no initial budget to buy trees or manage the campaign, at mobilizing the resources and inspiration of the community, including enlisting the services of a major advertising agency to design the campaign and the talent of the actor Gregory Peck to publicize it—both at no cost! Monetary resources to run the campaign came from small donations of TreePeople members and the public, and individuals and local businesses large and small donated labor and services. Not only were the trees planted, but the campaign succeeded in generating community spirit in what many consider the land of alienation.

Beatty and **Acosta** are both critical of the TreePeople campaign for not including follow-up maintenance and monitoring of trees in their Los Angeles campaign. In particular, there has been no follow-up survey of what percentage of the trees planted actually survived. It is certainly true that tree maintenance could be a major determinant in the outcome of such a program, and post-planting monitoring could have taught us much about the value of urban trees. But, in fairness, the TreePeople campaign was run on a shoe-string budget at no cost to the city, largely by volunteers, and the program was designed to maximize the survival potential of trees despite the fact that there were no resources for post-planting monitoring. The campaign focused on getting residents to buy and plant trees on their own property, assuming that those who paid for the trees would have the greatest interest in maintaining them. Although in hindsight, the program might have been improved—and TreePeople is working to do so in their new campaign to plant 2 to 5 million trees in Los Angeles. At the very least, the Lipkis's story teaches us that the community can be a valuable asset to the urban forest rather than merely the blight it is often considered to be by foresters.

Acosta characterizes this human blight as the Meanstreets philosophy, which destroys trees through vandalism and neglect. Acosta stresses the need to involve the community, individuals and local organizations, in the urban forestry program—especially to coopt those who might later adopt the Meanstreets viewpoint if not drawn into the Greenstreets viewpoint early on, in particular inner city kids. It appears that the Lipkis's talents at rallying the community around the cause of trees would make a valuable contribution to the longer-term efforts of established municipal forestry programs like that described by Acosta.

Beatty describes the general policies and ordinances related to planting trees in cities. No specific guidelines for future urban forestry programs are given, but the philosophy that should underlie them is introduced. In particular, Beatty stresses that the city should be considered as an ecosystem of which trees and vegetation are an essential component. The author stresses that most urban forests have been designed with aesthetic purposes in mind. Newly-developed, scientific criteria for planting to reduce urban heat islands could in some cases be incorporated through existing programs like **Acosta's** Office of Parks and Recreation in the City of Oakland. Such programs could be integrated with tree-planting campaigns like TreePeople's, and with various incentive programs instituted at the state and local levels.

Beatty's review of municipal tree-planting ordinances found that none yet addressed the issue of heat island mitigation except in an indirect way by requiring tree planting in parking lots. Beatty asserts that parking lots may cover as much as 25-30% of urban centers and therefore might provide a significant opportunity for heat island mitigation. The value of trees planted in parking lots to reduce urban heat islands raises some issues brought up in the introductions to Chapters 1 and 2. That is, parking lot trees will not directly shade buildings and, therefore, will not yield the direct benefits of reduced cooling-energy consumption by shading. However, if there is sufficient planting space and available subsurface water in parking lots, then the heat balance of the city at a larger scale might be altered by increased transpiration and correspondingly decreased sensible heat loading. If so, cooling-needs and air pollution concentrations could be indirectly lowered by reduced air-temperatures in and above the canopy layer. In addition, direct shading of cars produces an additional benefit by lowering smog-producing emissions of volatile hydrocarbons from gasoline tanks in vehicles parked in the lots.

THE ENVIRONMENTAL FUNCTION OF URBAN TREES: LIQUIDAMBAR STYRACIFLUA L. IN SEATTLE, WA

James R. Clark, Roger Kjelgren and Deane Wang
Center for Urban Horticulture
University of Washington

ABSTRACT

Successful mitigation of the effects of urban heat islands requires dense plantings of vigorous trees. In Seattle, a combination of harsh environmental conditions and diffuse planting arrangements limits the contribution of trees to overall site energy balance.

However, small assemblages of trees offer important environmental benefits. The value of trees as modifiers of urban heat islands is a function of their biomass, metabolic activity, and spatial distribution. Large numbers of vigorous trees provide the greatest degree of environmental function by, for example, increasing latent heat loss, acting as wind-breaks, and reducing solar gain. The ability of trees to successfully exploit these fragmented green spaces is related to the physical environment of the space, characteristics of the species, and management.

To understand both the physical environment of small spaces and the responses of trees within them, we studied the development of 15-year-old *Liquidambar styraciflua* (sweet gum) in three contrasting environments: park, plaza and urban canyon. These sites were distinguished by two features: extent of pavement and amount of radiant energy.

Trees growing in the urban canyon and park sites were similar in size and overall vigor, while plaza trees were much smaller. These patterns of development were attributable to the response of sweet gum to site-specific environmental variables. The greater evaporative demand at the plaza site induced the development of morphological and physiological features that served to reduce radiation loading, promote dissipation of sensible heat, and restrict water loss. These features restricted seasonal growth. In the canyon, sweet gum acclimated to the reduced radiant energy by developing shade-acclimation features, thereby permitting maximum utilization of limited solar inputs. Development was comparable to that found in trees located in the near-ideal conditions

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KEYWORDS: cooling, heat islands, microclimate, transpiration, urban trees, urban environment, water use

of the park site.

Understanding limitations on tree growth and patterns of tree function and development in the urban landscape is a key to optimizing the use of trees to enhance the quality of urban life.

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INTRODUCTION

The focus of much of the discussion regarding summer heat islands has been the role of plants, specifically trees, in ameliorating the extremes in urban environmental conditions. An integral part of this discussion deals with the impact that urban environments have on plant growth and development. Our research program has focused on several aspects of this second perspective, dealing with the growth responses of trees to fragmented, dissimilar urban spaces. The emphasis of our discussion is on the plant stress induced by high summer solar insolation, temperature, and dessication in Seattle, WA.

The value of any tree or assemblage of trees in reducing urban heat islands is directly related to their survival and performance in those conditions. To a large extent, environmental function of trees is controlled by tree performance, in both short-term physiological activity (such as transpiration) and long-term growth and development. Conversely, individual tree performance is also largely determined by environmental function. The processes that ameliorate temperature for humans also ameliorate growing conditions for plants. This positive feedback system is an important feature of the urban plant/environment relationship.

We suggest that the capacity for trees to provide climate amelioration is dependent upon at least 3 factors: 1) the amount of plant biomass on a site, 2) their physiological performance and 3) their spatial distribution (Table I). Each factor has both natural and man-made components. For example, the number of plants in an urban area results from a combination of natural regeneration in open space/wildland/park areas and artificial regeneration through planting programs. Each of these is in turn dependent upon the space available for plants.

SPATIAL DISTRIBUTION, ENVIRONMENTAL FUNCTION, AND TREE PERFORMANCE

The spatial distribution of plants throughout urban areas, while not random, is not at all uniform or symmetric. In Seattle, average densities of trees may range from 0.5-12 stems per hectare (Table II) as a function of land-use zone. We estimate that Seattle has 230,000 trees over its approximately 21,000 ha. This density of about 11 stems per ha is in sharp contrast to densities of 250 stems per ha in typical forest stands of the

Pacific Northwest.

In addition, there are very few large masses or assemblages of trees. On the other hand, large areas of turf-grass (for example cemeteries and golf courses) occur with much greater frequency. To our knowledge, the importance of such large turf areas on heat island mitigation has not been examined.

Two conclusions seem clear from these observations. One, the character of the urban environment as related to the distribution of trees (using Seattle as a typical example) is fragmented, with large variation from land-use zone to land-use zone in the density of planting. Second, the potential for urban forests, at the tree densities seen in Seattle, to contribute significantly to the energy balance of urban heat islands through transpiration is relatively small. There are simply not enough plants to have a large-scale impact.

A rigorous and generalized evaluation of the pattern of parks, greenbelts, boulevards, street tree plantings, etc. within urban areas is greatly needed. The environmental function of large masses vs. long strips of vegetation has not been determined. We believe that the more diffuse the arrangement of trees, the more limited their environmental and ecological value.

The most effective use of a limited number of trees may be to create relatively dense assemblages of trees. In light of the observations of Oke (1989), who observed that an inner city park area had a significant moderating influence on the air temperatures of the residential area adjacent to it, the value of these cool spots is clearly illustrated. In such situations, the tree assemblages themselves then benefit from the ameliorated climate, leading to improved performance.

TREES IN A MOSAIC OF URBAN SPACES

An examination of the spatial distribution of urban trees reinforces a sense that green space in urban areas is fragmented and lacking in continuity. Few analyses of this fragmented character have been attempted. Moll (1988) defined four types of space: suburban fringe, suburbs, city residential and city center, but did so in a general way.

To begin to understand the role of trees in the mosaic of urban spaces, we have used the approach of Federer (1971), who defined three types of spaces: park, plaza and canyon. These are distinguished by the extent of paved surface and openness to the sky. While the canyon and plaza have significant, if not complete, ground coverage by pavement, they are differentiated by the degree to which surrounding structures block incoming radiation. Plaza spaces are open to the sky, while canyons are associated with taller structures. Typical plazas might be parking lots and street/sidewalk plantings.

Parks typically lack tall buildings and extensive paved area. Instead, they possess large assemblages of plants. One, two or several layers of vegetation may be present.

Parks, greenbelts, boulevards and campus-environments might all be considered "parks" using Federer's classification.

THE NATURE OF THE PHYSICAL ENVIRONMENT IN PLAZA, PARK AND CANYON SPACES

Given the very different character of these three types of space, it is not surprising that they should possess different microclimates. Since photosynthesis and transpiration are critical to both plant performance and environmental function, we have evaluated how these microclimates differ in patterns of both radiant energy and evaporative demand. Details of the methods associated with the study may be found in Kjelgren (1988).

Parks and plazas have diurnal patterns of radiation typical of open spaces (Figure 1). Peak levels of radiant energy (measured as PPFD- photosynthetic photon flux density, 400-700 nm) in mid-summer reach 2000 umoles/m^2sec. In contrast, a canyon has a truncated pattern of radiation, with PPFD under 200 umoles/m^2sec for most of the day. For only 4 hours between mid-morning and early afternoon does the intensity of radiant energy at ground-level approach 2000 umoles/m^2sec. Similar results for urban canyons have been reported by Whitlow and Bassuk (1987).

The season-long effect of this truncated pattern is to greatly reduce the amount of potential radiant energy available to trees growing in the urban canyon. The canyon location we evaluated received only 50% of the potential seasonal PPFD. Amelioration of a canyon space will require plants able to tolerate and successfully develop under such conditions.

Although park and plaza spaces had similar patterns of incoming radiant energy, the plaza had 50% greater evaporative demand (measured with Piche evaporimeters) than either the park or canyon (Figure 2). The only difference in structure of park and plaza spaces is the presence of plants. The importance of these plants in reducing evaporative demand through creation of a more humid boundary layer in the strata of the plant canopy is quite clear: large, moderately dense assemblages planted in open spaces can ameliorate a harsh environment.

Additional Physical Factors

The importance of both edaphic (see reviews by Craul 1985 and Patterson 1980) and abiotic factors (Karnosky 1985) to the successful development of urban trees should not be minimized.

Further, tree performance and success, as measured by size, may be significantly limited by restrictions on the amount of available growing space above and below the ground. The presence of large expanses of pavement, overhead wires, proximity to buildings and limited soil volumes all serve to restrict crown and root development.

Two important urban tree management problems- management of trees under utility lines and root damage to sidewalks- are both a result of limited physical space. Such restrictions on size have a direct impact on environmental function.

DEVELOPMENTAL RESPONSES OF LIQUIDAMBAR STYRACIFLUA IN PARK, PLAZA, AND CANYON SPACES

In order for plants to ameliorate the environment of a space, they must be able to cope with a defined set of radiation and evaporative demand conditions. To understand how vigorous assemblages of plants can be developed in the park, plaza and canyon spaces, we must first understand how plants respond to the environmental conditions found within those spaces. To this end, we have monitored the growth and development of even-aged sweet gum, *Liquidambar styraciflua,* planted as street trees in Seattle. For a detailed review of the results, see Kjelgren (1988).

Trees growing at canyon and park locations were similar in height and stem diameter (Table III). Trees growing at the plaza were smaller in stature and were clearly not as vigorous. The environmental function of plants in the plaza was limited by their small size and low vigor.

Clearly, sweet gum was able to tolerate the reduced radiant energy conditions of the canyon, but not the conditions of the hot, dry plaza. Yet, an open, "plaza-like" space was transformed into a park through the use of plants. Such a transformation can only occur with external management inputs, for the combination of radiation and evaporative demand at the plaza creates a very stressful environment for plants.

Developmental Responses Of Canyon Trees

For most of a summer day, PPFD in the canyon environment is below 200 μmole/m^{2}sec. In response to this low flux density, canyon trees developed classical shade acclimation responses, including larger, thinner leaves presented horizontally to the ground (orthogonal to direct beam radiation). The degree of acclimation was a linear function of potential PPFD (Figure 3).

That sweet gum would develop such shade acclimation features was somewhat surprising, given its silvicultural reputation as a shade "intolerant" species. However, development of such features permitted this plant to successfully exploit its low radiation environment and to grow as large as similarly aged trees planted in the park. Since growth of trees planted in urban canyons is dependent upon acclimation to conditions of reduced radiation, their environmental function is also directly related to this acclimation.

Seasonal Plant Moisture Stress

The reduced growth of plaza trees may be attributed to the higher evaporative demand at the site—due to higher radiation and air flow across the leaves—coupled to a limited seasonal moisture reservoir (street trees in Seattle do not generally receive any supplemental irrigation). Sweet gum responded to a high demand for water and a limited supply by developing morphological and physiological features that restricted water loss. These included leaf presentation angles perpendicular to the ground (parallel to direct beam radiation), reduced heat loading, and mid-day stomatal closure. Sweet gum was very successful in this water loss restriction. Despite the greater demand for water placed on trees growing at the plaza, trees growing at the park had greater diurnal transpiration rates—probably due to the greater availability of water (Figure 4).

The importance of seasonal moisture status on tree growth cannot be understated. In Seattle, diameter increment is a direct consequence of water stress (Figure 5). A complex interaction of the site evaporative demand, soil moisture reservoir, plant character and supplemental management defines some level of potential growth. The effects of moisture deficits that develop are not restricted to that single growing season. Such deficits limit late summer meristematic activity, thereby impacting growth the following season as well.

At the plaza, the consequences of seasonal water stress on climate amelioration are both direct and indirect. The direct effect of water stress must be to limit latent heat loss of the site, with a concomitant increase in sensible or stored heat. The indirect effect is to limit plant growth, reducing the potential for the plaza to develop a dense assemblage of plants (and thereby become a park).

While the urban canyon had evaporative demand similar to the park, the question of water stress on canyon trees must remain an open one. Canyon trees did develop more severe leaf water stress than park trees, with smaller ring increments the result (Figure 5).

DESIGN AND MANAGEMENT CONSIDERATIONS FOR GROWING PLANTS IN URBAN AREAS

Managing urban plants to ameliorate the negative effects of urban heat islands has four integral components: 1) site evaluation, 2) species selection, 3) optimal arrangement of plants and 4) management. These determine tree performance, as measured long-term by size or short-term by transpiration and photosynthesis.

Site Evaluation

A rigorous site evaluation must characterize the nature of the overall space, such as park, plaza or canyon. In so doing, it must detail the existing physical environment, including radiant energy, evaporative demand, soil conditions, etc. Only when a well-defined description is established can appropriate plant selection occur.

Site evaluation should serve also to minimize potential management problems due to limited growing space. Many utilities recognize the value of such foresight, planting smaller trees under electrical lines. Unfortunately, this trend towards smaller plants (under 35 ft.) may conflict with heat island mitigation because environmental function is directly proportional to size.

Plant Selection

The nature of individual planting spaces, in conjunction with management, will determine a list of potential taxa. For example, the limited amount of radiant energy available in the canyon should restrict plant selection to those taxa able to develop shade acclimation responses. In the absence of management, selection of plants for plazas should concentrate on taxa able to successfully exploit the hot, dry, limited soil moisture situation. Although not common to urban plantings in the Pacific Northwest, broad-leaved evergreen trees may be appropriate in these conditions.

Plant Arrangement

We have suggested that, given the densities of plants found in urban areas, spatial arrangement is critical to environmental function. Yet little information is available on the importance or consequences of arrangement of plants on either plant growth or environmental function. We know very little about the relative values of long-linear plantings vs. dense masses. Despite the limited evidence, we believe the value of plants in "refugia" is significant, especially in situations where area and number of plants is restricted.

Management Considerations

Timely, routine management of urban trees plays a critical role in plant success, especially during establishment. The limitations of cities in maintaining street trees has been well-documented by Kielbaso (1988), who cited an average expenditure of $10.62 per tree per year in a survey of municipal tree care.

Timely management practice should include: mid-summer irrigation (perhaps based on monitoring either soil or plant moisture status) and routine fertilization. We have preliminary observations that such simple maintenance procedures may significantly increase the vigor of sweet gums growing in plaza spaces.

SUMMARY AND CONCLUSIONS

Urban areas are composed of a mosaic of small, discontinuous, fragmented spaces, each with its own set of environmental conditions. For sweet gum growing in Seattle, these spaces offer different potentials for development. Since plant growth is directly related to environmental function, the ability of plants to ameliorate harsh environmental conditions in each of these spaces is different as well.

The factor limiting environmental function and tree growth at the plaza appears to be water. Whether supplemental irrigation on this site, or larger soil moisture reservoirs at other sites, will minimize this stress cannot be answered at this time.

In the urban canyon, reduced radiation may limit plant growth. Since the canyon receives only a fraction of the potential PPFD available elsewhere, trees must frequently develop shade acclimation features. However, development of these features may not restrict either growth or function, as evidenced by the large size of canyon trees.

Tree performance and function are optimal in the park. Adequate soil moisture and nutrition have allowed the plants to respond to full sun conditions. The development of a canopy, with its own boundary layer, provides the maximum transfer of solar energy to latent heat.

While there does not appear to be sufficient "free" space in urban areas to permit the planting of the number of trees needed to drastically change an entire city's energy balance, the value of small masses of trees as "refugia" to localized areas may be very significant. These may be either densely planted parks or continuous, linear plantings running across cities. We have only begun to quantify the environmental value of trees in urban areas. The promise of significant benefits from trees cannot be overstated.

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Table I. Variables defining environmental function and their determinants in urban areas.

Variable	Urban determinant
1. Plant biomass	Number of plants (naturally regenerated and planted) Size
2. Performance	Species Physiological activity (reflecting site conditions)
3. Spatial distribution	Pattern of both natural regeneration and designed landscapes

Table II. Estimated tree population and distribution in Seattle, WA.

District	Area (ha)	Tree density (per ha)	Total Trees
Downtown core	1189	5	6000
Industrial	1500	0.5	800
Residential	18257	12	220000
Seattle	20946	11	230000

Table III. Planting conditions for *Liquidambar styraciflua* in park, plaza and canyon spaces.

Site	Year planted	Height[a] (m)	Diameter[a] (cm)	% sky view
Park	1975	7.5±0.7[a]	13.5±2.2	69
Plaza	1976	5.2±1.0	9.4±1.0	65
Canyon	1975	7.6±0.6	13.2±1.0	31

[a] Mean and standard error of the mean.

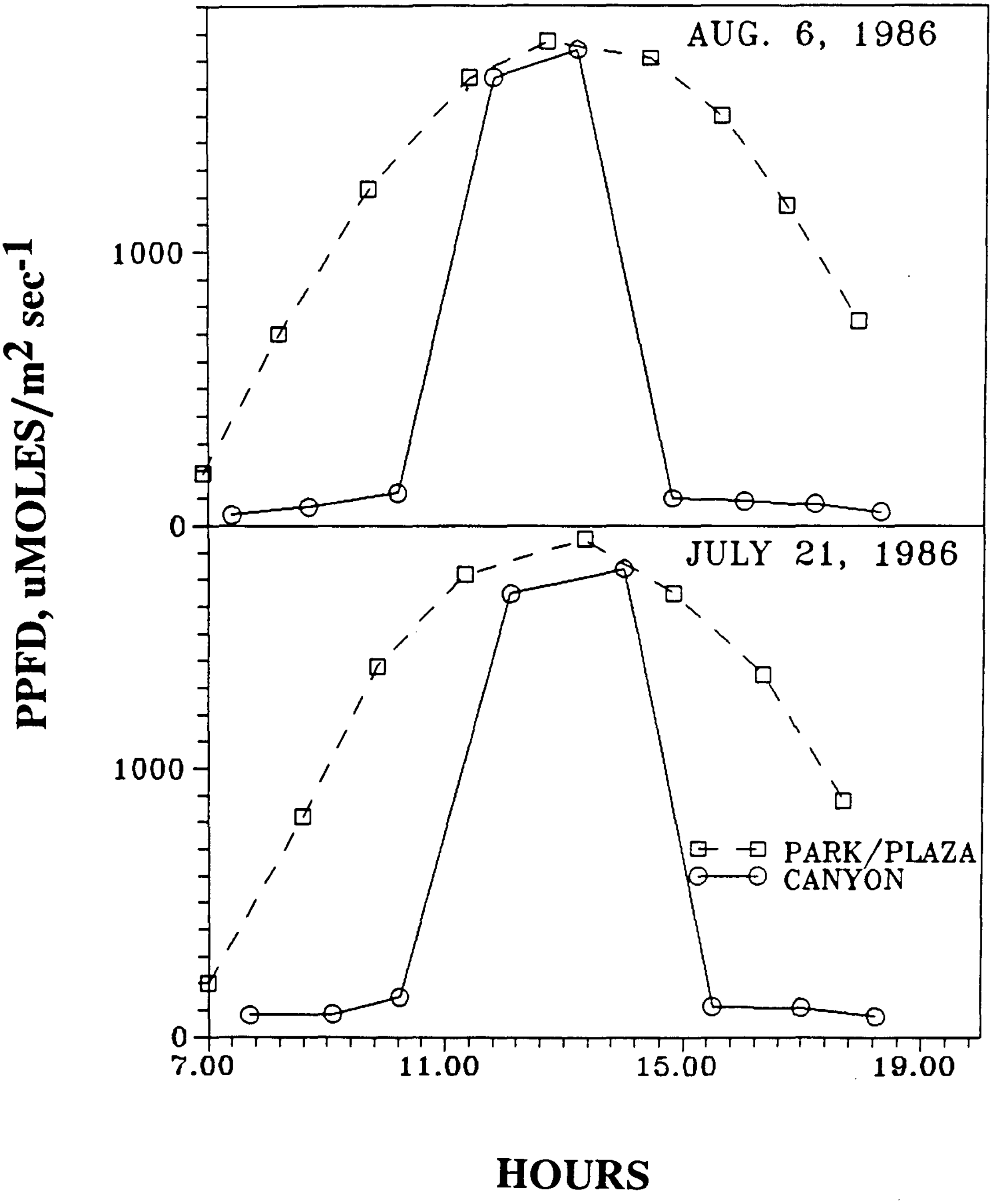

Figure 1. Diurnal pattern of photosynthetic photon flux density (PPFD) at canyon and park sites.

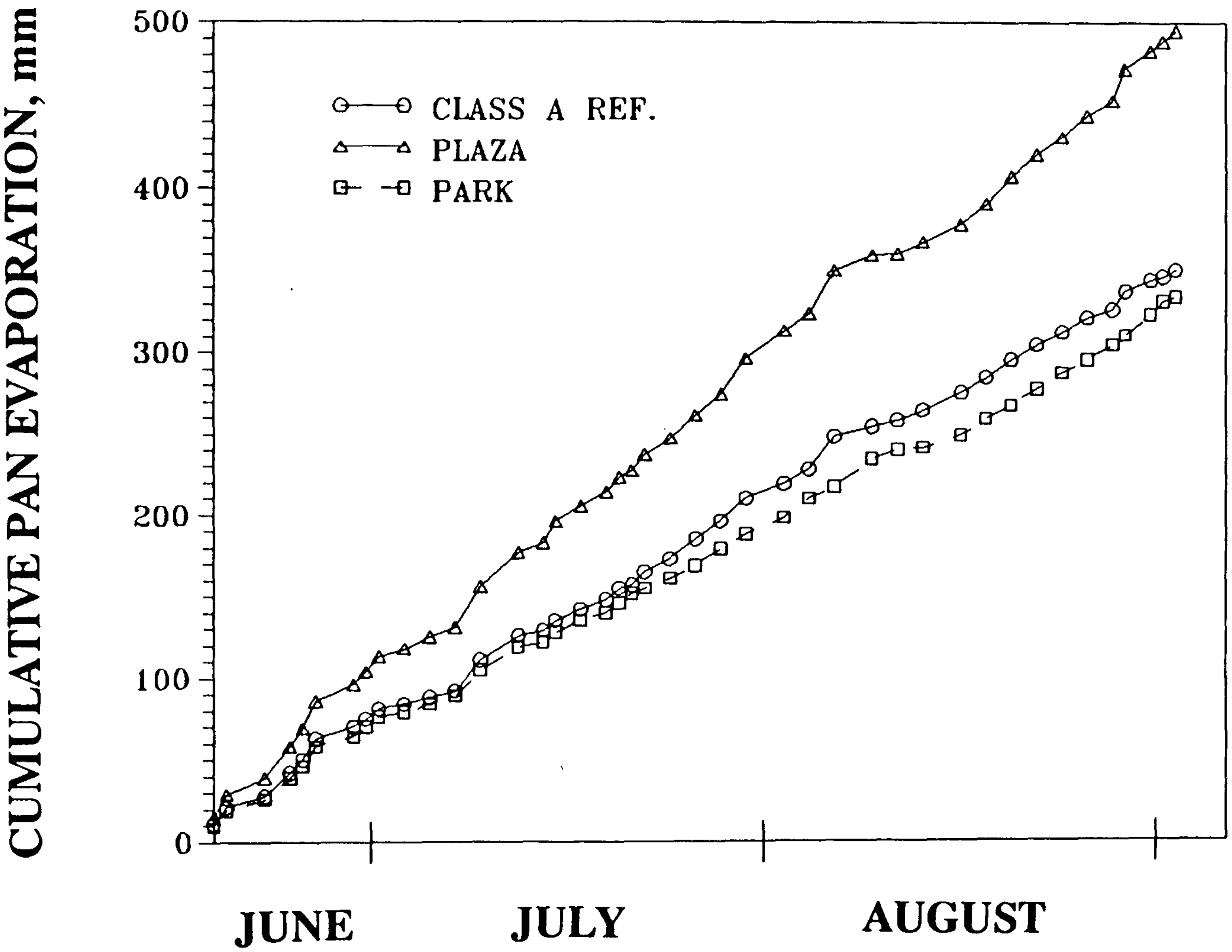

Figure 2. Cumulative evaporation for park and plaza sites, and for a USDA Class I reference pan at the Center for Urban Horticulture.

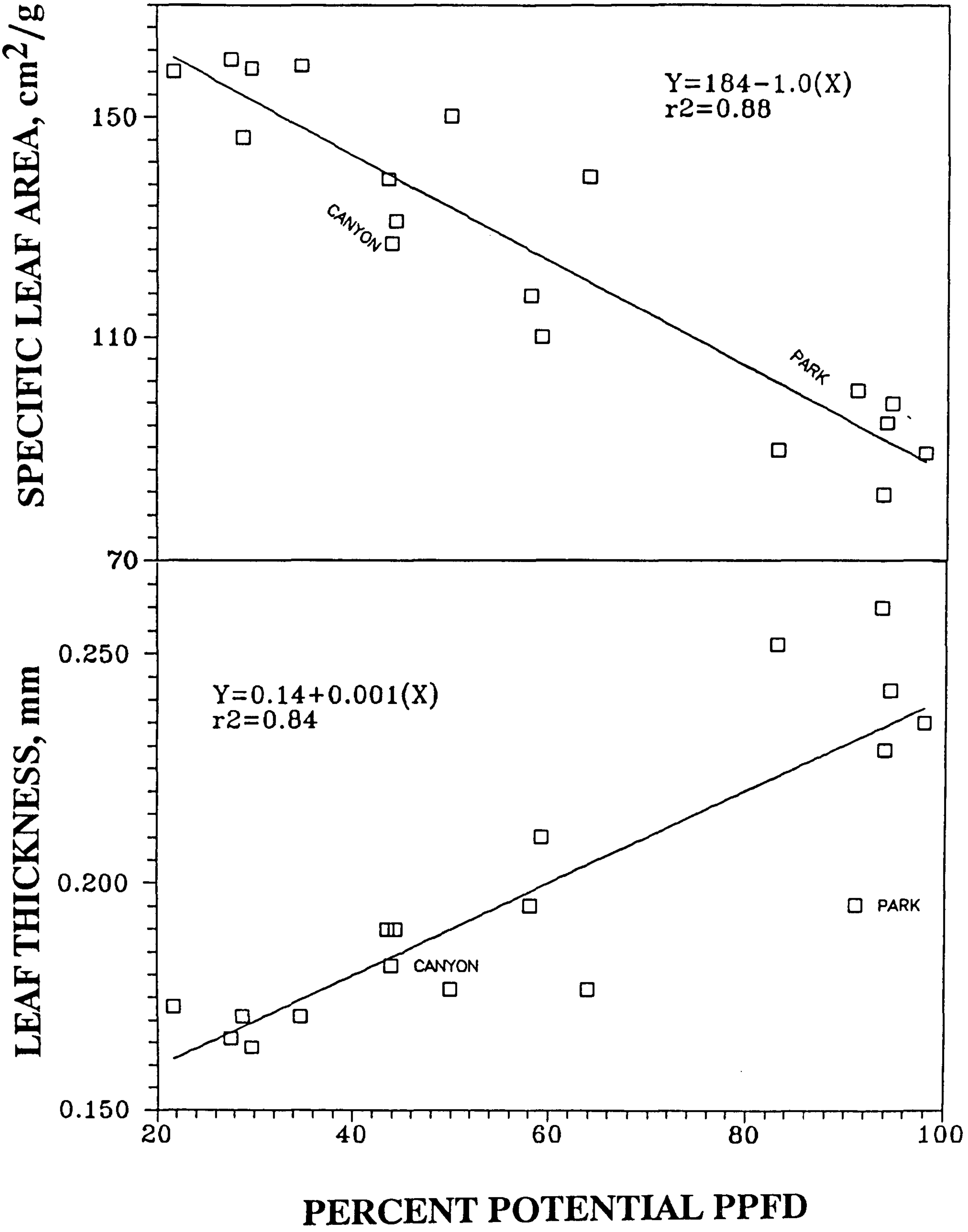

Figure 3. Relationship of specific leaf area and leaf thickness of Liquidambar styraciflua foliage to per cent potential PPFD.

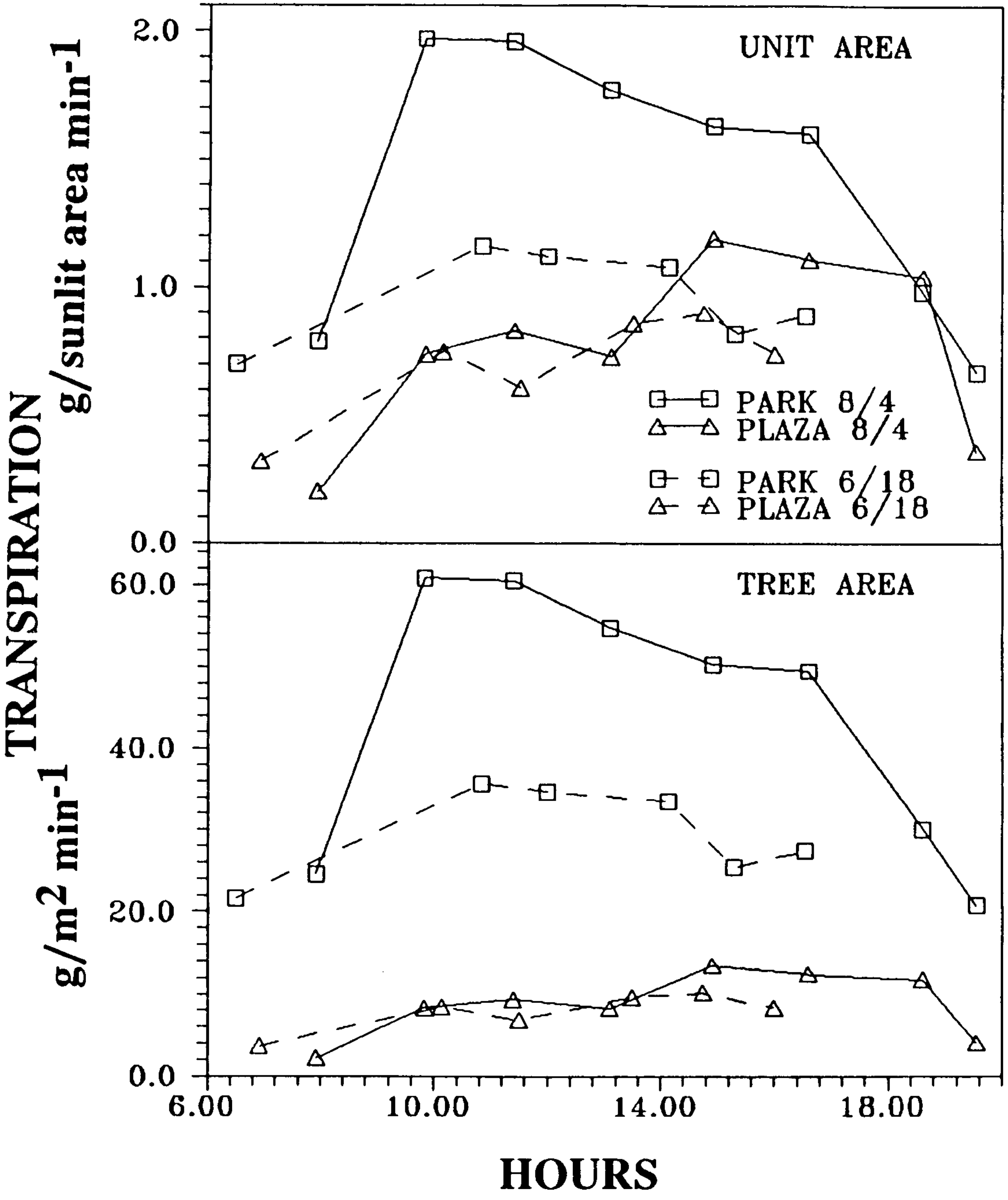

Figure 4. Diurnal pattern of estimated transpiration at plaza and park locations.

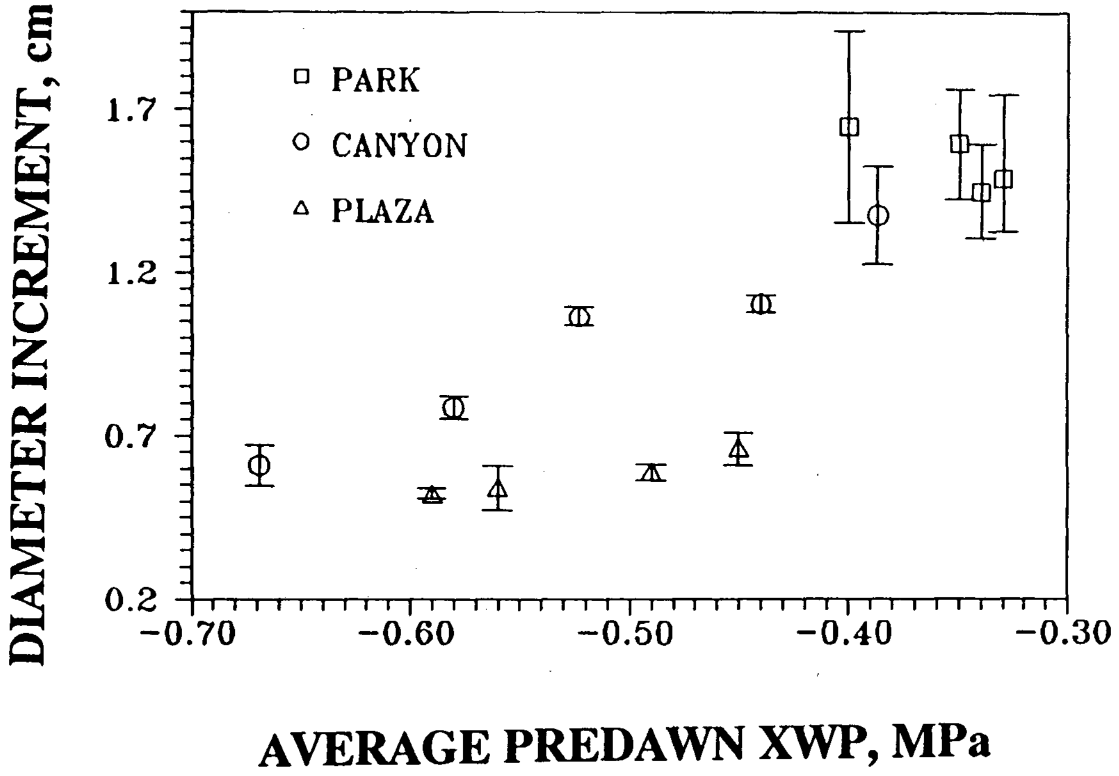

Figure 5. Relationship of predawn moisture stress to diameter increment of Liquidambar. Bars above and below the mean are standard errors.

TREE VALUES AND VALUE MEASUREMENTS

Gary A. Moll
The American Forestry Association
Washington, D.C.

ABSTRACT

There have been many techniques used to measure the dollar value of urban trees, each based on a different set of criteria. Sources of value measurement include: landscape values, aesthetic values, energy conservation, public health, real estate, and a host of ecological values. This presentation describes some of the methods used to estimate tree values.

A formula method was established by the Council of Tree and Landscape Appraisers many years ago to estimate landscape values. This formula is used to settle many court cases where damage has occurred. Aesthetic value is less predictable but often used in the market place. The American Forestry Association (AFA) and others have taken more interest in energy and ecological value measurements.

Ecological values include clean water, air quality, wildlife, and temperature moderation. In 1982, the AFA used these elements to estimate the future value of a 50-year old tree at $57,000. The role of trees in biospheric cycles is a value consideration that is hard to measure, but also significant. Recent concerns about global warming and the need to moderate the temperatures of urban heat islands have highlighted the contribution trees make to the quality of life in our cities and have undoubtedly moved to increase the ecological values of trees in the minds of urban residents.

KEYWORDS: landscape values, tree values, urban ecology, urban trees

TREE VALUES AND VALUE MEASUREMENTS

Gary A. Moll
The American Forestry Association
Washington, D.C.

The plant kingdom is one of the basic building blocks for life, using the sun's energy to produce everything from food and shelter to oxygen and fiber for our basic needs. Vegetation is the first building block of the food chain, and the essential thread holding soil and nutrients on the land and blessing us with clean water. Plants are the centerpiece of ecology and trees are the grandest of the plant kingdom.

Our understanding of the value of vegetation grows as our understanding of ecology and the environment matures. There is general agreement on the notion that trees are a valuable part of the natural environment and that they improve the quality of life in our communities. There has, however, always been a question of how much they are worth, and which values deserve economic measure. Trees have played a significant role in the economy of every major culture since the time of the Greeks and Romans, although their value for products have outweighed their ecologic value in these communities. Trees have always been cultivated for shade, food, and, beauty, but the value of tangible products (e.g., wood and fruit) have received the most economic attention.

As the decade of the 80's comes to a close, we face major adjustments in our understanding of the environment and in the significance trees play in our ecosystem. Scientists, like the ones gathered at this workshop, have been able to recognize and measure the connection between trees, the health of the planet, and the quality of life in our communities. Environmental concerns are now a political and economic concern of global consequence.

NASA scientist James Hansen captured the attention of the Congress and the media by using computer modeling to identify signs of global warming. Akbari, Rosenfeld and others have advanced public awareness of urban heat islands and helped create national interest in the scientific search for ways to save energy and cool the hot spots. The string of benefits trees supply, increases noticeably with this new information.

Akbari, Rosenfeld and others have suggested that adding trees to city environments could reduce cooling costs by 10 to 50 percent in warm cities, and make significant reductions in CO_2 emissions as a result of energy savings. The direct effect of trees on CO_2 (the amount of CO_2 absorbed during photosynthesis) varies with tree size and rate of growth.

Clearly a lot more of this type of research is needed, but it has already provided important information about the role of trees in our cities. When evaluating the role of trees and other vegetation in the city, it is important to consider the entire string of benefits they produce. Given below is a quick review of the benefits and the related accounting.

A couple of attempts have been made at determining the ecological value trees contribute to the environment. In 1980 many major newspapers carried the findings of Dr. T. M. Daas, a professor at the University of Calcutta. He estimated the monetary value of ecologic contributions of a 50 year old tree to be $31,250 in oxygen, $62,500 in pollution control, $31,500 in soil fertility and $37,500 in recycled water.

In 1985 the American Forestry Association attempted to repeat these measures using a simplified and very conservative format, and we arrived at a future value of $57,000 for the 50 year old tree. We concluded that on average it would supply annually air conditioning worth $73, soil benefits and erosion control worth $75, wildlife shelter worth another $75, and air pollution control worth $50. Total value in 1985 dollars: $273 per year (value produced would be less in the early years of growth and more in later years). The total value for the tree's lifetime, compounded at five percent interest for 50 years: $57,000. That estimate told us it was time we started thinking about trees as major contributors to our welfare, not just beautiful components of the landscape.

To the landscape architect, trees have been valued for their role in design. They attract the eye and bring scale, line, form, and structure to buildings, streets, and communities. They also supply shelter and food for wildlife. Trees are an essential element in parks and preserves and a source of recreation as well as a source of inspiration to artists and scientists alike (remember Newton and the apple tree). Trees help tie a community to the natural landscape allowing natural (life) cycles of air and water to operate in an efficient manner and not be short-circuited by poor city design.

Measurement of landscape values demonstrate the difference between the value of a tree as a forest product and as an element of the populated landscape. Roughly speaking, the value of an urban tree is 25 times that of its rural cousin. A formula method is commonly used by arborists and nurserymen to settle damage and replacement cases. In its simplest form it replaces damaged trees with new nursery stock. Each tree lost cannot always be replaced by one of equal size. Once a tree reaches six inches in diameter it must be replaced with two or three trees of smaller size.

Although the replacement method is financially simplistic, it is the source of some controversy in the nursery industry. Since a tree is measured by its diameter, but the total size of the tree is actually a volume measure, replacement values are often misleading and the value of tree cover can be underestimated using this method. For example, this replacement value method allows two smaller trees to be used to replace one larger tree. That is, a tree 4 inches in diameter can be replaced with two trees of 2-inch diameter. The area of wood in the single 4-inch diameter trunk is 12.6 sq.in.; but the area of the 2 2-inch diameter trunks is only 6.3 sq.in. Tree benefits, however, relate to total size, and replacement must represent this fact. After experiencing a loss of about 20% of its street trees over the last decade, New York City has made this area replacement the official measure in a program they call "Getting the Wood Back".

The most widely accepted formula for determining tree value is refereed by the Council of Tree and Landscape Appraisers. The formula allows a skilled "plantsman" to put a value on a tree of any size. The formula method considers the location, species, size, and condition of the tree. A value of $27 per square inch of trunk cross-section is used to calculate a base value of each tree, which is then multiplied by various factors to reflect the value of location, species, and condition.

Besides giving a value for the entire tree, it can also be used to estimate value reduction from damage to tree health. Some municipalities are pursuing this method to place a value on tree canopy losses. In Cincinnati, Ohio, utility and transportation trimming has been assessed a charge for value lost into their community. Funds collected are used to supplement the tree planting and maintenance budget.

Real estate values are determined by selling prices and by estimates of property value. In the late 1970's, Brian Payne of the U.S. Forest Service studied property values. He used photographs of identical homes both with and without landscaping to determine comparative values. Studies were repeated in the southeast by Andersen and Cordell. Property values increased from 3% to 20% on homes with trees. In other words, in 1989 you can expect the average home with trees to be worth about 5 thousand dollars more than an identical home without.

The added value of trees is so widely accepted in the real estate market that the values are written into many sales contracts. If you are looking for a lot in a large subdivision for example, the only difference in the price of two lots may be the value added by trees. In the Washington D.C. area it is common to find prices of 3 to 5 thousand dollars more for treed lots 1/4 acre in size.

Although any one of the benefits listed above may be sufficient reason to grow more trees in urban areas, tree value should be considered as the sum of many elements. This is especially true when considering the ecological benefits. Cooling an urban heat island lowers temperature but also increases moisture in the air and can lower pollution levels. Placing a value measure on temperature alone does not accurately represent the benefits of trees.

Some of the values in this multiple benefits package are difficult to place dollar measurements on, but they are none the less important to note. Noise reduction, for example, isn't easy to quantify or place a value on, but we know the city would be a lot noisier if all the vegetation were removed. Research shows that a 100-foot-wide patch of vegetation 45 feet high can reduce highway noise by nearly 50 percent. We also know that people are psychologically less bothered by noise when the source is screened from view by trees or other vegetation.

Most of us know we feel better living around trees, but until recently that has been hard to prove. So geographer Roger Ulrich of Texas A & M University, tackled the issue by checking health records at a suburban Pennsylvania hospital where some patients looked out windows at clumps of trees, while others viewed a bare brown-brick wall. Ulrich found that patients with a view of trees and plants had shorter hospital stays, received fewer negative comments in nursing reports, and took fewer strong pain-killers. That psychological effect has profound economic implications, of course. If post-operative hospital stays could be cut by the 8 percent, consistent with Ulrich's findings, national health cost savings as large as several hundred million dollars a year would be the result. Ulrich has extended his research to heart by-pass patients in Sweden. Preliminary results show patients recover faster and feel better when they have a photo of trees and water at the foot of their bed. These results have had enough impact on the managers of medical facilities to change the way hospitals are built. The new wing of an Oakland, California, Hospital has been designed to give patients a view.

In her book, The Granite Garden, landscape architect Anne Whinston Spirn describes the entry to a high-rise apartment complex for the elderly which was so windy that winter ice on the walk was impossible to control. Many planting and design configurations were tried at the immediate site to control the effect of the wind but they all failed. A look at the city as a whole, however, suggested a solution. Winter winds blew unimpeded across large parking lots and open areas, reaching the tall apartment complex in full force. Close in plantings could not buffer the icy chill of the wind, but adding trees to the parking lots on the northwest edge of the town did. The solution involved seeing the city as a whole and planning the urban forest accordingly.

Trees effect water quality and stormwater management on both the macro and micro scale. The contribution to regional water quality is a major, but often unqualified asset. In the Chesapeake Bay area, for example, the Maryland state legislature officially recognized waterside trees along its rapidly developing shoreline as "the least polluting land-use" for that threatened body of water. Estimates of sediment control reported in studies for the Chesapeake Bay found that using forest land as a base measure, farmland produced about 100 times the sediment load and urban land under construction produced about 1000 times that load. Established urban land produces only about 2 times as much sediment as forest land, but increases in stormwater runoff are staggering and chemical pollutants of many kinds are introduced to the runoff. Runoff from agricultural areas can introduce large amounts of nitrogen into surface waters causing severe eutrification, which can result in the destruction of coastal and fresh-water ecosystems. Tree cover encourages groundwater infiltration allowing some chemicals to be broken down by soil microorganisms.

Research by Rowan Rowntree of the U.S. Forest Service demonstrates how trees and plants can reduce peak storm runoff in a city by about 10-20%. The average city has a tree cover of about 30%, but the surface area of branches, leaves and trunks is about four times greater than the total of artificial surfaces. Rainwater falling on vegetation either adheres to this matrix of surfaces or flows slowly through crowns and stems. Reducing and/or slowing urban runoff reduces the required size of engineering structures, including treatment plants. Slower moving water picks up less sediment on its way to a stream. Slower moving water also causes less damage to saltwater ecosystems where organisms depend on specific water-to-salt ratios.

The values of trees to a city goes up as the quantity of the trees increase. In forests the recycling of forest debris, leaves and branches, forms the soil that grows big healthy trees, captures the polluting particulates of stormwater and provides shelter for wildlife. As tree cover is added to a community the overall microclimate changes in a way greater than the simple sum of all individual trees. Moderating climate and allowing soil to build up naturally creates conditions that allow trees to grow bigger, faster and live longer. Likewise, adding a number of small green spaces together to form greenways might make significant changes in the overall climate of a community, the quality of the water, and abundance of wildlife.

As a final perspective on the value and benefits of trees, consider the data on the health of urban trees and the cost of changing conditions in a city. The American Forestry Association evaluated the condition of the trees in 20 major cities and found trees to be in a serious decline, which has lasted over 10 years. By comparison, the average life span of an urban tree is 32 years. Since most of the benefits derived from trees are positively correlated with tree size and health, the longer we wait to commit to maintain and increase the urban forest, the longer it will take to reap the rewards.

The most serious limiting factor effecting tree health is space for growth. The pits we engineer into sidewalks do not supply the space to take advantage of the potential value of trees to our cities. Only a few cities have addressed the challenge of providing sufficient space for trees. Our estimate is that for each dollar spent on building the road system through a city, 2 cents will supply a quality tree and space for that tree and more than double the current value produced by our urban forest.

TAKING IT TO THE STREETS: INSPIRING PUBLIC ACTION

Andy and Katie Lipkis
President and Vice President
TreePeople, Los Angeles, CA

ABSTRACT

Hire a contractor to plant a city street, or to green the sidewalks of a suburban neighborhood, and you have a measurable goal. But how do you measure the success of a program that inspires ordinary individuals to pick up a shovel? And, moreover, how do you make such a program succeed?

These questions are fundamental to the future of urban forestry in this country. No longer can we rely on our governments to fund the greening of every sidewalk...not only because of the cost of planting but also because of the staggering cost of maintenance. Urban dwellers need to feel they can have an impact on their environment, and urban foresters need to find ways to safely involve non-professionals if urban forestry is going to survive—and thrive. Rather than being a threat, ordinary citizens can be a breath of fresh air for professionals, who should now jump at the chance to educate and to be better understood by the public.

In Los Angeles, TreePeople has been a bridge between the professionals and the public. Using resources that are not hidden, but are often simply overlooked, TreePeople successfully motivated the public to plant over one million trees in the three years leading to the 1984 Olympics. In the media capital of the world, TreePeople made tree-planting trendy.

TreePeople is currently researching the feasibility of an encore—to foster the planting of between 2 and 5 million trees in Los Angeles with the specific purpose of shading the city, cooling the urban heat island, and reducing Los Angeles' contribution to the Greenhouse Effect. TreePeople is also a participant in California Releaf—a coalition of state groups which holds a goal of planting 20 million trees before the year 2000. The American Forestry Association, the private, non-profit conservation association which is the mastermind of the Global Releaf effort, uses TreePeople as the model for what is possible in the greening of our cities.

KEYWORDS: publicity, trees, urban trees, volunteers.

This paper provides pointers learned from TreePeople's Olympics campaign which can be applied to the tremendous opportunity we now have to involve urban citizens in environmental work, and to take both quick, economical, and effective action to reduce Global Warming.

TAKING IT TO THE STREETS: INSPIRING PUBLIC ACTION

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INTRODUCTION

The advantage of involving private citizens in urban forestry has been demonstrated repeatedly in the past. However, the current state of American society and the threat of global environmental problems has turned it into a necessity. How do you reach the public? The challenge is to inform, enroll, guide, and inspire them on an ongoing basis—especially when neither you nor your organization or agency has a public relations or advertising budget. In this paper we describe many free or low-cost resources and techniques that can be utilized by urban foresters and community leaders to reach the public. To illustrate many of the points raised, we draw on the "million tree campaign" experience of TreePeople, a non-profit organization active in community forestry issues for 16 years.

The Need

There are new, even greater needs overriding every good reason previously stated for community involvement in urban forestry.

Legislation to impose a balanced budget on the federal government will certainly place even stronger limitations on its ability to fund viable urban forestry programs. With the growing awareness that trees are part of the solution to the greenhouse effect, most people envision acres on acres of forest trees rather than the more effective plantings that can occur in warm cities. (Because of their ability to shade buildings and cool the air, urban trees in warm cities can facilitate significantly larger reductions in carbon dioxide emissions (from the burning of fossil fuels) than rural trees can take into their bulk through photosynthesis.) Competition for urban budget dollars will increase. Without a visible, educated constituency in support of urban trees, tree maintenance budgets will take a back seat to "more vital" issues.

Urban foresters need leverage to get their jobs done. Such leverage can be obtained with community support. For example, neighborhood tree committees and volunteer corps can provide additional tree care. The awareness and commitment of your public is vital.

Most people appreciate the inherent beauty and shade of city trees. They agree they're necessary for the environment. Still, politicians and the public need to be "sold" on the value of a healthy urban forest, because it's probably a much more expensive ticket item than they would anticipate. Hence the reason for marketing urban forestry—to build active support to put public trees on the public agenda.

The urban forester needs public support. Not surprisingly, the public also has an increasing need to become involved in urban forestry. As technology becomes more pervasive, growing numbers of people feel alienated and powerless to have any impact on either the local or global environment. This is especially true in cities where urban youth, removed from greenery and surrounded by concrete monoliths, can easily feel as if their lives are of no consequence. Cynicism sets in. In extreme cases, kids turn to vandalism or gang involvement to express their frustration and demonstrate their power.

Young and old, people crave the sort of involvement that gives them a positive sense of power, and of belonging. Urban foresters have a fantastic opportunity—a responsibility—to take advantage of that. They should share the treasure they have to offer society. Involving the public will engender well-deserved support—and even assistance—for their own jobs. The icing on the cake will be the satisfaction of helping to heal one of society's greatest ills... urban alienation.

Urban forestry activities can show young people the difference they can make, and provide a challenge and channel for their energy. As people who work with trees, we know how they've enriched our lives. TreePeople has worked successfully with gang members in inner city neighborhoods, planting trees and painting over graffiti. The kids loved the work and the attention they got for their good deeds. TreePeople believes the involvement lowered the vandalism risk.

Forestry has much to contribute to our cities and the health of the earth. What better way to show individuals how they can have an impact on improving the global environment while improving their own neighborhood? So how do you show that?

THE PLAN

This paper assumes that your group or agency has little or no budget for advertising or public relations. It focuses on community resources that are either free or available at a nominal fee. If well planned and guided, a campaign thus produced can provide as much exposure as a multi-million dollar advertising campaign, and result in far greater public involvement.

The steps outlined are written from a private, non-profit perspective. Most tactics will be relevant for government agencies. Some, however may not be. It would be prudent for government agencies to explore establishing a private "Friends of the Urban Forest" committee or organization that exists to support the department. Such a committee can provide flexibility to operate outside government constraints when needed, and a place for business and community leaders to contribute their skills and resources. Although the tactics outlined made up a three year intensive effort, many are appropriate for use independently in smaller campaigns.

Before a campaign can be organized, one must do a bit of homework:

1. First identify the major issues you need to highlight...tackling the greenhouse effect through energy conservation (or protection from the hazards of the depleted ozone layer through shade production!), increasing property value, helping the city celebrate its bicentennial, enhanced air quality, etc. Make this specific to your city rather than just what's worked somewhere else. (TreePeople used the approaching Olympics as the reason, then focussed on a number of problems we thought urban forestry could help solve. Others may choose a certain percentage of tree cover as a goal.)

2. Know what you want the community to do. Do you just want to engender political support and awareness, or do you want people out planting and caring for trees?

3. Identify and enroll community leaders who can help you... including those from neighborhood organizations, the business community, churches, unions, celebrities, and the news media. Consider forming an informal working group of people who want to help you accomplish your goal.

4. Identify campaign resources. Look for people and companies who can donate all or most of the materials and services you'll need. Be careful you don't take on anyone without first checking the quality of their work! Seek out advertising agencies, public relations firms, printers, artists, designers or art directors, writers, photographers, a local newspaper, a radio or television station, or concerned newswriters or reporters.

   Also identify possible corporate sponsors. (TreePeople targeted an international advertising agency—Doyle Dane Bernbach—and persuaded the President to donate agency time and talent to help produce the million tree campaign).

   Use your creativity to tie together common interests for this and point 3 above—like a company that uses a tree as their logo, or suppliers known for their philanthropy.

5. Set the campaign's time period. Keep the community posted on your progress, and build in a completion and wrap-up phase. Create several stages so you can celebrate accomplishments along the way. Each phase completed gives you the opportunity for a media event.

THE ACTION

On July 1, 1981, TreePeople launched a campaign to inspire the planting of one million trees in Southern California before the 1984 Summer Olympics.

The figure one million was based on a Los Angeles City Planning Department report that had studied the effect on air pollution of massive tree planting in other cities. It claimed that one million trees, when mature in twenty years' time, would be capable of filtering up to 200 tons of particulates from the air daily.

The figure had a good solid ring about it—one that we felt could inspire great volunteer efforts within the community. The City's projected timeline for completion of the project—before enlisting the help of TreePeople—was twenty years at a cost of $200 million. So, TreePeople's "impossible" three-year goal, with no prior money allocated, fired the public's imagination.

Be courageous. People may think you're foolish, but they'll admire and may even support your courage with time, money, talent, resources or pure sweat.

With an overall game plan, but no set rules, TreePeople used the following methods to keep the goal (and the dream) alive in a city of 10 million people and 100 million causes. Note the failures. We learned as much from them as we did from the successes and thus, we'll highlight them as pitfalls that should be approached with caution.

A Pro-bono Advertising Campaign

Doyle Dane Bernbach (DDB) assigned a team to the "TreePeople account" (see point 4 above). We used them while they were fresh and inspired. The creative team needed to be briefed on the goals, values, and principles of the urban forest and our campaign...which was obviously vastly different from their usual accounts.

They then devised a fully integrated advertising strategy, along with the theme materials and artwork. The tag line was Turn Over A New Leaf, L.A.—Help Plant The Urban Forest, with one poster line they couldn't resist...Urban Releaf! (This has now been adopted by the American Forestry Association...Global Releaf...and the state consortium...California Releaf, along with numerous individual cities' efforts.)

Television Spots. DDB wrote a television script and gave us the job of enrolling the "talent." Persistence paid off. After dozens of phone calls and persuasive letters, Gregory Peck agreed to be our spokesperson.

General Telephone (who will appear again in this list) was asked to provide a video production crew, and a day-long shoot was produced for the cost of 16 McDonalds hamburgers. The 30 second spot got its fair share of airplay because it was a high quality piece featuring a well-known movie star.

Billboards and Bus Signs. (Most billboard companies provide small spaces to community causes as a public service, but they charge an average of $75 to post each board. Some companies even want to charge that monthly.)

Some billboard companies have a great distaste for trees because they block their boards. Without realizing this, we stumbled into a hornet's nest when we began asking for support. We discovered later that one company had just been prosecuted for a midnight massacre of a dozen trees. Even though our campaign focussed on people planting in their own yards, most firms remained cold. Despite the negativity, we found a company that loved the idea and posted 800 boards at no charge. We did have to pay $25 for each of the 400 bus signs posted.

DDB produced artwork for the billboards and bus signs, but we were unsuccessful in getting the printing donated. However, we found a printer who let us pay him when we could. The final installment was mailed two years later—the month the campaign ended.

Radio Spots. (Public service time on radio is the easiest form of free advertising, and easiest to produce. Most radio stations will accept either a written script or a 30 or 60 second tape. They usually require two weeks to get them on the air and will play them for at least a month.)

DDB wrote and produced a great radio commercial using Lohmann and Barkley, a local radio comedy team often used for paid commercials. Tapes were delivered to over 75 radio stations. Unfortunately, many of the stations refused to run the spots because they regarded Lohmann and Barkley as "competition" for their own comic acts.

Unless you can continue to furnish the stations with new versions, which is a very expensive option, you'll only get about a month's mileage out of each. Far more effective is to mail sets of "live" 10, 30 and 60 second scripts every month, enclosing a grateful cover letter. These are read by announcers and, when written well and typed clearly, are preferred by the stations to pre-recorded tapes.

TreePeople mailed "live announcer" scripts. The message was the same each month, but clever copywriting made it fresh and different every time. The writing was done by TreePeople staff.

Newspaper and Magazines. (The print media will, on rare occasions, run a public service ad. It's much more difficult for them, and very expensive. But with persistence and footwork, one can usually persuade an advertising editor to insert an ad at some time. However, it's extremely difficult to control when, where, and how big the ad will run.)

DDB also created artwork for a print ad, but we were unsuccessful in getting space donated. (This is much easier if you're in a small town. The L.A. Times has too many paying customers, and so doesn't have much surplus space available.)

However, print ads were run by companies who sponsored other parts of our campaign mentioned below—General Telephone, May Co., Louisiana-Pacific, Nurseryland. These ads promoted the campaign, but also highlighted the individual company's efforts.

Brochures. You'll always need materials to present the overview of your program to the general public, and it makes sense to have it coordinated with the rest of your campaign.

DDB designed a brochure which was written by TreePeople and printed by Southern California Edison. "Help Plant An Idea" explained the campaign and how people could participate. They also designed a bumper sticker—"I BRAKE FOR TREES". Although we paid for the printing of the stickers, we also sold a lot, which underwrote their cost and raised a bit extra.

"Point of Purchase" Materials. (The sign printing and the nursery kits mentioned below were the only printed items paid for during the campaign...and were not necessarily more vital to its success than the donated materials. Our lesson to keep the campaign economical came back to us in spades as we struggled to pay the bill!)

One tactic—necessary but very time consuming and often disheartening—was to involve the nursery trade. At a cost of $40 apiece, we produced with DDB a packet of materials to be given to 1,000 nurseries in the L.A. Basin. The nursery "kit" contained tree tags, banners that read "Urban Forest Headquarters," forms to confirm that trees were planted, and a display "mail box" to be periodically emptied by either the nursery personnel or TreePeople volunteers.

Our hope was that each nursery, seeing the value of our campaign for their business, would make a tax-deductible donation to cover the cost. For the most part, we were mistaken. Many, however, displayed the material and thousands of confirmation forms were mailed to us from eager customers who didn't want to use, or couldn't find, the "mail box."

We were puzzled by the general lack of interest on the part of the nurserymen. Only one major chain ran ads announcing their involvement. However, one of the larger nursery wholesalers who worked with us expressed his own ongoing frustration at the fierce independence of nurserymen and their lack of sophistication in regard to promotion.

Nonetheless, the sales force of Kelloggs Fertilizer Company volunteered to help distribute kits and collect confirmation cards as they made their biweekly visits to the nurseries. Another major wholesale grower was unsuccessful in mobilizing enough nurseries to participate in a cooperative ad campaign. Despite their apparent disinterest, several nurseries acknowledged that they benefited from the campaign.

News Events

Don't go to all the trouble of running a campaign unless you make sure everyone hears about it! There are several important rules for working with the news media, and numerous strategies to keep in mind.

Make Sure Your Events Are Interesting! Take the time to design an event with good visual interest. The only way to compete with TV violence is to give the media something more colorful or interesting. Charts, graphs, celebrities planting trees, are all better than a person in a suit behind a podium.

Use Institutions that Already Exist—like Arbor Day or Earth Day or a local equivalent—around which to build an event. Editors are always looking for stories relevant to time, season or occasion. They also like stories related to other major headlines. For instance, if there's a major global warming conference scheduled in your town, you might create an event that highlights how your program is helping cut summertime cooling-energy costs locally, thereby reducing carbon dioxide output and the greenhouse effect. Since trees can be part of the solution to many urban problems, there are lots of opportunities available. Another example would be to utilize gang members in a constructive project—that kind of story will always get some coverage.

Keep it Fresh! You need to find a new twist every time you stage an event, or the media will get very tired very fast.

Serve the Media. Don't overuse them or try to trick them. Be thoughtful when setting times for your events. The best time is weekdays at 10am. This will usually give you a fresh crew with time to shoot and edit your story before their schedule gets too hectic.

TV news editors are always looking for stories they can use on holiday weekends, but you should avoid weekend media events. Most stations have few or no camera crews on weekends, and crimes and disasters are their priority. Always have coffee, donuts or muffins, and press releases available at your event and, in the case of newspapers, stock black & white high contrast photos, in case they don't have a photographer.

Never think of your public education work as "PR." The media doesn't like giving free advertising and you're not advertising—you're inspiring and educating the public about something of vital importance to the environment everyone lives in. That's not "commercial time."

TreePeople enrolled a local TV station, KABC, and a newsman, Fred Anderson, to produce a five-night mini-series on various aspects of the campaign.* KABC took up the cause. They provided regular updates and a "tree-mometer" to measure progress. In

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*A 30 minute VHS video tape consisting of an edited version of the KABC News mini series and various television news clips of the campaign is available from TreePeople for $25.00).

fact, it was their innocent request for our phone number for people to call to confirm each planted tree that finally sent our tree count through the roof. Believe it or not, in the land of the telephone, we had been asking for planting confirmations in writing —on a postcard or even a scrap of paper. The immediacy (and obviousness) of a tree hotline and answering machines to take the calls 24-hours had passed us by.

TreePeople presented KABC with a special award at the end of the campaign and made sure the viewers were acknowledged for the major role they played. Everybody wins when everybody feels worthy and appreciated.

The Interview and Speaking Circuit

Make yourself fully available. TreePeople recruited and trained staff and volunteers for a speakers bureau. We appeared on TV and radio interview programs at a moment's notice—at 6 am or 12 midnight. Every opportunity to talk was taken. Every Rotary Club, Garden Club, or gathering of two or more got a speaker and a slide show. It may not look like progress at the time, but when you plant hundreds of seeds, some are sure to grow.

The Religious Community

Trees are a positive issue, and an important symbol in the ideology of many of the world's religions. TreePeople involved many church groups in aspects of the campaign. A presentation to the Inter-Religious Council of Southern California inspired leaders of many religions to get involved. A few individual congregations organized seedling distributions based on an urban forest sermon. It did not, however, result in widespread participation.

Don't expect interest to spread from the top down. Time and again, we were shown that the most powerful direction is from the bottom up!

The Corporate Community

Companies can be very helpful. Their executives can provide leadership both to your organization and the community. Their involvement also lends credibility to your cause. They can contribute resources, finances and volunteers. And reaching people where they work is an often overlooked route.

Many large corporations have in-house printing, and video and audio facilities. Having them contribute those resources is often easier than getting direct funding, and often much more valuable.

The TV spot we shot with GTE's crew would have cost at least $25,000 if we'd had to pay for professional services. Instead it cost us nothing. Southern California Edison contributed thousands of dollars in printing services over the years. Also, having a volunteer art director employed at a design firm means help from suppliers, who are usually happy to oblige their client.

The important thing is to allow a lot of time. Your project must fit into their profit-making schedule. Sometimes that can take months.

Large corporations are also a resource for volunteers. "Corporate Community Responsibility" is a big term these days. The White House issues annual awards to corporations who provide people for community service. There are often volunteer coordinators on staff and it's their job to recruit both executives and rank and file workers for service projects. The most forward thinking companies are even providing paid release time from daily duties for some volunteers. Also, some companies will contribute funds to organizations where their employees volunteer.

Early in the campaign, General Telephone's Vice President for Public Affairs joined our Board of Directors. We began working on a plan that developed into a major two year commitment from GTE. They invited their people to become "Urban Forest Rangers", to visit local elementary schools with urban forest information, stories, seeds, soil, mini greenhouse kits and follow-up curriculum packets for the teachers. Almost 700 people volunteered and GTE underwrote the entire $40,000 cost of the program, and the staff and resource time contributed was valued at another $100,000!

GTE's involvement paid off in riches beyond their dreams. Almost 70,000 kids participated and all their parents found out about it. The publicity was more believable than anything they could have bought, and their executive was featured in an article in Fortune magazine. Of course, it was also a great boost for TreePeople.

Although it didn't come to fruition until after the campaign, TreePeople's friendly cooperative approach to corporate involvement paid off again when the Southern California Honda Dealers Association committed major dollars and full page advertisements to a campaign to "Help Make Your Drive More Beautiful" by sponsoring the planting of 1000 trees a month for three months.

Another example is the Urban Forest Run. Four years in a row, TreePeople closed down a freeway and staged a 10k run sponsored by May Co., Louisiana-Pacific, The Gap, and Warner Bros. respectively. We worked hard to get these corporate sponsors but, once on board, they paid for the t-shirts and other promotional materials.

Use fun runs for publicity rather than to raise money, and you'll avoid disappointment!

Think of easy ways to involve corporations—like our tree dedication program. For $10 each, they can have trees planted in honor of customers or employees, or just to boost their public image. You can be great business for each other. Be open to their involvement.

But be careful. We were caught many times putting days and months into "ideas" that never happened. This is often a necessary investment to realize your dreams. The time wasted can be minimized if you inform the company at the outset that your resources are limited and that, without anything solid, your time is limited too. Be careful not to let their involvement divert you from your mission...simply try to make your agenda their agenda...and then let their involvement work for you.

Schools, Scouts, and Walking the Streets

Try to think of how many sub groups are in your community—and use their internal structure to get your message across. Catch people where they work, where they shop, where they play, where they live.

TreePeople used its established school program to spread the word. Many schools took on plantings in which every child (15,000 per year for three years) planted a tree at home. On safe plantings (those not involving freeways or large street trees), we used scouts and other youth groups who like to get involved in fresh, new group activities.

Free trees are often thrown away because they have no intrinsic value to the recipient. TreePeople distributed seedlings for $1 each at fairs and shopping malls, and even went door-to-door offering to plant seedlings in homeowners' gardens—just to spread the word. (This was very labor intensive and was dropped after a couple of months).

CONCLUSION

"Social forestry" is still a new concept. There is no certain method for achieving your goal because we are all pioneers. Aside from being creative, one must be persistent. Finding a new way involves the risk of failure as well as the chance of success.

We "TreePeople" often felt like rats in a maze, following every possible path. Some succeeded. Some were bitter failures. We're still learning from our oversights. For instance, how many of the million trees are alive today? We hadn't built in an assessment factor at all. We did, however, emphasize trees planted on private property, because we assumed a high survival rate. On reflection, we would have done more to educate people about the need not only to plant, but to commit to long-term care.

We encourage you to set up your program so that you have room to experiment and take risks. It's the creativity that catches attention and inspires others. Don't be discouraged by failure. Look at what worked and also at what didn't work. Learn your lessons and move on, trying other variations until you succeed.

This is just the beginning. Use it to inspire ever greater and more successful urban forestry efforts. We believe our job is to blaze trails down which others will not walk but run...trails used by all those in the community who want to see a greener world, rather than used simply by professionals.

By the way, our campaign was a success. It certainly didn't turn out according to plan, but the most important goal was accomplished...the people of Southern California—individuals, families, churches, service organizations, cities, the Forest Service, County Foresters, scouts, and corporations—reached our goal. After three years, four days before the lighting of the Olympic Flame, we received word that an apricot tree had been planted in Canoga Park. It was the confirmation of the planting of the millionth tree.

GREENSTREETS OR MEANSTREETS: CHALLENGES TO PLANTING URBAN TREES

Antonio E. Acosta
Office of Parks & Recreation
City of Oakland, CA

ABSTRACT

This paper outlines the major technical, sociological, and fiscal challenges to planting and maintenance of urban trees which have been encountered by the Office of Parks and Recreation of the City of Oakland, California. The paper stresses the importance of long-term planning for the establishment and survival of the urban forest and individual trees, as opposed to focusing merely on numerical goals of tree planting. The need for cooperation and integration of the community in planning the urban forest is emphasized.

KEYWORDS: tree maintenance, tree planting, urban forestry

GREENSTREETS OR MEANSTREETS: CHALLENGES TO PLANTING URBAN TREES

Antonio E. Acosta
Office of Parks & Recreation
City of Oakland, CA

INTRODUCTION

This workshop has served as a valuable forum for the exchange of information relevant to the phenomenon of urban heat islands. A number of excellent technical presentations have been delivered, with several emphasizing the mitigating effects vegetation can have upon the heat concentrations that modern cities create. And while the beneficial effects of various types of plants can be debated, few if any plants provide such benefits on a sustained basis better than trees.

The purpose of this presentation is to place the technical information provided at this workshop in the "real world" context of urban tree planting over the past ten years in Oakland, California. I hope that by the end of this brief and rather anecdotal presentation, participants at this workshop will have a clearer understanding of ten specific challenges that confront those who would seek to mitigate urban heat islands through the large-scale establishment of arboreal vegetation.

CHALLENGE NUMBER 1 is to adopt and promote the Greenstreets viewpoint, while recognizing and dealing with the Meanstreets viewpoint.

The terms "Greenstreets" and "Meanstreets" can be used to describe two alternative viewpoints of the inner city landscape. On the one had, Greenstreets reflects a viewpoint that values and promotes the long-term benefits we all receive from planting cities with trees. The term Meanstreets, on the other hand, reflects a pessimistic urban viewpoint that despairs of the aesthetic and environmental benefits trees might bring to even the most hostile streetscapes. Whereas the Greenstreets philosophy plants trees, the Meanstreets philosophy destroys trees through vandalism and neglect.

Those who would promote tree establishment in cities cannot assume that the Greenstreets viewpoint will be shared by all of those whose cooperation (or at least non-interference) is necessary for such programs to succeed. We must acknowledge the presence of the Meanstreets viewpoint, its influence on urban tree programs, and methods of dealing with it through outreach educational programs and neighborhood involvement programs

CHALLENGE NUMBER 2 is to adopt a concept of Urban Forestry as an interdisciplinary approach to resolving the many technical challenges confronting those committed to urban tree establishment.

In addition to recognizing the Greenstreets/Meanstreets dichotomy, it is useful to define the term "urban forestry," for when we discuss urban tree planting, we must address far more than the physical act of putting a tree in the ground.

It has been said that forestry is essentially tree farming: one either grows trees in a wildland setting and calls oneself a forester, or one grows trees in a developed area and calls oneself an urban forester. Obviously, there is more to urban forestry than this simplistic definition. Instead, I will propose to define urban forestry as the application of "classic" forestry principles to the urban setting. Three of the most useful and important classic forestry principles are: (1) sustained yield, meaning that tree-related benefits are maintained over time; (2) multiple use, meaning that trees are managed so that an optimal mix of benefits (both economic and non-economic) are enjoyed by urban residents; and (3) rotational management, (planted and removed) according to a useful lifespan cycle determined by inherent biotic (i.e., species) factors, maintenance cost factors, and relevant social factors.

CHALLENGE NUMBER 3 is to recognize that the true goal of any urban forestry program is to optimize the establishment of as many trees as is possible in appropriate locations resulting in acceptable growth form, health and vigor over the useful lifespan of each species.

The first philosophical challenge that must be addressed involves a term used frequently in the urban tree business. The term is planting, and it is practically irrelevant to urban forestry programs. It is irrelevant because, in my experience, it does not really matter how many trees we plant; what matters is how many trees we establish in appropriate locations that are well-formed, and maintained in a healthy, vigorous state over the long-run in the urban environment. Note that I have included three components in this definition of establishment:

> (1) APPROPRIATE LOCATION, in which the tree's natural characteristics complement its immediate environment. From a micro-viewpoint, anyone who has planted a large, fast-growing tree close to their house or on top of their sewer line can personally vouch for the importance of this component. From a macro-viewpoint, it might be argued that many tree species' water requirements would make many locations in California inappropriate.
>
> (2) WELL-FORMED, indicating that the tree has been properly maintained so that its size, shape, branch structure, and root growth are all representative of the species. Thus, trees that require extensive maintenance will be difficult to establish properly.

(3) HEALTHY AND VIGOROUS, meaning that the tree is reasonably free of pathogens, and has successfully adapted to its local microclimate. This requirement does not imply any preference for high growth rates; indeed, trees with moderate to slow growth rates may have other attributes such as drought tolerance and vandalism resistance that make them wiser choices than their fast-growing arboreal relatives.

CHALLENGE NUMBER 4 is to avoid relying on finite numerical goals for urban forestry programs ("the myth of numbers"), stressing instead a continuous, long-term commitment to public education, tree establishment, and proper maintenance of our expanding urban forest.

The myth of numbers in the field of urban forestry is a myth that can divert our attention away from achieving the basic goal of optimal tree establishment. The myth is a simple and rather seductive one; namely, that we can gauge the success of urban forestry programs by maximizing the number of trees planted over a given time period, i.e., that more is better than less.

One of the better examples of this myth involves the tree-planting program we have heard about earlier today, which took place in the Los Angeles area prior to the 1984 Olympic Games.* This program established, and claimed to meet, a goal of planting a million trees in roughly a one-year period. It sounded impressive and was hailed as a tremendous accomplishment. I respect the TreePeople organization, but I propose that this type of program essentially "missed the boat" in terms of achieving significant involvement in the status of urban forestry in Southern California.

First, we do not know how many of these trees are still alive five years later, what condition they are in, or if they have truly improved the urban environment; in short, we do not know how many of these million trees have become established. When we factor in the considerations I have proposed, it may well be that over 99% of these trees have failed to become established. Second, no program of maintenance or long-term follow-up has been established to ensure that any of these million trees will be properly managed during their useful lifespans. Third, the finite, quantitative nature of this program's objective failed to provide the framework required to translate it from a "one-shot deal" to an ongoing environmental improvement program. One million trees does not an urban forest make. Urban tree establishment is not a finite process, but must be nurtured and sustained in perpetuity in order to achieve its objectives.

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* (see Lipkis and Lipkis, herein)

CHALLENGE NUMBER 5 is therefore to reject the expert manager model of forest management in favor of a participative management model in which the general public becomes a partner with technical experts in planning, executing, and sustaining urban forestry programs.

The final philosophical challenge I will propose today takes me back to my college days at the University of California. I had a forestry professor who, like most forestry professors, adopted a systems view of the world. He would develop intricate models of vegetative systems, relating the many variables which contributed to the overall system's outputs. And invariably, he would describe the last variable of the forest system with a mixture of fear, disdain, and apology: people, or the human variable. He would tell us about people (not to be confused with students); those unpredictable organisms who could usually be counted on to ruin any respectable systems model with their irrational and destructive inputs. People, who usually required so much education in order to understand their proper role in the system that it was better to minimize their exposure to it if at all possible. People, the pathogens who think!

It is fairly obvious that we minimize social considerations in the urban forest at our extreme peril. The truth is, people function in completely different ways in the two forest environments, and we had better understand this distinction if we are to have any chance of success.

The primary positive human input in wildland forestry is assumed to be that of the expert forester, the provider of sustained and multiple uses. Other, non-expert humans provide mainly negative inputs to the forest, such as fire, vandalism, and adverse tax codes. This viewpoint, which I will call the traditional expert-manager model of forest management, is essentially hostile to the general public and falls into the trap I call "The Professional Knows Best". The problem with such a viewpoint in an urban context arises from the rather obvious fact that people often outnumber trees in the urban forest. The human factor is the predominant one in urban forestry, for it directly determines the success of any tree-planting program. We cannot plan around people if we are to succeed; rather, we must involve people at every step of the way as we develop and implement urban forestry programs.

As an example, consider the fate of 2000 Ginkgo trees planted by the City of Oakland during the early 1970's under the auspices of the Model Cities program. Nobody in the surrounding community was asked to contribute in any way to the planting decision: species, location and planting method were all handled by the professionals working for the city. Today, only about 10 of these trees are still alive.

Contrast this with Oakland's current Greenstreets program in which

* residents determine the species to be planted in their neighborhoods (selecting from a tree palette developed by the city),

* trees are planted only where requested,

* residents are encouraged to participate in the planting process if they wish to, and

* every participant is required to water their tree the first year, and maintain the tree's base free of weeds and debris.

As you might guess, the mortality rate of the Greenstreets program is a small fraction of its Model Cities predecessor, averaging 10-15% on an annual basis.

CHALLENGE NUMBER 6 is the most basic challenge confronting urban foresters today: absence of adequate funding for education, tree establishment, and ongoing maintenance.

With public resources largely unavailable for expansion or creation of urban forestry programs, meeting this challenge requires efforts to maintain existing levels of program funding while developing new funding sources. An example of the latter may be found in recent successful efforts to include urban forestry grant allocations in the programs funded by State Park Bond Measures. Other options include utilizing urban redevelopment and community development programs (for environmental improvements such as street trees), the hunger/food programs (for fruit tree establishment programs), and energy conservation programs (for heat island mitigation).

Creativity in expanding the linkages between urban forestry programs and available funding sources will be essential to securing the funding levels necessary for expansion of the urban forest, and will also make the urban forest better suited to the communities' needs.

CHALLENGE NUMBER 7 is to develop partnerships with governmental agencies (federal, state, regional, and local), private sector corporations, non-profit groups, community organization, and neighborhoods to provide urban forestry programs where Challenge Number 6 can be met.

Having stated the obvious in terms of fiscal resource availability, it must also be pointed out that there are many alternatives to government funding. Partnerships can, and must, be developed between governmental agencies, private sector firms, local non-profit and community-based organizations, and especially neighborhoods to develop, implement, and maintain urban forestry programs. An example of how such linkages can work is the "Adopt-A-Block" tree-planting program, in which municipal tree agencies provide technical and administrative support, private firms and/or non-profit organizations provide sponsorship (financial and/or staffing), and neighborhoods provide labor and a commitment to ongoing tree maintenance (in conjunction with the municipal tree agency).

CHALLENGE NUMBER 8 is to recognize and satisfy local governmental jurisdictional and regulatory responsibilities which may impact urban forestry programs.

One factor frequently overlooked by those operating outside the framework of local government (e.g., community organizations, private sector firms, state/federal agencies) are local regulatory and jurisdictional requirements. These requirements define who has the authority to plant trees on public (and even private) property, which species may or may not be planted, and who will ultimately be responsible for maintenance of the trees in questions. Well-intentioned efforts can easily unravel if an unforeseen bureaucratic obstacle is encountered late in a program's development cycle, so these factors must be researched and resolved early in the planning process.

CHALLENGE NUMBER 9 requires that the social context of urban forestry be understood and appropriately dealt with.

Each urban forestry program operates within a unique social context defined by the community the program serves. In Oakland, years of community involvement has resulted in a typology of common attitudes toward trees which must be recognized, understand and managed. These attitudes are characterized by

TRUE BELIEVERS - those individuals who cherish trees and need little motivation to participate in urban forestry programs. In fact, TRUE BELIEVERS typically form the basis for coalescing and sustaining neighborhood tree establishment programs (using the Tree Warden concept). The cyclical success and failure of most urban forestry programs over time can usually be traced to the presence or absence of TRUE BELIEVERS in a given neighborhood.

FOLLOWERS - those who will follow program experts and true believers, providing essential program support (summarized by the "Sounds good, Why not?" concept).

CHILDREN - whose energy and enthusiasm are second only to the true believers', and whose active participation in urban forestry programs is essential to program success. Every child not involved in forestry programs becomes a potential vandal (see below).

NON-PARTICIPANTS - those who choose not to take part in urban forestry programs, citing reasons ranging from maintenance concerns (disliking leaf drop) to security concerns (fear of shadows, potential attackers hiding behind trees, etc.). It is important to sell even NON-PARTICIPANTS on the positive aspects of tree-establishment programs, lest they, too, become active members of the vandal community.

VANDALS - those whose destructive Meanstreets actions threaten all tree-related programs, and who must be co-opted through educational programs, involvement of children, and law enforcement (where necessary, as a last resort).

CHALLENGE NUMBER 10 is to develop and sustain active, ongoing educational and promotional urban forestry programs that take advantage of all available opportunities.

The final challenge identified through Oakland's experience in building a community-based urban forestry program is to promote urban forestry activities and educational programs over time so that urban forestry becomes a natural part of the urban social landscape. Examples of methods that can be employed to this end include: exploiting traditional tree-related holidays such as Arbor Day and Christmas for their urban forestry value; using topics of current interest such as global warming (the greenhouse effect) and tropical rainforest depletion in urban forestry programs to establish linkages between local tree establishment efforts and issues of global significance; and developing unique tree-related events, such as memorial tree plantings, non-Anglo American cultural holidays/events, and any other creative "happening" that can be organized and carried out.

CONCLUSION

It might seem, from the catalog of challenges presented above, that too many obstacles exist for urban forestry programs to ever have a chance of succeeding. Such is not the case, however, for the simple reason that every challenge represents an opportunity. As we proceed from research to implementation, I hope that identifying these challenges will assist program planners and managers to develop urban forestry programs that have the best possible chance of succeeding in diverse urban social environments.

PLANTING GUIDELINES FOR HEAT ISLAND MITIGATION AND ENERGY CONSERVATION

Russell A. Beatty
Department of Landscape Architecture
University of California at Berkeley

ABSTRACT

A critical need exists to translate scientific data on heat island mitigation and energy conservation into implementable procedures for city planners, architects and landscape architects. Planning strategies for urban forestry and community development rarely consider the value of plants (vegetation) for heat island mitigation and energy conservation. The means of implementing such planting strategies are through the development of municipal policies, ordinances and site design and planting guidelines and in the preparation and implementation of urban forestry plans.

In addition to achieving the desired environmental changes, the visual (aesthetic) effects and the long-term management of plantings and existing trees are important factors to consider at both the city-wide scale and in the site planning and design.

The implementation of policies for such environmental amelioration can take several forms. One is through municipal ordinances or codes. Such legal forms of enforcement should be complemented by design guidelines. On the larger municipal scale, the development and implementation of an urban forestry plan can serve to guide the planting of trees by both the municipality as well as other agencies who manage large areas of potential urban forest (water districts, flood control, highway department, schools and other institutions, etc.). Strategies for preserving and planting trees on streets, parking lots, certain roof tops and vacant land can be developed in such a plan. Plant selection criteria and lists of suitable species for various types of planting situations should be incorporated into the plan along with general maintenance criteria to achieve the desired environmental changes.

KEYWORDS: landscape ordinance, parking lots, trees, urban forest, urban planning.

PLANTING GUIDELINES FOR HEAT ISLAND MITIGATION AND ENERGY CONSERVATION

Russell A. Beatty
Department of Landscape Architecture
University of California at Berkeley

INTRODUCTION

Landscape architects have been instrumental in planting what we now call the "urban forests" of our cities for over one hundred years. Frederick Law Olmsted, Charles Eliot, Horace Cleveland and other visionary landscape architects have left a legacy of park systems, planted streets and boulevards, cemeteries and open space preserves that comprise a large portion of the urban forest in many American cities (Zube, 1973). Contemporary landscape architects are responsible for continuing this legacy in the monumental effort to "green" our expanding towns, cities and metropolitan regions.

Our work has been more intuitive than systematic. We have worked from the premise that trees and green open space help to create a more comfortable, healthier urban environment and one that is aesthetically pleasing. Olmsted called his parks "lungs" for the crowded, industrial cities of the 19th Century.

Today, we have learned from scientific research that our intuitive approach has been more or less correct. We know that trees and other vegetation:

- cool a site as much as 10-15 ° C in summer
- help cleanse the air by intercepting dust and by contributing oxygen
- help reduce strong winds
- provide habitats for birds and other small wildlife
- create places of great beauty as relief and escape from the harshness of the urban environment
- help to heal the human spirit and hasten healing of the body

Still, there are many who consider planting to be somewhat of a luxury—cosmetic decoration to hide, soften or disguise an otherwise unpleasant environment of concrete and steel. The term "landscaping" tends to relegate planting to this rather superficial role.

URBAN FORESTRY

The rise of urban forestry has given new support for and meaning to the planting of our cities with more purposeful intent. The urban forestry movement of the 1970s has stagnated during the past eight years of federal and state environmental neglect.

The realization that planting can reduce the urban heat island effect and possibly slow global warming has now become a great stimulus to urban forestry in the United States. With the support of scientific evidence we can substantiate what we have known intuitively—that trees and other vegetation can improve, perhaps heal, the urban environment as the least expensive, most cost effective solution (Ottman & Kielbaso, 1976).

PLANNING THE URBAN FOREST

Planting trees and systems of trees traditionally has not been well integrated into the design and planning of most towns and cities, with the exception of the great boulevards and park systems in such cities as Washington, D.C., Boston and Minneapolis. The focus of urban tree planting has been more horticultural than ecological. Until recently the city has not been recognized as an ecosystem, of which trees and vegetation are an essential component. There are, however, several significant examples where urban planning has incorporated the concept of urban forestry, primarily to provide summer cooling.

In Nanjing, China the average summer temperature has dropped 5 °F (2.8 °C) from 90 to 85 °F since 1949 due to the planting of some 34 million trees (Bartenstein, 1981; Schumann, 1981). In Stuttgart, West Germany fingers of green open space now penetrate the city center to convey flows of cooling night air and to reduce daytime summer temperatures (Loessner, 1978). The Dayton (Ohio) Climate Project was a sound, well conceived plan to reduce summer temperatures in the downtown by massive planting of trees in parking lots (Bartenstein, 1981). Unfortunately, it was never implemented due to resistance from merchants and others who were reluctant to accept the necessary changes to restructure downtown parking areas. This latter example underscores the importance of understanding the social and political ramifications of urban tree planting in a democratic society. Any urban forestry effort, no matter how well intended or scientifically sound, must recognize the socio-political influences and integrate the people of the community into the process (Bartenstein, 1980; Bartenstein, 1982).

Planning the urban forest for heat island mitigation must be done in a systematic way if the anticipated effects are to be realized. There are several examples of massive tree planting efforts that have failed to achieve their good intentions because they lacked a systematic process to guide the planning, design, implementation and management of the planting programs.

A massive tree planting program was instituted in Mexico City to combat air pollution in the 1970s. Millions of trees were planted helter-skelter without careful species selection in unsuitable places and without consideration for what the people of the city wanted or needed. Open play spaces in crowded neighborhoods were filled with trees, only to be removed or trampled by young people playing in the green space.

The Los Angeles effort to plant a million trees for the 1984 Olympics is another example in which a more systematic approach would have ensured a more successful effort. There was no systematic follow-up and it is not known how many trees survived.

ATTRIBUTES OF URBAN FOREST PLANNING

Although there is much literature on urban forestry, very few publications have addressed the planning and design process necessary to effectively implement an urban forestry plan. In previous papers I have suggested that urban forest planning have the following attributes:

1. Comprehensive in scope

   The plan should include the total potential urban forest regardless of land use and ownership patterns in three broad categories:

   a. municipal lands (city parks, boulevards, streets, golf courses, etc.)

   b. public agency lands (state highways, flood control district, water district, etc.)

   c. private lands (shopping centers, residential complexes, single family residences, etc.)

2. Broad range of benefits

   The plan should address the key benefits of tree planting for any particular city such as:

   a. heat island mitigation

   b. site specific microclimate modification

   c. energy conservation

   d. aesthetic quality of the community

   e. environmental improvement (air quality, noise abatement, wildlife habitats, watershed management, etc.)

3. Community participation

The community should be involved throughout the entire process and in a variety of ways such as:

a. municipal forestry board or commission (to serve as an official advocate in city hall)

b. neighborhood or community action groups

c. private benefactors or sponsors (individuals, corporations, businesses, merchants groups)

An important benefit of developing a systematic planning approach is long-term effectiveness of the effort. Tree selection and planting should result from a careful analysis of urban microclimate zones, soils, goals of the urban forest plan such as water conservation or wildlife habitat, and design criteria for particular planting situations (parking lots, narrow streets, wide boulevards, riparian zones and so forth) (Beatty & Heckman, 1981; Beatty, 1985).

DESIGN GUIDELINES

In California we have three examples of design guidelines prepared for different sizes of cities. *Trees for Lafayette* (Beatty, 1977) is a comprehensive guide based on an ecological approach to planting trees in various types of sites—streets, plazas, creeks, parking lots, etc. Each type of site is analyzed first, in relation to the context of the city and second, relative to the aesthetic and physical characteristics and requirements of the typical planting situations. Each prototypical site is illustrated with detailed sketches to show the form, size and compositional arrangement of trees. Detailed maintenance procedures are also included in the guide. The guide was published so that it would have broad appeal and serve as an educational document.

A similar approach was taken in the Landscape Design Guidelines for Roseville, California (Smith, 1985). And the street master plan for Oakland, *Greenstreets,* followed a somewhat similar approach, but focused only on street and boulevard trees.

LANDSCAPE ORDINANCES

The official mechanism for implementing tree planting guidelines is through the development and enforcement of municipal ordinances. Most cities have some sort of landscape or tree ordinance, however, they vary widely from city to city. The main intent of such ordinances is to ensure adequate "landscaping" (meaning primarily planting) for new development. The focus is on aesthetics—the provision of trees, shrubs and groundcover to dilute, screen or soften the buildings and paving in any new development. Such ordinances may require a substantial portion of the site to be "landscaped", depending on land use. Generally more planting space is required of multi-family residential development than for commercial complexes (shopping centers, etc.).

Parking Lot Requirements

In a quick review of thirteen cities' landscape ordinances, I found that none had addressed the issue of heat island mitigation, except in an indirect way by requiring tree planting in parking lots. I analyzed and compared how the various cities' ordinances addressed planting requirements in parking lots, because of their role in contributing to urban heat islands.

Tree planting requirements tend to follow one of the following types of standards:

1. X number of trees/ sq. ft. of parking area

   Example: Tampa, Florida requires 1 tree/4500 sq. ft. in multi-family residential lots.

2. One tree/x number of spaces

   Example: Long Beach, California requires one tree per five parking spaces; Los Angeles requires one tree per four spaces.

3. Percentage of the parking area

   Example: This standard varies widely from 1% to 7.5% of the total parking area. Most cities distinguish between the total lot area, the perimeter area and the interior of the lot. Richardson, Texas requires 2% of the total area and 50% of the internal area to be "landscaped".

Some cities use a combination of several of these standards. Palo Alto, California requires the following for parking lots (Figure 1):

- 5' wide perimeter planting strip
- 5-10% of interior area to be "landscaped" depending on size of lot 5% — under 14,999 sq. ft.

  7.5% — 15,000-29,999 sq. ft.

  10% — > 30,000 sq. ft.
- or 1 tree/6 parking stalls with 50% of perimeter trees counted

Obviously, there is no agreement on how to best require planting for parking lots. Furthermore, the requirements are established, first, to screen cars from view and, only secondarily, to provide shade. Some cities require that 50% of the pavement is to be shaded in x number of years (usually 10-15 years). But there is no means of assuring that objective due to the variables of soils, climate, species selected and maintenance.

To compare these various standards I have plotted a hypothetical parking lot for 50 standard vehicles to determine the tree shading potential by using two different cities' standards. The parking lot measures 26,000 sq. ft. and has a 10' wide perimeter planting strip around three sides. The maximum number of trees was plotted for each city based on their individual standards. These are summarized as follows:

Corpus Christi, Texas (Figure 2):

Formula: 20 sq. ft. landscaped area/parking space

Total planting area: 1,000 sq. ft.

Total number of trees: 40-44 internal

(**Note:** This standard does not specify numbers of trees. I assumed a minimum area for each tree to be 25 sq. ft.; tree canopy was plotted at a 20' diameter; tree spacing averaged 20' on center with 15' on center at the ends of parking bays.)

Long Beach, California (Figure 3):

Formula: 1 tree/5 parking spaces

Total planting area: not specified; depends upon size of tree planting islands.

Total number of trees: 10 internal

(Note: By changing the formula to 1 tree/4 spaces, as in the Los Angeles ordinance, only two more trees are added to this parking lot.)

This comparative analysis is in a very preliminary stage of research. Clearly, the current standards vary tremendously as with these two examples. There will be great difference in shading a parking lot if one uses the Corpus Christi model which yields 40-44 trees, or nearly one tree per parking space rather than the Long Beach model which results in a token planting of only 10 trees. Most parking lot ordinances reviewed are similar to the Long Beach model in the resulting amount of landscape area and possible number of trees.

Parking lots may cover as much as 25-30% of urban downtowns. Their role in contributing to the urban heat island is significant. Much more research is needed to determine the optimum tree planting patterns for parking lots. We need to know what amount of shadow coverage is optimum to significantly reduce heat build-up over parking lots. By working backward to determine tree spacing, pattern, and tree selection criteria, we can develop more meaningful standards to incorporate in urban design guidelines and landscape ordinances.

CONCLUSION

A major step in combating the urban heat island effect is through increased tree planting efforts. Planting trees in the hostile environment of cities requires careful planning. By employing systematic urban forestry planning methods for any city, a comprehensive plan can be prepared and implemented which addresses multiple benefits from trees including their social and aesthetic values as well as their value in ameliorating urban microclimate and ultimately reducing the heat island effect.

Design guidelines are needed to ensure that this multiplicity of values is addressed from both an ecological and an aesthetic perspective. Mathematical formulas do not ensure either good aesthetic results or effective heat island mitigation. More research is needed to incorporate scientific modeling into design guidelines for such key urban land uses as parking lots so that tree planting requirements can be made effective in reducing heat build-up over pavement and in shading vehicles to reduce the use of air conditioners and CO_2 emissions. Such comprehensive guidelines are essential for planners, urban foresters, and landscape architects who are responsible for implementing urban tree plantings to improve our cities in the future.

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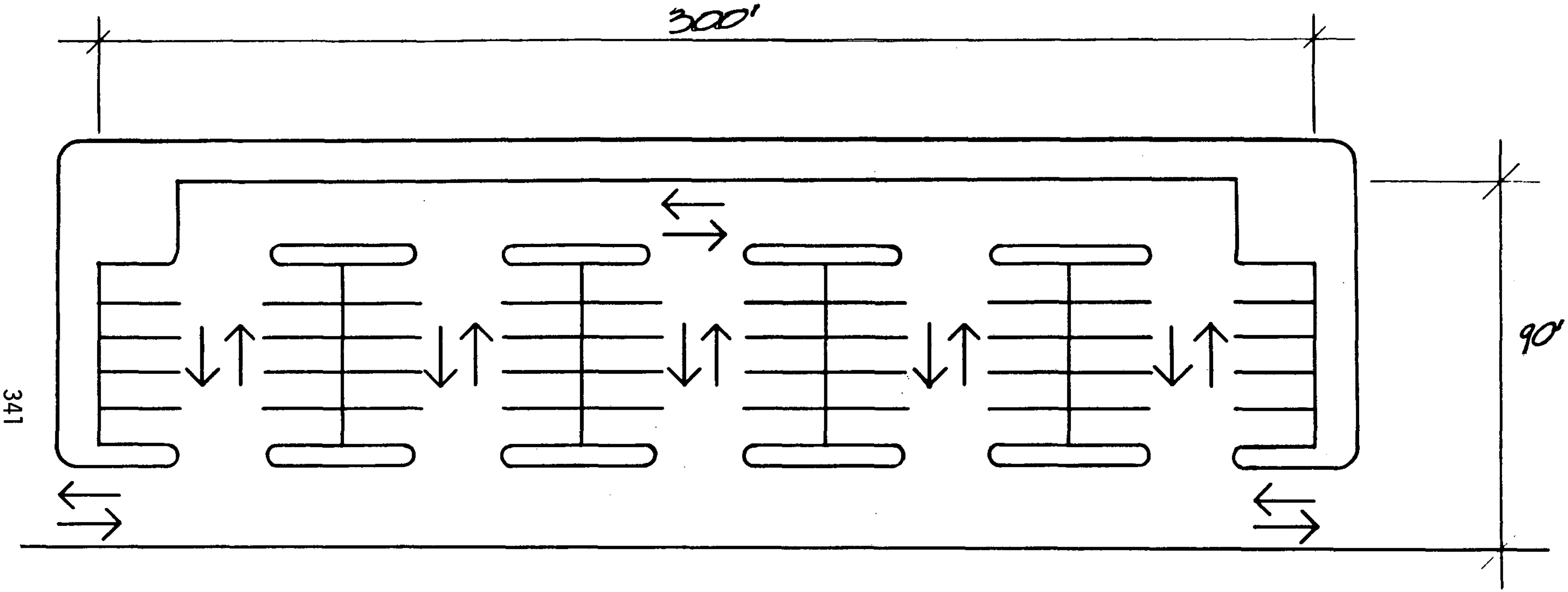

Figure 1. Hypothetical Parking Lot. 50 vehicles with 26,000 sq. ft. of pavement, including a minimum of 6,024 sq. ft. of planting area.

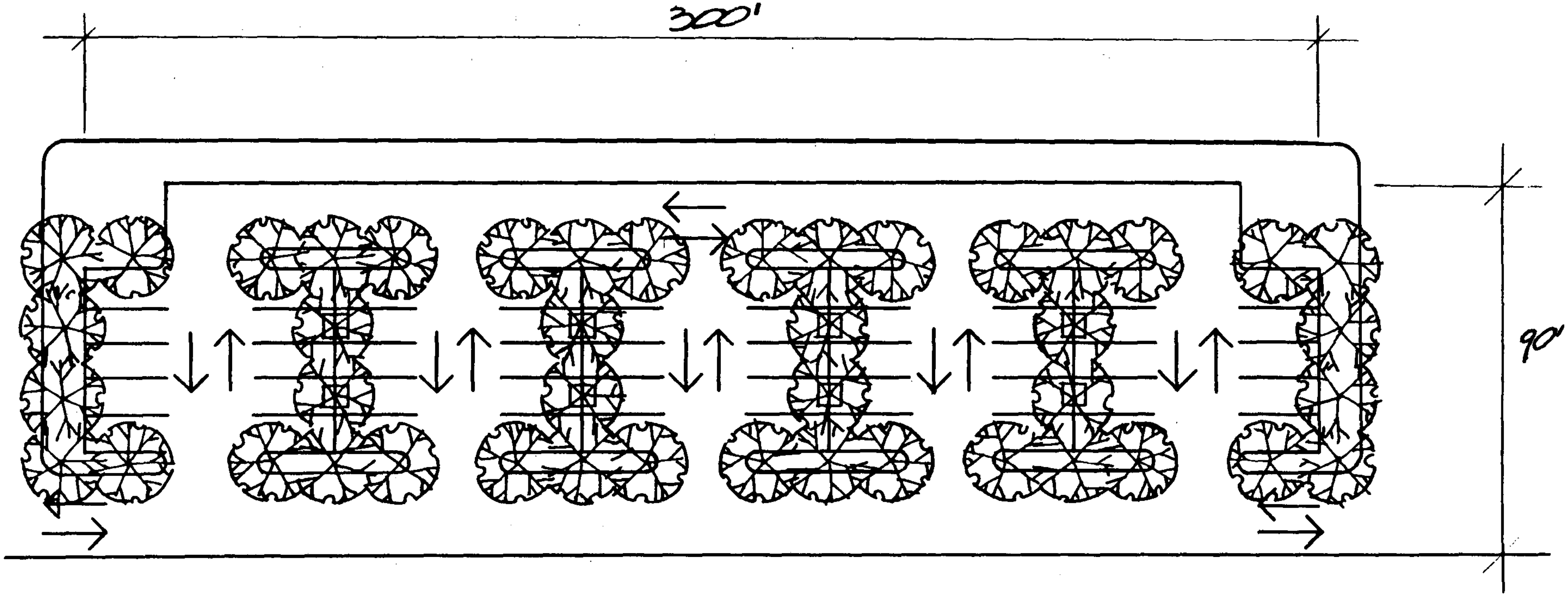

Figure 2. Corpus Christi Parking Lot Formula. 20 sq. ft. of planting per parking space; net 40-44 internal trees @ 25 sq. ft. each per 50 parking spaces.

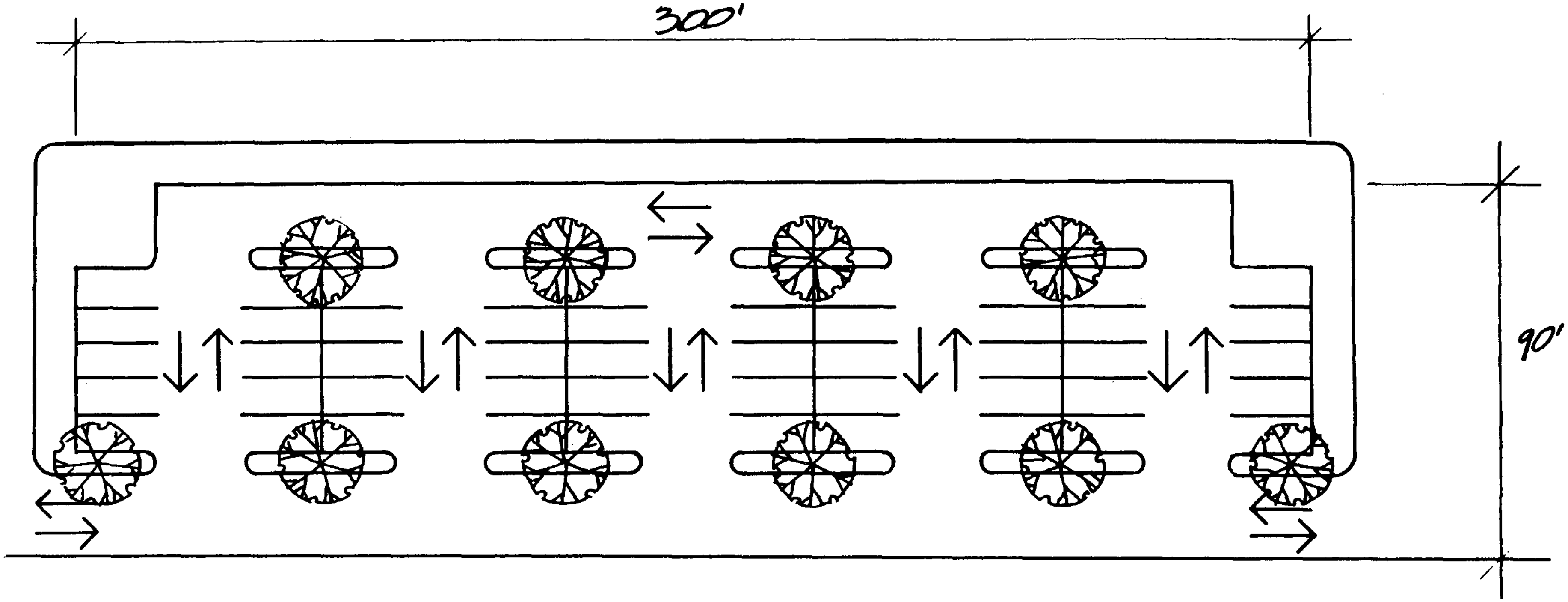

Figure 3. Long Beach Parking Lot Formula. One tree per five parking spaces; net ten internal trees per 50 parking spaces.

HEAT ISLAND WORKSHOP REGISTRANTS

Acosta, Tony
Office of Parks and Recreation
1520 Lakeside Drive
Oakland, CA 94612
(415) 273-3494

Akbari, Hashem
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720
(415) 486-4287

Al-Eslawi, Saud
Graduate School of Architecture
and Urban Planning
UCLA, 405 Hilgard Ave.
Los Angeles, CA 90024

Al-Hemiddi, Nasser
Graduate School of Architecture
and Urban Planning
UCLA, 405 Hilgard Ave.
Los Angeles, CA 90024

Andrasko, Ken, PM 221
EPA
401 M Street, SW
Washington, DC 20460
(202) 382-5603
FTS 382-5603

Baxter, Lester
California Energy Commission
1516 Ninth Street, MS 22
Sacramento, CA 95814
(916) 324-3114

Beals, Gordon
EPRI
M.S. 4202
P.O. Box 10412
Palo Alto, CA 94303
(415) 855-2591

Beatty, Russell
Dept. of Landscape Architecture
UC Berkeley
Berkeley, CA 94720
(415) 642-2421

Blumstein, Carl
UC Berkeley
UERG, 216 T-9
Berkeley, CA 94720
(415) 462-9588

Bornstein, Bob
San Jose State Univ.
Dept. of Meteorology
San Jose, CA 95192
(408) 924-5205

Brest, Chris
NASA/GISS
Goddard Inst.
2880 Broadway
New York, NY 10025
(202) 678-5565

Brice, Arthur A.
L.A. Dept. Water and Power
Box 111
Los Angeles, CA 90051
(213) 481-3358

Carhart, Ralph
CalTrans
1120 N St. Rm 5306
Sacramento, CA 95814

Carlson, Toby
Dept. of Meteorology
Pennsylvania State Univ.
University Park, PA 16802
(814) 863-1582

Chang, Jerry
Graduate School of Architecture
and Urban Planning
UCLA, 405 Hilgard Ave.
Los Angeles, CA 90024

Clark, James
Center for Urban Horticulture
University of Washington GF-15
Seattle, WA 98195
(206) 543-8603

Corcos, Gilles
6101 Etcheverry Hall
UC Berkeley
Berkeley, CA 94720

Crossman, Joshua
1130 Guerrero Ave., Apt. 4
San Francisco, CA 94110

*Dasovich, Jeff
CPUC
State Building
505 Van Ness Ave
San Francisco, CA 94102

DeLaCroix, Linda
DOE, CE 133
Building Services Div.
Forrestal Bldg.
1000 Independence Ave., SW
Washington, DC 20585
(202) 586-1851
FTS 896-1851

DiMassa, Frank
Municipal Program Manager
Bureau of Energy Conservation
110 McAlister Street
San Francisco, CA 94102

Djen, Chow Shu
c/o Dr. Wang Xing-Jie
Lasdon House
420 East 70th St.
Room 2L
New York, NY 10021

Ellefsen, Richard
Geography/Env. Studies
BT 550D
San Jose State Univ.
San Jose, CA 95192

*Freais, William
Wieidenfeld & Nicolson, Publishers
1763 Evers Ave.
Oakland, CA 94602
(415) 482-5480

Gamez, Charles
Dept. of Landscape Architecture
UC Berkeley
Berkeley, CA 94720

Garbesi, Karina
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720
(415) 486-5180

Giallombardo, Debbie
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720
(415) 486-4834

Gillies, Rob
Dept. of Meteorology
Pennsylvania State Univ.
University Park, PA 16802

Givoni, Baruch
Graduate School of Architecture
and Urban Planning
UCLA, 405 Hilgard Ave.
Los Angeles, CA 90024
(213) 825-2067
(h) 829-0447

Gordon, Debbie
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

Grether, Don
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720
(415) 486-6283

Hanser, Phil
EPRI
P.O. Box 10412
Palo Alto, CA 94303
(415) 855-7954

Harris, Jeff
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720
(415) 486-4362

Harte, John
ERG, 100 T-4
UC Berkeley
Berkeley, CA 94720
(415) 642-8553
(415) 486-5068

Heisler, Gordon
USDA Forest Service
Northeastern Forest Experiment Station
301 Forest Resources Lab
University Park, PA 16802
(814) 863-1933

Herber, Rosanna
1540 River Park Drive
Suite 201
Sacramento, CA 95815

Herrera, Raul
California Energy Commission
1516 Ninth Street, MS 22
Sacramento, CA 95814

Hitch, Charles
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720
(415) 486-4110

Holmes, Jay
DOE, CE 133
Building Services Div.
Forrestal Bldg.
1000 Independence Ave., SW
Washington, DC 20585
(202) 586-9837
FTS 896-9837

Huang, Joe
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720
(415) 486-7082

Imamura, Ruri
Dept. of Meteorology
San Jose State Univ.
San Jose, CA 95192
(415) 387-8812

Johnson, Huey
Director, The New Renaissance Center
Building 1065, Fort Conkhite
Sausalito, CA 94065

Khan, Homayun
Graduate School of Architecture and Urban Planning
UCLA, 405 Hilgard Ave.
Los Angeles, CA 90024

Kaminsky, Jacob
DOE, CE 133
Forrestal Bldg.
1000 Independence Ave., SW
Washington, DC 20585
(202) 586-9304
FTS 896-9204

Kneisel, Bob
Planning Division
SCAQMD
9150 East Flair Street
El Monte, CA 91731

Koomey, Jon
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720
(415) 486-5974

Krantz, Marshall
P.O. Box 5637
Berkeley, CA 94705

Krause, Florentin
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720
(415) 486-7260

Kress, Ed
CalTrans
1120 N St. Rm 5306
Sacramento, CA 95814

Leber, Jon
California Energy Commission
1516 Ninth Street
Sacramento, CA 95814

Ledbetter, Marc
ACEEE
Suite 535
1001 Connecticut Ave, NW
Washington, DC 20036
(202) 429-8873

Levenson, Leo
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

Levine, Mark
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720
(415) 486-5238

Lipkis, Andy
Tree People
12601 Mulholland Drive
Beverly Hills, CA 90210
(213) 399-2277

Maechling, Phil
City Planning Dept.
202 C Street, MS 5B
San Diego, CA 92101

Martien, Phil
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720
(415) 486-7279

McLaughlin, Ralph
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720
(415) 486-4508

McLaughlin, Sylvia
1450 Hawthorne Terr.
Berkeley, CA 94708

McPherson, Greg
Dept. of Landscape Architecture
Univ. of Arizona
Tucson, AZ 85721
(602) 621-7146
(h) 323-7557

Miller, Peggy
California Energy Commission
1516 Ninth Street, MS 22
Sacramento, CA 95814

Moll, Gary
AFA
P.O. Box 2000
Washington, DC 20013
(1-800) 368-5748

Monismith, Carl
Dept. of Transportation Engr.
115 McLaughlin
UC Berkeley
Berkeley, CA 94720
(415) 642-9067
(415) 231-9560

Noteware, Warren
California Energy Commission
1516 Ninth Street
Sacramento, CA 95814

Oke, Tim
Univ. of British Columbia
Dept. Geography
Vancouver, B.C V6T 1WS
Canada
(604) 228-2900

Olienyk, Deborah
Urban Forester
21266 Kahlerd Ave.
Castro Valley, CA 94546

Park, Yoonsup
Graduate School of Architecture
and Urban Planning
UCLA, 405 Hilgard Ave.
Los Angeles, CA 90024

Parker, John
Dept. of Chemistry
Florida International Univ.
Tamiami Campus
Miami, FL 33199
(305) 554-2606

Paw U, Kyaw Tha
Dept. of Land & Air Resources
UC Davis
Davis, CA 95616
(916) 752-1510

Perhac, Ralph
EPRI
P.O. Box 10412
Palo Alto, CA 94303

Pielke, Roger
Dept. of Atmospheric Science
Colorado State University
Fort Collins, CO 80523
(303) 491-8293
(303) 491-8360

Quintanilha, Alex
Lawrence Berkekey Laboratory
University of California
Berkeley, CA 94720

Rainer, Leo
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720
(415) 486-7473

Rosenfeld, Art
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720
(415) 486-4834

Rowntree, Rowan
U.S. Forest Service Research
1960 Addison Street
Berkeley, CA 94704
(415) 486-3191

Schiavo, Karl
1245 Sierra Village Place
San Jose, CA 95132

Schmugge, Tom
USDA Hydrology Lab
BARC-East
Beltsville, MD 20705
(301) 344-1554

Sharp, Glen
California Energy Commission
1516 Ninth Street, MS 22
Sacramento, CA 95814

Sherman, Rick
6101 Etcheverry Hall
UC Berkeley
Berkeley, CA 94720

Simpson, Jim
Dept. of Soil and Water Science
Univ. of Arizona
Tucson, AZ 85721

Squitieri, Ray
EPRI
P.O. Box 10412
Palo Alto, CA 94303

Taha, Haider
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720
(415) 486-7473

Thom, Belinda
M. E. Student
2419 Durant Street, # 30
Berkeley, CA 94704

Thorson, Patrick
BAAQMD
939 Ellis Street
San Francisco, CA 94109

Totten, Mike
Office of Rep. Schneider
1512 Longworth H.O.B.
Washington, DC 20515

Tretheway, Ray
Sacramento Tree Foundation
1540 River Park Drive
Suite 201
Sacramento, CA 95815

Vine, Ed
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720
(415) 486-6047

Wade, Isabel
President
Urban Resources Systems
783 Buena Vista West
San Francisco, CA 94117

David Ware
California Energy Commission
1516 Ninth Street
Sacramento, CA 95814

Yuliademo, Upadi
Graduate School of Architecture
and Urban Planning
UCLA, 405 Hilgard Ave.
Los Angeles, CA 90024

* Registered but could not attend.

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