Title

Energy Efficiency and the Environment: Innovative Ways to Improve Air Quality in the Los Angeles Basin

Permalink

https://escholarship.org/uc/item/5rh387fm

Authors

Akbari, H.
Sezgen, O.

Publication Date

1993-02-01

LBL-33725
UC-000

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

ENERGY & ENVIRONMENT DIVISION

Presented at the Eighty-Ninth Annual Meeting of Association
of American Geographers, Atlanta, GA, April 6–10, 1993,
and to be published in the Proceedings

Energy Efficiency and the Environment: Innovative Ways to Improve Air Quality in the Los Angeles Basin

R. Ritschard

February 1993

ENERGY & ENVIRONMENT
DIVISION

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

DISCLAIMER

Neither the United States Department of Energy (DOE) nor any agency thereof, nor The Regents of the University of California (The Regents), nor the California Institute for Energy Efficiency (CIEE), nor any of CIEE's sponsors or supporters (including California electric and gas utilities), nor any of these organizations' employees, make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by DOE or any agency thereof, or The Regents, or CIEE, or any of CIEE's sponsors or supporters. The views and opinions of authors expressed herein do not necessarily state or reflect those of DOE or of any agency thereof, of The Regents, of CIEE, or any of CIEE's sponsors or supporters, and the names of any such organizations or their employees shall not be used for advertising or product endorsement purposes.

Lawrence Berkeley Laboratory is an equal opportunity employer.

LBL-33725
UC-000

ENERGY EFFICIENCY AND THE ENVIRONMENT: INNOVATIVE WAYS TO IMPROVE AIR QUALITY IN THE LOS ANGELES BASIN

Ronald Ritschard†
Energy and Environment Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA
(510) 486-6328

Presented at
89th Annual Meeting
Association of American Geographers
Atlanta, GA
April 6-10, 1993

February 1993

This work is supported by the California Institute for Energy Efficiency, Contract No. BG-90-080 through the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

†Currently Vice President, Senior Scientist, Tennessee Valley Authority, Muscle Shoals, AL 35660.

ABSTRACT

This paper focuses on novel, innovative approaches for reducing or delaying the production of photochemical smog in the Los Angeles Basin. These approaches include modifying the surface characteristics of the basin by increasing surface albedo and an extensive tree-planting program. The changes in surface conditions are designed to reduce the basin air temperatures, especially during the summer months, which will result in two possible effects. First, a decrease in temperature would lead to a reduction in energy use with an associated decline in emissions of nitrogen oxides (NO_x) and a lowering of evaporative emissions of reactive organic gases. Reductions in these smog precursors could improve the air quality of the basin without imposing additional emissions regulations. The second effect is associated with the possible causal relationship between air temperature and smog formation (i.e., lower temperatures and lower incidence of smog). Since this approach to mitigating air emissions is broad, the studies to date have concentrated on how changes in surface characteristics affect the meteorological conditions of the basin and on how these meteorological changes subsequently affect smog production. A geographic information system database of key surface characteristics (i.e., vegetative cover, albedo, moisture availability, and roughness) was compiled, and these characteristics were evaluated using prognostic meteorological models. The results of two- and three-dimensional meteorological simulations will be presented and discussed in this paper.

1.0 INTRODUCTION

California's air basins are negatively affected by nitrogen oxide (NO_x) emissions generated from a wide variety of fuel-combustion sources, including automobiles, boilers, stationary gas turbines, and space and water heating for commercial, industrial, and residential end-use. The Los Angeles Basin, which comprises all of Orange County and the non-desert portions of Los Angeles, Riverside, and San Bernardino Counties, has the worst air quality in the nation. In spite of many strict controls, the basin still fails to meet the federal and California air quality standards for four of the six criteria pollutants, including ozone. To begin to address this major air quality issue, a multiyear project was started last year as part of the California Institute for Energy-Efficiency's (CIEE), a utility-funded research organization, Air Quality Impacts of Energy-Efficiency Program.

The purpose of this study is to investigate the direct and indirect effects of end-use efficiency on the reduction of photochemical smog in the Los Angeles Basin of California. The project addresses two aspects of this broad research area by focusing on (1) existing methods for projecting emissions from fuel combustion and opportunities for reducing these emissions through energy-efficiency improvements in the buildings sector, and on (2) novel, indirect approaches for reducing or delaying the production of photochemical smog that include the temperature effects of variations in the surface characteristics (i.e., vegetative cover, surface albedo, soil moisture, and roughness length) of the Los Angeles Basin resulting from trees and changes in albedo. These changes in surface characteristics are designed primarily to reduce the air temperature of the basin during the summer months. We hypothesize that temperature changes can have two possible effects. First, an overall decreased temperature would lead to a reduction in energy use with an associated decline in the emissions of nitrogen oxides (NO_x), as well as to lower evaporative emissions of reactive organic gases (ROG) from a variety of sources. Reductions in these photochemical smog precursors would lead to improvements in air quality without imposing additional emissions regulations. The second effect is associated with the possible causal relationship between air temperature and photochemical smog formation (i.e., lower temperatures and lower incidence of smog).

Although the buildings sector contributes an average of only 14% of the annual NO_x emissions in the Los Angeles Basin, preliminary analyses indicate that measures intended to reduce building cooling loads, such as planting trees and whitening surfaces, may significantly reduce both NO_x emissions and smog-forming temperatures in the lower troposphere. The overall goal of this study is to assess both the *direct effects* of end-use efficiency on emissions (e.g., NO_x) from the buildings sector and environmental variables, such as temperature affecting them, and the *indirect effects* of surface changes resulting from trees and white surfaces on smog formation (see Fig. 1). Since the indirect approach is broad, the studies during the first year focused on how changes in surface characteristics affect meteorological conditions within the basin (modeled with the Colorado State University Mesoscale Model, CSUMM).

These results are presented below. In the second phase of this study, we will begin to evaluate how these surface modifications might affect the production of smog in the basin, using the Urban Airshed Model (UAM) as an analytical tool.

Three interrelated project efforts conducted by an interdisciplinary research team from Lawrence Berkeley Laboratory (LBL), University of California at Los Angeles (UCLA), and Systems Applications International (SAI) were funded during the first year to establish the critical technical links between energy end-use efficiency and air quality. The project elements include: (1) *emissions studies* (LBL and UCLA) to develop data on fuel combustion sources and on trees that can directly serve as precursors to photochemical smog formation, (2) *surface characterization* of the basin (LBL and UCLA) to compile information about vegetative biomass, surface roughness, albedo, and surface moisture, and (3) *modeling studies* (LBL and SAI) to assess the effects of various surface modifications on existing meteorological conditions and the level of smog production resulting from these modifications. It is anticipated that this multiyear study will help resolve the issue of the causality between urban temperature reduction and smog formation in the Los Angeles Basin and will develop data and model enhancements that can be incorporated into future air quality assessments.

In the remainder of the paper we first provide background information about the air quality problem within the basin, including sources of emissions and estimates of these pollutants. In addition, we briefly describe the typical meteorological conditions of the basin and demonstrate the relationship between air temperature and ozone. We also characterize the major study elements. Next, we offer a description of the methods and data used to generate the study's results. First, we describe the nature of the vegetation database and the various surface characteristics, including surface albedo, roughness, and moisture availability. Second, the biogenic emissions inventory used in this study is described. This discussion includes estimates of biogenic hydrocarbon emissions from vegetation and the effects of temperature on these emission rates. Finally, this section includes a brief description of the methods used in the meteorological simulations.

In the next section, the results are given for the emission studies and for both the two- and three-dimensional sensitivity analyses. Finally, we present the major conclusions of the study and their significance. Overall, the results showed great promise that the goal of developing improved models and data for assessing the relationships among end-use efficiency, pollutant emissions, and resultant air quality can be accomplished over the duration of the study.

2.0 BACKGROUND

2.1 Air Quality Problem

The Los Angeles Basin is in compliance with the federal and California standards for sulfur dioxide and lead. However, the maximum ozone concentrations reach about three times the federal standard (12 parts per hundred million, pphm; 1-hour average) and four times the California standard (9 pphm; 1-hour average). Exceeding the ozone standards is far more frequent in the basin than in other parts of the nation. For example, the federal ozone standard was exceeded over three times as frequently as in any other area of the U.S. Furthermore, one or more air-monitoring stations in the basin have exceeded the federal ozone standard on more than 100 days of the year. Carbon monoxide (CO) and fine particulate matter (PM_{10}) concentrations reach about twice the federal standard. The highest annual average PM_{10} concentrations were also recorded in the basin and were 1.2 times as high as the highest in the U.S. The maximum 24-hour average PM_{10} concentrations reach about six times the California standard. Also, the basin is the only area in the country that still fails to meet the nitrogen dioxide (NO_2) standards.

In 1991, the South Coast Air Quality Management District (SCAQMD) updated its air quality management plan (AQMP). The plan is designed to achieve the air quality standards at the earliest possible date, but not later than 2000 for NO_2, 2005 for CO, and 2010 for ozone and PM_{10}. The California 1-hour ozone standard and the annual 24-hour standard for PM_{10} are not expected to be met until after 2010. The plan also includes an interim goal (for the year 2000) to reduce maximum ozone concentrations to no higher than the Stage I emergency level (20 pphm) and to reduce the average per capita exposure to ozone above 12 pphm by 70% compared to 1985. The 1991 AQMP was developed using an updated baseline inventory of emissions including the addition of hydrocarbon emissions from trees and emissions of greenhouse gases.

A large number of sources contribute to the air quality pollution problem in the basin. Figures 2 and 3 show the relative contributions of emissions from each of the major categories of sources in 1987. For some pollutants, the emissions are overwhelmingly due to mobile sources. For other pollutants, ROG and NO_x, the precursors of ozone, the sources are more diverse (see for example, Table 1). The ozone and PM_{10} air quality problems cannot be solved by controlling any one category of sources alone. Substantial controls are needed on almost all of the categories of emissions to attain the standards.

The population of the basin is expected to increase by 37% by the year 2010. Emission forecasts for 2010 show that population growth and the associated increases in jobs (47%), housing (46%), and traffic (68%), will almost offset the effects of the emission controls adopted before 1988. Furthermore, the spatial pattern of emissions will change over the years, with a significant decrease in emissions in the western part of the basin and an increase in the eastern part. Computer modeling (the UAM) of air quality in 2010 without additional control measures indicates the maximum ozone concentrations will be 30 pphm or only 6 pphm lower than in 1987. The modeling results also suggest that areas experiencing the highest ozone level would shift eastward and would be larger than in 1987.

Table 1. Emissions of Ozone Precursors in 1987 (tons/day)

Source	ROG	NO_x
Residential	151	48
Commercial	220	97
Industrial	358	217
Transportation	646	846
Total Emissions	1375	1208

Clearly, the severity of the air quality problem in the Los Angeles Basin and the limitations of known technologies to solve the problem demand investigation of technical approaches and other novel means of improving air quality. For example, the SCAQMD has recently added urban tree-planting and light-colored surfaces to their list of mitigation measures for reducing air-conditioning energy usage. In this multiyear study both the direct and indirect effects of end-use efficiency measures on the reduction of smog formation are identified and evaluated. This study focuses on the indirect effects of trees and changes in surface albedo (white reflective surfaces) on atmospheric temperatures. Although causality has yet to be demonstrated conclusively, ozone levels in the basin (as in many other airsheds) appear to correlate with temperature (Kamens et al. 1982; Gery et al. 1987; Morris et al. 1989) suggesting that reduction of basin temperature could be beneficial to air quality by delaying or reducing smog episodes.

2.2 Urban Temperature Trends and Smog Formation

Because of its location at the ocean, the Los Angeles Basin derives its climatic features from its proximity to a major water body, especially from the presence of sea breeze circulation that is driven by thermal gradients from the cool coastal areas to the hot desert. The dispersion of pollutants follows this circulation. However, topography also plays an important role. The basin is defined by mountain ranges at the north and east. Being open only to the west and southwest on the Pacific Ocean, this area is commonly referred to as the Los Angeles or the South Coast Air Basin. The basin's topography is responsible for the poor air quality over that region, since it prevents advected air masses from effectively dispersing atmospheric pollutants.

Climatologists have found that urban temperatures have been steadily increasing, and that, in general, average monthly minima show the greatest rise (Goodridge 1987; Jones et al. 1989; Karl and Jones 1989). For example, the annual maximum (summer daytime) temperature in Los Angeles has risen by 0.75°C per decade. Figure 4 depicts a time series of downtown Los Angeles' annual maximum temperatures. It is speculated that the pre-1930 cooling trend shown in this figure was a result of evaporative cooling from expanding agricultural lands. After 1940, the warming trend was probably a result of increased urbanization and the destruction of vegetation around the civic center area, where the recording weather station is located. Because of the 4°C rise in peak summer temperature over the last 60 years (as shown in Fig. 4), the people of the Los Angeles Basin now pay an estimated extra $150,000 per hour on a hot day in utility costs just to compensate for this heating effect (Akbari and Rosenfeld 1990). Furthermore, an increased demand for cooling energy will result in additional emissions of photochemical smog precursors, such as NO_x, into the basin from power-generating plants located there.

The effects of urban warming are not just restricted to increased energy use or greater thermal discomfort, but also have implications on air quality. Higher urban air temperatures increase the rates of atmospheric chemical reactions that produce photochemical smog (solar radiation is the other limiting factor). It is known that tropospheric ozone levels are highest during warm and stagnant summer days. Data from smog chamber experiments suggest that high temperatures can increase ozone formation by affecting the rate at which ozone is photochemically generated from a given mixture of reactive hydrocarbons and NO_x.

In Figure 5, data from Los Angeles are presented in terms of maximum daily ozone concentrations in pphm versus daily maximum urban air temperatures (°C). The National Atmospheric Air Quality Standard (NAAQS) is shown as a horizontal line at 12 pphm. As shown in this figure, as long as the maximum temperature does not exceed 23°C, there are no unhealthy smog episodes. But at higher temperatures, ozone levels in Los Angeles exceed the NAAQS in almost a linear fashion. The regression line (broken) indicates that for each 1°C increase in maximum urban air temperature, ozone concentrations increase by ~0.13 pphm. The solid line in the figure represents the upper bound of the scatter.

Temperature can also affect other aspects of the emissions rates. Biogenic emissions from vegetation, such as isoprene and monoterpene are also sensitive to temperature. Research results suggest that a temperature increase can cause an increase in natural hydrocarbon emissions. Therefore, the temperature effect of solar radiation on natural volatile organic compounds (VOC) emissions, precursors to photochemical smog, can contribute significantly to urban ozone concentrations. In addition to its effect on natural VOC emissions, temperature also has a tangible impact on anthropogenic hydrocarbon emissions. For instance, it has been recognized that an increase in ambient temperature enhances the evaporative emissions of hydrocarbons from automobiles and other motor vehicles. Increases in ambient temperature would affect the formation of smog by the way of additional anthropogenic VOC emissions, especially in areas like Los Angeles, where traffic can be heavy.

This relationship between air temperature and smog episodes forms the basis for the various mitigation strategies (e.g., changes in surface albedo and massive tree-planting programs) that are investigated in this study. If urban air temperatures can be reduced through the implementation of these measures, then cooling energy use and NO_x emissions and VOC emissions from the transportation sector could be reduced and the incidence of photochemical smog formation could also be reduced or delayed.

We next provide a brief background on the three major study elements: end-use emissions, surface characteristics, and meteorological and air quality modeling.

2.3 Energy End-Use Emissions

The SCAQMD in cooperation with the California Air Resources Board (ARB) and the Southern California Association of Governments periodically develops a complete emissions inventory for the Los Angeles Basin (SCAQMD 1991). The two general categories of stationary sources included in the inventory are point sources resulting from one or more emission sources at a facility with an identified location (e.g., power plant), and area sources consisting of many small emission sources for which locations are not specifically identified but for which emissions over a given area may be calculated using socioeconomic data (e.g., residential heaters). The existing emissions projection procedure relies upon a base-year inventory and projects future emissions from that base year. This projection method does not directly treat emissions from fuel combustion as a byproduct of energy demand but rather as a product of economic activity. The linkage between energy demand and emissions must be established in these procedures so that end-use efficiency improvements can be included in the analysis.

In a recent report, Jaske (1990) described the California Energy Commission's (CEC) efforts to integrate the emission projections and energy-demand forecasting models. Using this approach, air pollution emissions (e.g., reactive organic gases, nitrogen oxides, and carbon dioxide) from stationary fuel combustion sources were projected by end-use. This paper (Jaske 1990) also identified the need for additional research within the basin to improve the current SCAQMD/ARB method of projecting emissions for fuel combustion sources, improve our understanding of stationary fuels usage within the SCAQMD region, and resolve ambiguities regarding the correlation of fuel combustion and emissions.

2.4 Surface Characteristics

Two important energy efficiency strategies that can modify the surface characteristics of the Los Angeles Basin, reduce temperatures, and reduce cooling energy demand are changes in surface albedo (reflectance) and trees. For the past several years, researchers at the Lawrence Berkeley Laboratory have worked with numerical models of urban climate to identify site-specific and urban-scale design modifications that would reduce the energy consumption in conditioning buildings (Huang et al. 1987; Akbari et al. 1988; Taha et al. 1988). These studies focused on predicting the ability of changes in surface albedo and vegetation to reduce cooling of the urban climate. Energy savings were calculated by coupling a numerical model of the thermal performance of buildings with urban-climate models (Martien et al. 1989a). Preliminary analysis in these studies has demonstrated that by simulating a change in overall surface albedo of the city of Sacramento, California, from an existing 10-15% to a "whitewashed" 40%, peak cooling demand will drop by 60% (Taha et al. 1988).

In addition to albedo modifications, strategic planting of shade trees (Akbari et al. 1986; 1987; 1988) can change the surface roughness of large urban airsheds. A tree-planting program in the basin can have additional secondary air quality benefits in terms of reducing electricity demand for residential cooling (Parker 1983; Huang et al. 1987), with concomitant reduction in NO_x emissions from in-basin generating facilities, as well as providing enhanced surface area for removal of coarse and fine particulate and labile air pollutants, such as ozone and peroxyacetylnitrate (PAN) and nitric acid (HNO_3) by surface deposition. Apart from these regional considerations, tree-planting programs have also been increasingly advocated as a means for sequestering carbon on a sufficient level to aid in reducing the accumulation of carbon dioxide in the global atmosphere, thereby also reducing the warming of the earth's atmosphere.

A comprehensive evaluation of the beneficial effects of trees as energy-efficiency strategies must also include a study of the effects of biogenic emissions from various tree species. For example, it is well established (Zimmerman 1979; Tingey et al. 1979; 1980; Evans et al. 1982; Lamb et al. 1985; Zimmerman et al. 1988; Winer et al. 1983; 1989; 1992) that many species of vegetation, including coniferous and deciduous trees, emit VOC, and more than 70 such compounds have been identified as emissions from ornamental, agricultural, and natural plant species (Isidorov et al. 1985; Winer et al. 1989; 1992).

Most, if not all of these compounds can, in the presence of sunlight and oxides of nitrogen (NO_x), lead to the formation of photochemical air pollution in the lower troposphere, with attendant manifestations of ozone formation, gas-to-particle conversion, and visibility impairment (Seinfeld 1989). Indeed, laboratory studies have shown that isoprene and monoterpenes are highly reactive compounds under tropospheric conditions (Killus and Whitten 1984; Winer et al. 1984; Atkinson and Carter 1984; Atkinson et al. 1986; 1988) and recent computer modeling studies, using isoprene as a surrogate for biogenic non-methane hydrocarbons, have shown that vegetative emissions may play important roles in the production of ozone in urban (Chameides et al. 1988) and rural (Trainer et al. 1987a) areas, and in the chemistry of the lower troposphere (Trainer et al. 1987b; Jacob and Wofsy 1988).

2.5 Meteorological and Air Quality Modeling

Accurate characterizations of the physical processes occurring close to the ground are crucial in linking changes in surface albedo and vegetation to air quality in the Los Angeles Air Basin. The surface layer momentum, energy, and water balances are directly affected by changes in albedo and vegetation; in turn, these physical processes modify pollutant transport, dispersion, and deposition patterns. The only practical way to describe these cause-effect relationships and their influence on local meteorology is through mathematical modeling. Simple wind field models commonly in use today that rely on interpolation schemes are inappropriate because they are incapable of treating the fundamental physical processes of importance. Fortunately, prognostic meteorological models offer significant potential for quantifying the effects of changes in urban fabric and texture on meteorology and quality meteorology.

The CSUMM, developed by Pielke and associates, is well suited to estimate the effect on mesoscale airflow of anthropogenically-induced spatial variations in surface characteristics. In the "basic" version of the CSUMM, such variability can be represented through input of spatially-varying gridded fields of the following parameters: surface roughness, surface albedo, surface moisture availability, and subsurface soil characteristics (i.e., density, specific heat, and thermal diffusivity). Each of these parameters affects the surface heat balance; spatial variability of surface characteristics would be expected to generate spatial variability in atmospheric temperature, which in turn would generate mesoscale circulations similar to sea breezes (Ookouchi et al. 1984; Kessler et al. 1985; Avissar and Pielke 1989; Segal et al. 1989). Three-dimensional simulations of mesoscale airflow in the Los Angeles area are the basis for current CSUMM simulations (Ulrickson and Mass 1990). The results of these simulations serve as input to the UAM experiments.

The UAM is being used to assess the effects on the Los Angeles photochemical air quality of subregional surface modifications (increased albedo and massive tree planting) intended to reduce energy demand by reducing local low-level daytime temperatures. Decreased subregional temperature may affect the Los Angeles Basin meteorology, chemistry, gaseous deposition, and emissions in ways that will be accounted for in the UAM. The UAM will be used initially to determine its sensitivity to mixing heights (e.g., planetary boundary layer), low-level air temperatures, and vertical and horizontal wind speeds. Using the meteorological profiles that result from the modified surface conditions described above and gridded emissions of biogenic, building sector end-uses, and other anthropogenic sources within the basin, we will perform a preliminary assessment of the air quality effects of several strategies.

3.0 METHODS

In this section we describe the methods and data used in our analysis of new ways to improve air quality in the Los Angeles Basin. This description is organized into four sections (e.g., vegetation inventory, surface characteristics, etc.) corresponding to the elements of this study.

3.1 Vegetation Inventory

An initial attempt to quantify the biomass in the Los Angeles area was conducted by Winer et al. (1983) with support from the California Air Resources Board. The study used a combination of aerial photography (Brown and Winer 1986) and ground surveys, and provided the first estimate of vegetative biomass in the Los Angeles Basin. The 1983 study by Winer and co-workers became the starting point for a more recent investigation of the basin conducted by Horie et al. (1990). Through the use of aerial photography, Horie et al. divided the urban areas in the basin into areas of similar land use, designated as Urban Terrain Zones (UTZs). He identified 21 different UTZs identified in the Los Angeles Basin. Horie and co-workers next combined similar UTZs into the 14 Land Use Categories (LUC), shown in Table 2, composed of either single-terrain zones or combinations of them.

The vegetation type and amount found in each LUC was determined by low-altitude photography and field surveys. The low-altitude photographic flights divided the vegetation in the basin into trees, shrubs, ground covers, and lawns. The trees were then divided into four structural classes (conifers, broadleaf deciduous, broadleaf evergreen, and palms) with each structural class further subdivided into four size classes based on crown diameter (10 m, 5 m, 3 m, and 1 m). The species composition and area-to-volume conversions were determined by the ground survey. At least two field surveys were conducted in each LUC at locations chosen at random (Horie et al. 1990). The average leaf biomass for each UTZ (in kg hectare^{-1}) was determined through the use of species-specific vegetation data for each LUC and a biomass conversion factor developed by Winer et al. (1983).

The leaf biomass in each grid cell was determined from the area of the grid covered by each LUC multiplied by the average leaf biomass for that LUC. The final products of this survey were a gridded inventory of biomass in 5 km by 5 km grids and a listing of over 480 identified plant species found in the basin (see Fig. 6). This gridded inventory was utilized, along with an estimate of the emission rates for these 480 species, as an input into the air quality model (UAM). The vegetation biomass database developed by Horie et al. (1990) provided the initial estimate of the vegetative biomass in the Los Angeles Basin used in this study. The methods and results employed by Horie and co-workers have been extensively evaluated at the basin scale for accuracy and completeness.

Table 2. Land Use Categories in SoCAB[a]

Land Use Category	Specific Urban Terrain Zones	SoCAB Area (ha)	Percent
Close-set houses	Dc3, A3	160075	32.6
Open-set houses	Do3	32184	6.6
Close-set apartments	Dc2	23745	4.8
Open-set apartments	Do2	13108	2.6
Administrative and cultural	Do6	24079	4.9
City core/commercial highrises	A1,A2,Dc1,Dc8	5384	1.1
Recent commercial ribbons	Do1,Do5	9113	1.9
Old commercial ribbons	A5,Dc5	16208	3.3
Old industrial and storage	A4,Dc4	26400	5.3
Recent industrial and storage	Do4	28947	5.9
Freeways and other infrastructure	N/A[b]	8735	1.8
Open areas	N/A[b]	60687	12.4
Wooded areas	N/A[b]	8630	1.8
Natural areas[c]	N/A[b]	73469	15.0

[a] Taken from Horie et al. 1990.

[b] Freeways, open, wooded, and natural areas are classified as distinct zones.

[c] Natural areas are distinct from Open or Wooded areas by the absence of all human development.

The original charts used to identify the LUCs of the urban areas of the basin, which show the location and boundaries of all UTZs (as identified by Horie et al. 1990), were obtained (Ellefsen 1992). These data were input into a Geographic Information System (GIS) developed by Clark University (IDRISI). The GIS database allowed the overlay of other databases for the Los Angeles Basin (e.g., UAM grid coordinate system, elevation projection charts, albedo estimates, etc.) and the mathematical manipulation on grid cells of interest. The GIS was also used to develop and examine the massive tree-planting and albedo-modification scenarios. Finally, the format of the land-use data will be particularly useful in calculations of spatial distribution of vegetation, albedo, and roughness measurements.

3.2 Surface Characteristics

For this study we used values available from the literature and existing methods to estimate the most important surface parameters (albedo, moisture availability, and roughness length) needed as inputs to the meteorological simulations. Through a comprehensive literature search, we found, however, that measured data on surface conditions specific to the Los Angeles Basin were not available. Therefore, we developed first approximations of these surface parameters that will be refined in future years through the use of data from satellites, air-borne sensors, and *in situ* measurements.

An albedo database for the basin was developed using space-averaging of individual albedo values of surface components (LUCs). For each 5 km by 5 km grid cell, an effective albedo was computed by considering the individual albedo and area percentage of each and all land uses within a cell, using the following relationship:

$$\alpha_e = \frac{\sum A_i \alpha_i}{\sum A_i} \qquad (1)$$

where α_e is effective albedo, A_i is the surface area of component i, and α_i is its albedo. Major and minor land uses were equally considered in this equation. Preliminary meteorological simulations using the CSUMM were performed (and will be discussed below) using these albedo values. In developing the preliminary database, representative albedo values from several sources were examined and the most appropriate was assigned for each land-use category using the equation shown above. Table 3 lists some of these values. Note that albedo values presented in the literature are not generally given in terms of LUCs but rather in terms of land cover and surface types. We used our best judgment to assign appropriate albedo values to each LUC within the Los Angeles Basin.

In order to refine the albedo database and render the values more site-specific to the basin, we are currently evaluating albedo values from Advanced Very High Resolution Radiometer (AVHRR) satellite data. These satellite estimates will be compared to *in situ* measurements obtained during simultaneous overpasses. This calibration of satellite data with surface-based measurements will provide some validation to the values derived from AVHRR data. In addition, we plan to obtain comparable albedo measurements from pyranometers mounted on a low-altitude airplane that will be flown in various traverse paths across the Los Angeles Basin. The results of these measurements will provide the most comprehensive albedo database available anywhere in the country.

Table 3. Albedo Ranges and Selected Values

LUC	Albedo Range	Source	Value Used†
Close-set houses	0.08-0.20	Oke [1987], Sellers [1965]	0.16
Open-set houses	0.08-0.20	Oke [1987], Sellers [1965]	0.16
Close-set apartments	0.08-0.20	Oke [1987], Sellers [1965]	0.16
Open-set apartments	0.08-0.20	Oke [1987], Sellers [1965]	0.16
Admin/Cultural	0.08-0.20	Oke [1987], Sellers [1965]	0.16
City core	0.08-0.23	Threlkeld [1962], Kung et al. [1964]	0.14
Recent commercial	0.08-0.20	Oke [1987], Sellers [1965]	0.14
Old commercial	0.08-0.18	Threlkeld [1962]	0.14
Recent industrial	0.08-0.20	Oke [1987], Sellers [1965]	0.12
Old industrial	0.08-0.18	Threlkeld [1962]	0.12
Freeway/infrastructure	0.05-0.20	Oke [1974], Taha et al. [1992]	0.14
Open areas/parks	0.17-0.22	Taha et al. [1992]	0.20
Wooded areas	0.05-0.25	Wechsler & Glaser [1966]	0.20
Desert suburban	0.11-0.24	Kung et al. [1964]	0.15
Agricultural	0.18-0.25	Sellers [1965], Monteith [1973]	0.20
Grasslands	0.18-0.30	Monteith & Szeicz [1961], Taha et al. [1992]	0.20
Sagebrush	0.10-0.20	Sellers [1965]	0.15
Chamise Chaparral	0.15-0.20	Sellers [1965]	0.15
Chaparral	0.15-0.20	Sellers [1965]	0.15
Woodlands	0.15-0.22	Sellers [1965], Monteith [1973]	0.20
Pinyon pine/Juniper	0.10-0.20	Stewart [1971]	0.20
Forests	0.05-0.20	Sellers [1965], Monteith [1973]	0.18
Desert	0.15-0.45	Sellers [1965], Monteith [1973]	0.15

†Value used in equation (1) to generate effective albedos. We chose these values either as mid-points in the ranges at left or as most frequently used values in simulations and/or references.

Similar to the albedo input requirements in CSUMM, soil moisture content (or surface moisture availability) must be specified over each 5 km by 5 km cell in the model's domain. No site-specific soil moisture data of the type and resolution needed for this study was found in the literature. As with albedo, we used a linear averaging relationship to compute effective moisture availability in each grid cell. However, while albedo changes over time are relatively small, soil moisture content may vary significantly on a daily basis as well as through seasonal cycles. Rainfall amounts, surface, porosity, degree of soil compactness, and water table levels are factors that highly affect the soil moisture content of the same type of soil or land-use category. Therefore, in using the linear averaging technique, we are implicitly assuming that the variations in moisture availability due to these factors are negligible and that the values obtained are representative averages of them. This assumption is not realistic, but is the best method available short of actually measuring the soil moisture conditions within each LUC.

In Table 4 we show the soil moisture ranges for each LUC as described in the literature, including the value assumed in our study. However, it should be noted that these sources specify moisture content in terms of soil and vegetation types, not in terms of land use as required in this study. Also, the vertical profile of soil moisture is highly variable (i.e., soil moisture content is a function of depth). In later phases of this study, we plan to improve the current database of soil moisture values by developing a more accurate approximation method and by finding more representative values corresponding to each type of ground cover. We also may perform limited measurements to determine the soil moisture content of the most representative land uses and soil types in the basin, e.g., parks/vegetation, commercial/downtown, and residential/suburban.

A preliminary surface roughness database for the Los Angeles Basin has been compiled. Based on the land-use classification developed by Horie et al. (1990), the surface structure in each of the grid cells throughout the basin was characterized. The land-use types were classified into 23 LUCs, of which 10 are for built areas (e.g., houses and commercial buildings) and 13 are for non-built areas, such as freeways, open or wooded areas, and natural areas. For each of the 23 LUCs, a minimum possible, maximum possible, and recommended value were chosen for surface roughness values. The selection of the assumed values was based on an extensive literature review of suggested roughness length estimates and the degree of correlation between the literal description of land-use types in published literature and the "standardized" land-use descriptors, LUCs.

By using two of several possible combination techniques, a cell-representative roughness length for each of the 5 km by 5 km gird cells was determined. The combination techniques include either averaging the roughness lengths (measured or taken from the literature) of various land covers to arrive at a cell-representative value or using linear combinations of sub-grid roughness lengths (Kondo and Yamazawa 1986). In later phases of this study, we may need to estimate roughness length through *in situ* measurements at specific representative locations.

3.3 Biogenic Emissions

Smog arises from a complex series of photochemical reactions involving a wide variety of hydrocarbons, including those biogenic emissions from vegetation and NO_x emissions from fuel combustion, and other sources. For the purposes of this study, we estimated the volatile hydrocarbons, primarily isoprene and various monoterpenes emitted from vegetation. In addition, for the air quality simulations, we will use existing emissions profiles available from the SCAQMD for other anthropogenic emissions (both point and area sources) and for mobile sources as input. These latter two emission profiles, however, were not modified or estimated in this study.

Table 4. Soil Moisture Ranges and Selected Values

LUC	Soil moisture range	Value used†
Close-set houses	0.08-0.20	0.10
Open-set houses	0.08-0.20	0.20
Close-set apartments	0.02-0.15	0.10
Open-set apartments	0.02-0.20	0.20
Admin/Cultural	0.02-0.10	0.10
City core	0.02-0.10	0.10
Recent commercial	0.02-0.10	0.10
Old commercial	0.02-0.10	0.10
Recent industrial	0.02-0.10	0.10
Old industrial	0.02-0.10	0.10
Freeway/infrastructure	0.01-0.08	0.05
Open areas/parks	0.01-0.40	0.40
Wooded areas	0.05-0.30	0.30
Desert suburban	0.03-0.26	0.05
Agricultural	0.12-0.32	0.30
Grasslands	0.01-0.40	0.30
Sagebrush	0.01-0.40	0.10
Chamise Chaparral	0.10-0.30	0.30
Chaparral	0.04-0.30	0.30
Woodlands	0.01-0.40	0.20
Pinyon pine/Juniper	0.05-0.30	0.30
Forests	0.05-0.30	0.30
Desert	0.03-0.26	0.05

†Value used in equation 1 to generate effective soil moisture values. We chose these values either as mid-points in the ranges at left, or as values most commonly used in simulations and/or references.

Three factors must be known in order to determine an estimate of the total vegetative hydrocarbons emitted for a specific region. First, a gridded estimate of the total biomass for the region must be determined. Second, vegetative ROG emissions (hydrocarbons) from the plants in the region must be estimated. Finally, in order to determine the daily inventory of these biogenic emissions, the environmental factors (e.g., temperature and light intensity) affecting these emissions must be identified and applied. A proper quantitative accounting of such factors is essential because the corresponding algorithms must be applied to all emission rates for all plant species.

Winer et al. (1983) produced the first estimate of biogenic emission rates for over 60 plant species within the Los Angeles Basin. An estimate of a total biogenic emission inventory required the determination of a specific emission rate for each of the species that were identified in the basin (Horie et al. 1990). The existing database of measured emission rates provided values for less than 20% of the species found in the basin. Therefore, a technique to estimate emission values for those species without measured emission rates was developed. This approach made use of the existing emissions database and supplementary information on phytochemistry and plant phylogeny (Siegler 1981; Charlwood and Charlwood 1991). It relied on the most current phylogenetic relationships among plant families (Woodland 1991).

The basic premise of this method is that, within broad qualitative ranges, species from the same family will have similar emission rates. There has been some recent phytochemical research that tends to support this hypothesis. For example, it has been established that only certain families of plants accumulate and store monoterpenes (Siegler 1981). There is also evidence indicating a predominance of monoterpene emitters among families found in Mediterranean climates (Ross and Sombrero 1991). These data seem to demonstrate that the highest level of organization that can be used to group plant emitters is at the family level. This has been the basis for our method of estimating the emissions from the majority of plant species found in the Los Angeles Basin.

The current research involving the environmental controls of hydrocarbon emissions from plants has demonstrated that temperature and light intensity appear to be the important factors for both isoprene and monoterpene emissions (Westberg and Rassmussen 1972; Tingey et al. 1979; 1981; 1987; 1991; Walter et al. 1989). The temperature dependence of these emissions is especially critical to the Los Angeles Basin where changes in daily and seasonal temperatures fall within crucial portions of the temperature response curves (see Fig. 7). For the purposes of this study, we chose the Guenther et al. (1991) algorithm, which was developed using the most modern emission-measurement techniques and research on the physiological basis of hydrocarbon emissions. We believe it will provide the best representation of the effects on monoterpene emission rates resulting from changes in temperature and on isoprene emission rates resulting from changes in temperature, light intensity, humidity, and carbon dioxide.

The existing gridded vegetative emission inventory (Causley and Wilson 1991) for the Los Angeles Basin was revised in two ways. The first revision dealt with the methodology of assigning emission rates to those species without measured emission rates using the phylogenetic rather than the morphological method. The second revision encompassed the change in the algorithm that accounts for changes in environmental factors. The modified Tingey (1979) algorithm used in compiling earlier estimates was replaced with the algorithm developed by Guenther and co-workers (1991). In sum, the vegetative biomass, biogenic emissions data, and environmental-correction algorithms were combined into a regional emissions inventory using a modified data management program (VEGIES) originally developed by SAI for the SCAQMD. The resulting gridded emissions inventory for vegetative hydrocarbons was calculated for each of three emissions databases: low-, mid-, and high-range estimates of hydrocarbon emissions for the plant species within the Los Angeles Basin. These data files will be used as input to the UAM for the air quality simulations.

3.4 Meteorological Modeling

A modified version of the CSUMM was used to predict meteorological variables such as air temperatures and wind speeds. The output from the meteorological model is useful in several ways. First, it can explicitly quantify the impact of surface modifications on meteorological variables. Second, the behavior of variables such as vertical wind speed and planetary boundary layer (PBL) height can serve as indicators of pollutant transport and diffusion. Finally, the output from the CSUMM can be used directly in a photochemical model to yield quantitative predictions of the impact of surface modifications on pollutant levels. The CSUMM is more fully described elsewhere (Mahrer and Pielke 1977; 1978; Arritt 1985; Kessler 1989).

For the two-dimensional simulations, the simulation domain consisted of 64 east-west grid cells and 22 vertical grid cells. The three-dimensional simulation domain uses 65 east-west cells, 40 north-south cells, and 22 vertical cells. The horizontal spacing is 5 km. The time step is 120 seconds for the two-dimensional simulations. For model stability, however, higher temporal resolution was required for the strongly heterogeneous three-dimensional simulations. In these cases, a time step of 30 seconds was used.

The general approach of the two-dimensional experiments was to determine the model's sensitivity to variations in several parameters at three horizontal scales of interest. These scales are domain-wide, subregional, and local. The parameters of interest were those that would be modified substantially by the increase of surface albedo and vegetation cover in the Los Angeles Basin. The three-dimensional experiments began with a base case that utilizes a database of LUCs to estimate surface characteristics in the basin. This base case mirrored, as closely as possible, the current surface conditions in the basin during a typical summer day. Topography, land/water boundary information, moisture availability, vegetation, substrate properties, surface roughness, and albedo were all allowed to vary from grid cell to grid cell.

The urban terrain zone database contained land-use information for each 5 km by 5 km grid cell in the domain. Each terrain zone had associated with it distinct values of the various surface characteristics as shown in Table 5. As mentioned previously, the values in this table were taken from various literature sources, which do not necessarily apply to the Los Angeles Basin. We also are currently using AVHRR satellite images to determine albedo and vegetative covers for each 5 km grid cell. After appropriate calibration of the albedo data with *in situ* measurements, these satellite estimates will replace the preliminary data obtained from the urban terrain zone database.

Most vegetation parameterizations for use in meteorological models are quite complex requiring a great deal of information on vegetation characteristics in the computational domain (Deardorff 1978). In addition, these parameterizations significantly increase the computational requirements of the model. In this study, we used a simpler approach. Clearly, the addition of vegetation directly modifies the surface albedo and roughness values. Furthermore, vegetation acts as a pump that extracts water from the root zone and evaporates it from leaf surfaces (evapotranspiration). As a rough approximation of these processes, we modeled them by simply augmenting the surface moisture available for evaporation through the use of an existing one-dimensional model that has a complete vegetation parameterization. From these simulations, we found that each percent increase in vegetation cover could be approximated by an increase of 0.004 in the moisture availability. Further investigation of this parameterization will be pursued in later phases of this study.

Out of a total of approximately 2600 individual grid cells, we limited the scope of our surface modifications by considering only grid cells that were composed of at least partially developed areas, that is, those areas that have been significantly modified by human activity. Of these selected grid cells, many already had a high albedo or high vegetation cover. We therefore used the urban terrain zone database to identify which of these cells had potential for significant modification. With the albedo case, we modified the appropriate grid cells (e.g., those with existing albedo less than 20%) by 15 percentage points. For the vegetation scenario, those grid cells that have vegetative cover less than 30% will be increased to 45%. The output from the three-dimensional simulations will serve as input to the photochemical model (UAM) to obtain quantitative estimates of the potential to reduce smog in the Los Angeles Basin through tree-planting and high albedo programs.

4.0 RESULTS

In this section the results generated during the first phase of this study are reported. We first present the effects of temperature on biogenic hydrocarbons from vegetation. Next, the results of the three-dimensional meteorological simulations are addressed. Finally, these results are discussed in light of their potential effects on air quality in the Los Angeles Basin.

Table 5. Terrain Zones and Their Characteristics*

TZ	Description	Alb	Rough (cm)	Swet	Sden (g cm^{-3})	Sdiff (cm^2 s^{-1})	Sspec (cal $g^{-1}K^{-1}$)
1	Close-set houses	0.18	40	0.15	1.5	0.0028	0.24
2	Open-set houses	0.15	30	0.25	1.6	0.0031	0.40
3	Close-set apartments	0.18	60	0.10	1.5	0.0030	0.22
4	Open-set apartments	0.15	50	0.20	1.6	0.0036	0.35
5	Admin/Cultural	0.15	50	0.10	1.6	0.0021	0.30
6	City core	0.20	150	0.15	1.6	0.0026	0.24
7	Recent commercial	0.14	50	0.15	1.6	0.0042	0.30
8	Old commercial	0.14	50	0.10	1.6	0.0042	0.30
9	Old industrial	0.18	75	0.05	1.6	0.0052	0.24
10	Recent industrial	0.14	75	0.10	1.6	0.0052	0.24
11	Freeway/infra.	0.15	5	0.03	1.6	0.0052	0.24
12	Open areas (parks)	0.18	15	0.50	2.4	0.0047	0.44
13	Wooded areas	0.20	50	0.30	2.0	0.0057	0.35
14	Desert suburban	0.20	10	0.05	2.0	0.0050	0.30
15	Agricultural	0.20	10	0.50	2.4	0.0038	0.44
16	Grasslands	0.20	5	0.30	2.0	0.0050	0.40
17	Sagebrush	0.15	10	0.05	2.0	0.0050	0.30
18	Chamise Chaparral	0.15	10	0.30	2.2	0.0026	0.35
19	Chaparral	0.15	10	0.30	2.2	0.0026	0.35
20	Woodlands	0.20	100	0.25	2.0	0.0057	0.35
21	Pinyon pine/Juniper	0.20	100	0.25	2.0	0.0057	0.35

*Compiled with data from Oke (1987), Seaman et al. (1989), Hjelmfelt (1982), and Stull (1988).

Alb= albedo
Rough= roughness length
Swet= moisture availability
Sden= soil density
Sdiff= soil diffusivity
Sspec= soil specific heat

4.1 Biogenic Emissions and the Effects of Temperature

Using the revisions and updates mentioned above to the previous work conducted by Horie et al. (1990) and Causley and Wilson (1991), we estimated vegetative hydrocarbon emissions within the Los Angeles Basin. These estimates are summarized in Table 6 and compared to the estimates from other previous work. The mid-range emissions summer inventory from this study is lower than the original estimate of Causley and Wilson (1991) by approximately 10 tons of hydrocarbon emissions per day. The lower summer emissions estimate can be linked to the revised inventory of species-specific emission rates. The database developed by Horie et al. (1990) and used by Causley and Wilson (1991) assigned emissions rates based on structural class, which were especially important for the Los Angeles Basin. This is a significant assumption because the majority of the biomass in the basin is due to shrubs (~60%) and most shrubs do not have measured emission rates. This study assigned emission rates based on phylogenetic relations, and many of the shrubs within the basin were assigned emission rates of zero, which decreased the overall emissions inventory estimate for the Los Angeles Basin.

Table 6. Hydrocarbon Emissions from Vegetation

Study	Summer (TPD)*	Winter (TPD)*
Winer et al. 1983**	25-80	
Causley & Wilson 1991	98	28
Current study		
High	105	35
Mid-range	90	27
Low	70	20

*TPD = metric tons per day

**This range represents approximately half of the geographic area of the basin.

The mid-range emissions winter inventory is approximately equal to the original estimate by Causley and Wilson (1991). The value of the estimate for the winter inventory in this study was influenced by the use of the Guenther algorithm (Guenther et al. 1991), which predicts higher isoprene emissions at lower light levels than did the previously used algorithm (Tingey et al. 1979). The daily gridded emissions inventory for vegetative hydrocarbons within the Los Angeles Basin was calculated for each of the three emission databases: low-, mid-, and high-range estimates of hydrocarbon emissions for the plant species in the basin. These data files will be used as input to the UAM for future air quality modeling.

In an attempt to determine the effects of a massive tree-planting program within the Los Angeles Basin, we estimated the potential emissions of vegetative hydrocarbons from an additional 10 million adult trees using the biomass database from Horie et al. (1990) and the Guenther et al. (1991) algorithm, which accounts for the effects of environmental factors such as temperature and light intensity. We found that about 40 TPD of biogenic emissions would result from this tree-planting scenario compared to total basin-wide emissions of about 2000 TPD. This calculation assumed that the tree species selected for planting were appropriately chosen to minimize biogenic emissions (i.e., low emitters) and to meet other important implementation considerations, such as water and maintenance requirements, planting space, and survivability. If one assumes that the air temperature within the basin can be reduced by 2-3°C from the effects of these additional trees and changes in surface albedo, this reduction in temperature can largely mitigate the biogenic hydrocarbons from these additional trees. For example, the present estimated isoprene summer inventory within the Los Angeles Basin is ~65 TPD and an additional 10 million trees would add about 35 TPD for a total of ~100 TPD. Our preliminary calculations suggest that a midday temperature reduction of between 2 and 3°C would result in a total isoprene emissions of ~65 TPD. Thus, the impacts of a massive tree-planting program, if species are properly selected, would be beneficial by reducing the existing air temperature and, at the same time, would not add to the present inventory of hydrocarbons from vegetation. These estimates should be considered as preliminary at this time. Additional experimental emission rate data are needed to support this finding.

One potential output from this multiyear study will be a list of recommended candidate tree species for massive tree-planting programs within the basin. Interest to date has focused on the potential ranking of tree species by emission rate factors only. However, policy recommendations based solely on emission rate factors would be premature. During the second phase of this work, a wide range of environmental factors, such as water use, spatial requirements, and potential for future fire hazard, that might influence the effectiveness of a major tree planting program in the Los Angeles Basin will be considered. Only after such an assessment has been performed can a recommended candidate list of trees be established based on both technical and practical considerations.

Several authors have also hypothesized that vegetation can improve the air quality of a region by removing both gaseous and particulate air pollutants (Smith and Dochinger 1976; Fowler et al. 1989; NRC 1991). An initial estimate of the pollutant-removal capacity of vegetation in the Los Angeles Basin was initiated last year. Quantification of the rates of pollutant-removal by vegetation is subject to significant uncertainties. The results of our initial literature survey suggest that for most pollutants, existing vegetation removes only a modest percentage of the atmospheric pollutants emitted into the basin.

Thus, improvement in air quality resulting from a massive tree-planting program is likely to be nominal when compared to the restrictions imposed by stringent emission-control strategies (SCAQMD 1991).

4.2 Meteorological Results

The goal of the three-dimensional meteorological simulations was to provide a detailed and realistic representation of the impact of surface characteristics in the Los Angeles Basin. A series of two-dimensional simulations were first completed and used as a scoping tool. For example, we concluded from the two-dimensional results that albedo modifications and moisture availability produced the most significant results, while surface roughness and substrate properties (e.g., density, diffusivity, specific heat) had little impact on local meteorology. These simulations produced useful and interesting results, but to study the actual meteorology in a topographically complex domain, we conducted three-dimensional simulations. Some of the major findings from these simulations are described below.

Although the CSUMM produces results at any specified time interval throughout the day, outputs were developed for specific simulation times (1200 and 1600 LST). The results at 1200 are useful in terms of understanding the formation of photochemical smog, while the afternoon results are useful in understanding the urban heat island.

A homogeneous surface base case simulation was first run to approximate the present state of meteorological modeling used by air quality scientists in the study of the Los Angeles Basin. Improvements were then made to this base case by using an approximation of the actual distribution of the various surface characteristics throughout the modeling domain. This approximation used the urban terrain zone database, which specifies the distribution of land use in each of the 5 km grid cells. In addition, representative values of surface characteristics were assigned to each terrain type as described above. This improved base case, which we compared to all other cases, is termed the heterogeneous surface case.

The heterogeneous surface case demonstrated the impact of topographical variations and coastal proximity on wind speeds and temperatures. In Figure 8 a map of the terrain contours (contours every 300 m) is provided for clarification. At 1200 LST the sea breeze is well developed with a peak horizontal velocity of 3.99 m s^{-1}. The wind vectors in Figure 9 demonstrate the strong influence topography and surface characteristics have on the wind field. At 1600 LST low-level wind speeds varied across the modeling domain from a low value of 0.1 m s^{-1} to a high value of 7.3 m s^{-1}.

In comparing the air temperature results for the homogeneous and heterogeneous surface cases, we found that at 1200 LST, the low-level air is cooler in the heterogeneous case by an average of 0.48°C. The total range of temperature differences between these two cases was from +0.30 to -2.90°C.

These temperature differences are a direct result of using the urban terrain zone surface characteristics. At 1600 LST the average temperature difference between the two cases was -0.44°C. The corresponding range of temperature differences was from +0.70 to -3.20°C. If the analysis was restricted to several cities of interest (e.g., Los Angeles, Anaheim, and Riverside), air temperatures would vary by as much as 5°C in the late afternoon.

An important aspect of this study was to determine the potential for active mitigation of urban pollution through implementation programs and policies that seek to modify the existing urban surface in a positive way (tree planting and increased surface albedo). To meet this objective, mitigation scenarios were developed. Here we report on the results of one such scenario: namely a "moderate" increase in albedo by up to 0.15. Although the potential modification for the Los Angeles Basin may actually be much higher than 0.15, we made a conservative estimate based on other published data for California cities (Martien et al. 1989b). The resulting geographical distribution of albedo modification was concentrated in and around downtown Los Angeles, as depicted in Figure 10. Out of a total of 2600 grid cells in the domain, only 410 were marked for albedo modification. The mean of the albedo modification was 0.08, but the majority of modified cells had their albedo modified by less than 0.05 or more than 0.10. The average modification, considering all 2600 cells of the modeling domain, was only 0.012.

The results of this albedo scenario when compared to the heterogeneous base case were quite remarkable. For example, the domain-wide wind speeds were decreased substantially in the morning (from 3.99 m s^{-1} to 1.75 m s^{-1} at 1200 LST) and only slightly in the afternoon. The average depression in wind speed was found to be 0.029 m s^{-1} (see Fig. 11). Furthermore, the PBL (mixing layer) heights were depressed over the modified areas by as much as 100 m. The decrease in both wind speeds and in PBL heights has a potential negative impact on air quality by reducing mixing and advection. On the other hand, the air temperatures over the modified areas were depressed by 1 to 2°C, with an average domain-wide reduction of 0.91 and 0.65°C at 1200 and 1600 LST, respectively. In Figure 12 we show the range of temperature depressions at selected locations within the basin. This decrease in air temperatures has a positive impact on air quality by lowering the rate constants for the photochemical reactions. The net effect on smog formation, however, can only be evaluated through simulations, which are currently being undertaken, using an air quality model (UAM).

4.3 Potential Effects on Air Quality

The overall goal of this study is to improve the air quality, especially the formation of photochemical smog, using new and innovative ways that are both direct and indirect. The direct methods involve reductions in end-use emissions from fuel combustion for cooling buildings. Through improvements in energy efficiency (e.g., equipment efficiency and conservation measures such as improved insulation or glazings), NO_x can be reduced. These reduced-emission profiles should provide fewer precursors for the formation of ozone and other smog-forming chemicals and thus reduce the episodes of smog within the Los Angeles Basin. Since fuel combustion NO_x emissions from the buildings sector in the basin represent only about 12% of total emissions and some of these are emissions during the winter months due to space and water heating, this strategy would not be expected to mitigate the existing smog conditions to any great extent. Therefore in this study we emphasized the so-called indirect effects resulting from changes in important surface characteristics.

The surface modifications that were considered in this study included changes in surface albedo, moisture availability, roughness, and substrate properties. In particular, increased albedo from whitening urban surfaces and moisture availability from a massive tree-planting program are expected to reduce air temperatures in the basin by as much 2-3°C. These reductions in air temperature, in turn, can have several effects that relate to air quality. First, they can reduce the need for energy use, especially in the summertime (air-conditioning loads) which will reduce the release of various pollutants, including NO_x, from in-basin power plants. Again, this reduction in emissions can lead to few smog precursors. In addition, reduced air temperatures can lower evaporative emissions of various reactive organic gases from both area-wide non-combustion and mobile sources. Although these evaporative emissions have not been considered in the current study, they may become an integral part of any future analyses.

The planting of additional trees (maybe as many as 10 million) within the basin will not only offer the potential for increasing surface albedo, moisture availability, and roughness, but it may contribute more biogenic hydrocarbon emissions. Since these emissions are affected by environmental factors such as air temperature and light intensity, it became important to accurately estimate the level of biogenic emissions that might be added to the basin. Our preliminary analysis suggests that the temperature reductions that can result from this increase in vegetative cover will offset their emissions if the selected plant species are chosen carefully.

Finally, this study addresses the effects of lower air temperature and changes in other meteorological conditions (e.g., wind speed, PBL heights) on the formation of smog. A relationship exists between temperature and smog formation as discussed earlier, but at this time, we have not yet quantified that correlation. Using the "modified" profiles of both end-use and biogenic emissions in conjunction with the "modified" local meteorological conditions, which result from changes in albedo and other surface characteristics, we expect in our future work to address this causal relationship. The temperature changes estimated in the three-dimensional meteorological simulations conducted to date strongly suggest that air quality mitigation strategies that include albedo modifications or increases in vegetative cover may effectively improve the air quality of the Los Angeles Basin. The comprehensive modeling effort using the UAM that is currently underway will answer this important question.

5.0 CONCLUSIONS

Several conclusions can be drawn from the first year's effort to investigate the effects of end-use efficiency on the reduction of photochemical smog in the Los Angeles Basin. However, it should first be noted that these conclusions are preliminary and they may be revised or expanded in subsequent phases of this study as the data and models are improved, and as the air quality simulations are performed.

We found from a review of existing emission-calculation procedures routinely used by the AQMDs in California that these methods do not allow for the consideration of end-use efficiency improvements. Therefore we conclude that new "models" are needed that can link energy efficiency to air emissions. In this regard, a new "model" was developed for estimating NO_x emissions from residential and commercial fuel combustion end-uses (space and water heating). This "model" allowed for the consideration of the effects of building age, building type (e.g., single-family and multifamily residential), climate variations, and energy efficiency. Using this "model," NO_x emissions were estimated for different end uses in the buildings sector. We conclude from this analysis that residential water heating offers the greatest opportunity for improving energy efficiency and reducing NO_x emissions. The implementation of cost-effective measures in the buildings sector may provide 15 to 20% reductions in the NO_x emissions. As this method is improved and expanded in the future, we will come closer to meeting the goal of developing better models and data for use by AQMDs. In addition, these new methods will help incorporate energy-efficiency benefits into air quality planning, regulatory, and policy decisions, and will demonstrate that energy-efficiency improvements in the buildings sector can be linked to improvements in basin-wide air quality.

Revisions were made to the methods used to assign hydrocarbon emission rates to those species of vegetation that to date were without measured emission rates. Using a phylogenetic relationship rather than a morphological one, hydrocarbon emission rates were assigned to 414 plant species within the basin. This procedure resulted in a reduction in the total inventory of biogenic emissions in the Los Angeles Basin, especially emissions from shrubs, which account for approximately 70% of the vegetative biomass. In addition, we also focused on the algorithm that accounts for changes in environmental factors, such as temperature and light intensity. Replacing the algorithm used in compiling earlier estimates with the Guenther algorithm increased the rate of isoprene emissions at lower temperatures and light intensities. Using these two revisions, several preliminary conclusions can be drawn with respect to the emissions of hydrocarbons from vegetation. First, vegetative emissions are not presently expected to contribute significantly to air quality problems within the Los Angeles Basin although additional experimental emission rate data are needed to support this conclusion. Second, hydrocarbon emissions from 10 million additional trees (if appropriately chosen) will be about 40 TPD compared to total basin-wide emissions of about 2000 TPD. Third, the reduction of air temperature by 2-3°C, resulting from additional trees and changes in surface albedo, would largely mitigate the biogenic emissions from these additional trees. Finally, although quantification of the rates of pollutant removal by vegetation is subject to significant uncertainties, the results of our survey suggested that for most pollutants, existing vegetation removes only a modest percentage of the anthropogenic pollutants emitted into the atmosphere of the basin. In the future, an array of physical and biological characteristics will be considered in developing a list of candidate trees for such a massive tree-planting strategy.

In order to accurately test the hypothesis that modifications in the surface characteristics can affect meteorological conditions (i.e., air temperature, wind speed, and mixing layer height) of the Los Angeles Basin, we needed to create a database of surface albedo, roughness, and moisture availability. In addition, a leaf biomass inventory was required for the basin in the appropriate format (5km by 5km grid cells). With the exception of the biomass inventory, no measured data specific to the basin exist in the published literature. Instead, using available published data for each surface variable (albedo, roughness, and moisture availability) by land-use category, we computed the surface characteristics for each grid cell through the use of linear averaging techniques. This analysis produced the first comprehensive database of surface characteristics for the basin. This database formed the base case conditions that were evaluated using a prognostic meteorological model. The vegetation biomass inventory selected for the study was that of Horie et al. (1990), which was previously developed for the Los Angeles Basin. These two databases will be used to develop preliminary mitigation scenarios (i.e., increased vegetation and surface albedo), since they can be used to identify the potential for increased tree planting and modifications to the surface albedo. The major conclusion drawn is that basin-specific data are lacking on most of the surface variables. Therefore in the future, we plan to improve these inventories through collection and analysis of data from satellites, airborne sensors, and on-site measurements. These data will meet a project goal of developing a credible and comprehensive database on surface characteristics that can be used in the subsequent meteorological simulations and can be employed by the local AQMD in its regulatory function.

Using the CSUMM we conducted two- and three-dimensional simulations to determine the sensitivity of local meteorology of the Los Angeles Basin to surface characteristics. These simulations employed the databases mentioned previously. Several conclusions can be drawn from this effort. First, we established that albedo modifications and moisture availability produced the most significant results. Surface roughness and substrate properties had little impact on local meteorology. From the two-dimensional studies, we found that increasing albedo or moisture availability reduced wind speeds by 10 to 20% and lowered air temperatures by as much as 5°C. Second, the effects of albedo or moisture availability were dependent on whether the modifications were assumed to be near the coast or inland. Increasing albedo or moisture availability near the ocean reduced the peak sea-breeze velocities, increased the penetration of the sea-breeze front, and reduced air temperatures. On the other hand, if these modifications were made inland, there was little impact on the developing sea-breeze, but they generated significant inland circulation patterns. From our three-dimensional results, we conclude that an increase of albedo in 410 grid cells (average 8% increase per cell) of 2600 total grid cells resulted in moderate impacts in terms of wind speeds and air temperatures. Specifically, domain-wide wind speeds were increased substantially in the morning and only slightly in the afternoon. Planetary boundary layer (PBL) heights were depressed over the modified areas by as much as 100 m. Air temperatures were depressed over the modified areas by 1 to 2°C, while domain-wide air temperatures were decreased by an average of 0.91 to 0.65°C at 1200 and 1600 LST, respectively. The decrease in air temperatures has a *positive* impact on air quality by lowering the rate constants of the photochemical equations. The decrease in PBL heights and wind speeds has a potential *negative* impact on air quality by reducing mixing and advection. Although these meteorological results show both *positive* and *negative* impacts on air quality, the net effect on photochemical smog formation can only be evaluated through simulations with a photochemical model such as UAM. These air quality simulations are currently being initiated. Furthermore, future meteorological simulations will benefit from the improved inventories of biogenic emissions and surface characteristics. If the overall effects are *positive*, novel and innovative ways to reduce photochemical smog will be available that can improve air quality without imposing additional emissions regulations.

6.0 ACKNOWLEDGMENTS

This work is supported by the California Institute for Energy Efficiency, Contract No. BG-90-080, through the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. The author also wishes to recognize the other members of the study team including Dr. Arthur Winer, UCLA; Dr. Robert Kessler, SAI; Dr. Hashem Akbari, Dr. Haider Taha, David Sailor, and Benson Huang from LBL. The editorial suggestions made by Ted Gartner and other reviewers are also greatly appreciated. The author was awarded the Daniel Luten Award by the Association of American Geographers (AAG) for the best paper in the Energy and Environment Specialty Group. He wishes to thank AAG for this honor.

7.0 REFERENCES

Akbari, H., Taha, H., Huang, J. and Rosenfeld, A. 1986. Undoing uncomfortable summer heat islands can save gigawatts of peak power. Proceedings of the ACEEE Conference, Santa Cruz, CA, August 1986, Vol. 2, pp. 7-22.

Akbari, H., Taha, H., Martien, P. and Huang J. 1987. Strategies for reducing urban heat islands: Savings, conflicts, and city's role. Proceedings of the First National Conference on Energy Efficient Cooling, San Jose, CA, October 21-22, 1987.

Akbari, H., Huang, J., Martien, P., Rainer, L., Rosenfeld, A. and Taha, H. 1988. The impact of summer heat islands on cooling and energy consumption and global CO_2 concentration. Proceedings of ACEEE 1988 Summer Study on Energy Efficiency in Buildings, Vol. 5, pp. 11-23, Asilomar, CA, August 1988.

Akbari, H. and Rosenfeld, A. 1990. Urban trees and white surfaces for saving energy and reducing atmospheric pollution. Testimony before the Subcommittee on Forests, Family Farms, and Energy of the Committee on Agriculture, U.S. House of Representatives, Serial No. 101-37, 7 June 1989, pp. 35-80.

Arritt, R.W. 1985. Numerical studies of thermally and mechanically forced circulations over complex terrain. Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins, CO.

Atkinson, R. and Carter, W. P. L. 1984. Kinetics and mechanisms of the gas-phase reactions of O_3 with organic compounds under atmospheric conditions. Chem. Rev., 84, 437.

Atkinson, R., Aschmann, S. M. and Pitts, J. N., Jr. 1986. Rate constants for the gas-phase reactions of the OH radical with a series of monoterpenes at 294 K. Int. J. Chem. Kinet., 18, 287.

Atkinson, R., Aschmann, S. M. and Pitts, J. N., Jr. 1988. Rate constants for the gas-phase reactions of the NO_3 radical with a series of organic compounds at 296 K. J. Phys. Chem., 92, 3454.

Avissar, R. and Pielke, R.A. 1989. A parameterization of heterogeneous land surfaces for atmospheric numerical models and its impacts on regional meteorology. Mon. Wea. Rev., 117, 2113-2136.

Brown, D.D. and Winer, A.W. 1986. Estimating urban vegetation cover in Los Angeles. Photogrammetric Engineering and Remote Sensing 52 (1):117-123.

Causley, M.C. and Wilson, G.M. 1991. Seasonal and annual average biogenic emissions for the South Coast Air Basin generated by the SCAQMD biogenic data base system, Final Report, Contract No. 90177, South Coast Air Management District, El Monte, CA.

Charlwood, B.V. and Charlwood, K. 1991. Terpenoid production in plant cell cultures, in <u>Ecological Chemistry and Biochemistry of Plant Terpenoids</u>, eds. J.B. Harborne and F. Tomas-Barberan. Oxford University Press, Cambridge, UK, 439 pp.

Chameides, W. L., Lindsay, R. W., Richardson, J. and Kiang, C. S. 1988. The role of biogenic hydrocarbons in urban photochemical smog: Atlanta as a case study. Science, 241, 1473.

Deardorff, J.W. 1978. Efficient prediction of ground surface temperature and moisture with inclusion of a layer of vegetation. Jour. Geophys. Res. 83 (4):1889-1903.

Ellefsen, R. 1992. Personal communication.

Evans, R. C., Tingey, D. T., Gumpertz, M. L. and Burns, W. F. 1982. Estimates of isoprene and monoterpene emission rates in plants. Bot. Gaz., 143, 304.

EPA 1985. Compilation of Air Pollution Emission Factors, Fourth Edition, AP-41. Supplements A (1986), B (1988), and C (1990). Office of Air Quality Planning and Standards, Research Triangle Park, NC.

Fowler, D., Cape, J.N., and Unsworth, M.H. 1989. Deposition of atmospheric pollutants over forests. Trans. Royal Society of London, Biology 324:247-265.

Gery, M.W., Edmond, R.D. and Whitten, G.Z. 1987. Tropospheric ultraviolet radiation: Assessment of existing data and effect on ozone formation. EPA Report 600/3-87/047, Environmental Protection Agency, Washington, D.C.

Goodridge, J. 1987. Population and temperature trends in California. Proceedings of the Pacific Workshop, Pacific Grove, CA. March 22-26.

Guenther, A.B., Monson, R.K., and Fall, R. 1991. Isoprene and monoterpene emission rate variability: Observations with Eucalyptus and emission rate algorithm development. Jour. Geophys. Res. 96 (10):10,779-10,808.

Hjelmfelt, M.R. 1982. Numerical simulations of the effects of St. Louis on mesoscale boundary-layer airflow and vertical air motion: Simulations of urban vs. non-urban effects. Journal of Applied Meteorology 21:1239-1257.

Horie, Y., Sidawi, S., and Ellefsen, R. 1990. Inventory of leaf biomass and emission factors for vegetation in California's South Coast Air Basin, Final Report, Contract No. 90163, South Coast Air Quality Management District, El Monte, CA.

Huang, Y. J., Akbari, H. and Rosenfeld, A. H. 1987. The potential of vegetation in reducing summer cooling loads in residential buildings. J. of Climate and Applied Meteorology, 26, 1103.

Isidorov, V. A., Zenkevich, I. G. and Ioffe, B. V. 1985. Volatile organic compounds in the atmosphere of forests. Atmos. Environ., 19, 1.

Jacob, D. J. and Wofsy, S. C. 1988. Photochemistry of biogenic emissions over the Amazon forest. J. Geophys. Res., 93, 1477.

Jaske, M.R. 1990. Air pollution projection methodologies: Integrating emission projections with energy forecasts. Proceedings of the ACEEE 1990 Summer Study on Energy Efficiency in Buildings, American Council for an Energy-Efficient Economy, Washington, D.C., pp. 4.87.

Jones, P.D., Kelly, P.M., Goodess, C.M., and Karl T. 1989. The effect of urban warming on the Northern Hemisphere temperature average. J. Clim. 2:285-290.

Kamens, R.M., Jeffries, H.E., Sexton, K.G. and Gerhardt, A.A. 1982. Smog chamber experiments to test oxidant-related control strategy issues. EPA Report 600/3-82/014, Environmental Protection Agency, Washington, D.C.

Karl, T. and Jones, P. 1989. Urban biases in area-averaged surface air temperature trends. Bull. Amer. Met. Soc. 70 (3):265-270.

Kessler, R.C., Eppel, D., Pielke, R.A. and McQueen, J. 1985. A numerical study of the effects of a large sandbar upon sea breeze development. Arch. Met. Geoph. Biokl., Series A, 34, 3-26.

Kessler, R.C. 1989. User's guide: Systems Applications Intl. Version of the Colorado State University Mesoscale Model, SAI Document, San Rafael, CA.

Killus, J. P. and Whitten, G. Z. 1984. Isoprene: a photochemical kinetic mechanism. Environ. Sci. Technol., 18, 142.

Kondo, J. and Yamazawa, H. 1986. Aerodynamic roughness over an inhomogeneous ground surface. Boundary Layer Meteorology 35:331-348.

Kung, E.C., Bryson, R.A. and Lenschow, D.H. 1964. Study of a continental surface albedo on the basis of flight measurements and structure of the earth's surface cover over North America. Monthly Weather Review 92:543-564.

Lamb, B.K., Westberg, H.H., Quaries, T. and Flyckt, D.L. 1985. Natural hydrocarbon emission rate measurements from selected forest sites. EPA Report 600/3-84/001, Environmental Protection Agency, Washington, D.C.

Mahrer, Y. and Pielke, R.A. 1977. A numerical study of the air flow over irregular terrain. Contr. Atmos. Phys. 50:98-117.

Mahrer, Y. and Pielke, R.A. 1978. A test of an upstream spline interpolation technique for the advective terms in a numerical mesoscale model. Monthly Weather Review 106:818-830.

Martien, P., Akbari, H., Rosenfeld, A. and Duchesne, J. 1989a. Approaches to using models of urban climate in building energy simulations. Proceedings of the Workshop on Saving Energy and Reducing Atmospheric Pollution by Controlling Summer Heat Islands (LBL-27872), Berkeley, CA, February 23-24, 1989.

Martien, P., Akbari, H., and Rosenfeld, A. 1989b. Light-colored surfaces to reduce summertime urban temperatures: Benefits, costs, and implementation issues. Proceedings of the 9th Miami International Congress on Energy and Environment, Miami, FL, 11-13 December, 1989.

Monteith, J.L. 1973. Principles of Environmental Physics. Edward Arnold, London.

Monteith, J.L. and Szeicz, G. 1961. The radiation balance of bare soil and vegetation. Quart. Jour. Roy. Meteor. Soc. 87:159-170.

Morris, R.E., Gery, M.W., Liu, M.K., Moore, G.E., Daly, C. and Greenfield, S.M. 1989. Examination of the sensitivity of a regional oxidant model to climate variations. In: The Potential Effects of Global Climate Change on the United States: Report to Congress, Eds: Smith, J.B. and Tirpak, D.A., Environmental Protection Agency, Washington, D.C.

NRC (National Research Council) 1991. Rethinking the Ozone Problem in Urban and Regional Air Pollution. National Academy Press, Washington, D.C., 489 pp.

Ookouchi, Y., Segal, M., Kessler, R.C. and Pielke, R.A. 1984. Evaluation of soil moisture effects on the induction and modification of mesoscale circulations. Mon. Wea. Rev. 112, 2281-2292.

Oke, T.R. 1987. Boundary Layer Climates. Methuen and Co., London.

Parker, J. H. 1983. Landscaping to reduce the energy used in cooling building. J. Forestry, 81, 82.

Ross, J.D. and Sombrero, C. 1991. Environmental control of essential oil production in Mediterranean plants, in Ecological Chemistry and Biochemistry of Plant Terpnoids, eds. J. Harborne and F. Tomas-Bareran. Oxford University Press, Cambridge UK, 439 pp.

SCAQMD 1991. Final 1991 Air Quality Management Plan, South Coast Air Basin, South Coast Air Quality Management District, El Monte, CA.

Seaman, N.L., Ludwig, F.L., Donall, E.G. and Warner, T.T. 1989. Numerical studies of urban planetary boundary-layer structure under realistic synoptic conditions. Journal of Applied Meteorology 28:760-781.

Segal, M., Schrieber, W.E., Kallos, G., Garratt, J.R., Rodi, A., Weaver, J. and Pielke, R.A. 1989. The impact of crop areas in northeast Colorado on midsummer mesoscale thermal circulations. Mon. Wea., Rev. 117: 809-825.

Seigler, D.S. 1981. Terpenes and plant phylogency, in Phytochemistry and Angiosperm Phylogeny, eds. D. Young and D.S. Siegler. Praeger Publishers, New York, NY 295 pp.

Seinfeld, J.H. 1989. Urban air pollution: State of the science. Science 243:745.

Seller, W.D. 1965. Physical Climatology. University of Chicago Press, Chicago IL.

Smith, W.H. and Dochinger, L.S. 1976. Capability of metropolitan trees to reduce atmospheric pollutants, in Proceeding of the Symposium on Better Trees for Metropolitan Landscapes. USDA Forest Service General Techn. Report NE-22.

Stewart, J.B. 1971. The albedo of a pine forest. Quart. Jour. Roy. Meteor. Soc. 97:561-564.

Stull, R.B. 1988. An Introduction to Boundary Layer Meteorology. Kluwer Academic Publishers, Norwell, MA.

Taha, H., Akbari, H. and Rosenfeld A. 1988. Residential cooling loads and the urban heat island: The effects of albedo. Building and Environment 23:271.

Taha, H., Sailor, D. and Akbari, H. 1992. High albedo materials for reducing building cooling energy use. Lawrence Berkeley Laboratory Report No. LBL-31721, Berkeley CA.

Threlkeld, J.L. 1962. Thermal Environmental Engineering. Prentice-Hall International, London.

Tingey, D. T., Manning, M., Grothaus, L. C. and Burns, W. F. 1979. The influence of light and temperature on isoprene emission rates from live oak. Physiol. Plant. 47:112.

Tingey, D. T. and Burns, W. F. 1980. Hydrocarbon emissions from vegetation. In: Proceedings, Symposium on Effects of Air Pollutants on Mediterranean and Temperate Forest Ecosystems, Riverside, CA, June 22-27, and references therein.

Tingey, D.T., Evans, R.C. and M.L. Gumpertz 1981. Effects of environmental conditions on isoprebe emissions from live oak. Planta 152:565-570.

Tingey, D.T., Evans, R.C., Bates, E.H. and M.L. Gumpertz 1987. Isoprene emissions and photosynthesis in three ferns — the influence of light and temperature. Physiological Plantarum 69:609-612.

Tingey, D.T., Turner, D.P. and J. Weber 1991. Factors controlling the emissions of monoterpenes and other volatile organic compounds, in Trace Gas Emissions by Plants, eds. T.D. Sharkey, E. Holland, and H. Mooney. Academic Press, New York, NY, 365 pp.

Trainer, M. Williams, E. J., Parrish, D. D., Buhr, M. P., Allwine, E. J., Westberg, H. H., Fehsenfeld, F.C. and Liu, S. C. 1987a. Models and observations of the impact of natural hydrocarbons on rural ozone. Nature, 329, 705.

Trainer, M., Hsie, E. Y., McKeen, S. A., Tallamraju, R., Parrish, D. D., Fehsenfeld, F. C. and Liu, S.C. 1987b. Impact of natural hydrocarbons on hydroxyl and peroxy radicals at a remote site. J. Geophys. Res. 92, 1189.

Ulrickson, B.L. and Mass, C.F. 1990. Numerical investigation of mesoscale circulation over the Los Angeles Basin (in two parts), Mon. Wea. Rev., 118, 2117-2161.

Walter, J., Charon, J., Marpeau, J., and Launay, J. 1989. Effects of wounding on terpene content of twigs of maritime pine (*Pinus pinaster* Ait.). Trees 4:210-219.

Wechsler, A.E. and Glaser, P.E. 1966. Surface characteristics effect on thermal regime: Phase I, special report (88), U.S. Army CRREL, Hanover NH.

Westberg, H.H. and R. Rassmussen 1972. Atmospheric photochemical reactivity of monoterpene hydrocarbons. Chemosphere 1 (4):163-168.

Winer, A. M., Fitz, D. R. and Miller, P. R. 1983. Investigation of the role of natural hydrocarbons in photochemical smog formation in California. Final Report to California Air Resources Board, Sacramento, CA. Contract No. AO-056-32.

Winer, A. M., Atkinson, R. and Pitts, J. N., Jr. 1984. Gaseous nitrate radical: Possible nighttime atmospheric sink for biogenic organic compounds. Science, 224, 156-159 (1984).

Winer, A.M., Arey, J., Aschmann, S., Atkinson, R., Long, W. D., Morrison, L. C. and Olszyk, D.M. 1989. Hydrocarbon emissions from vegetation found in California's Central Valley, Final Report to Air Resources Board Contract A732-155, November 30, 1989.

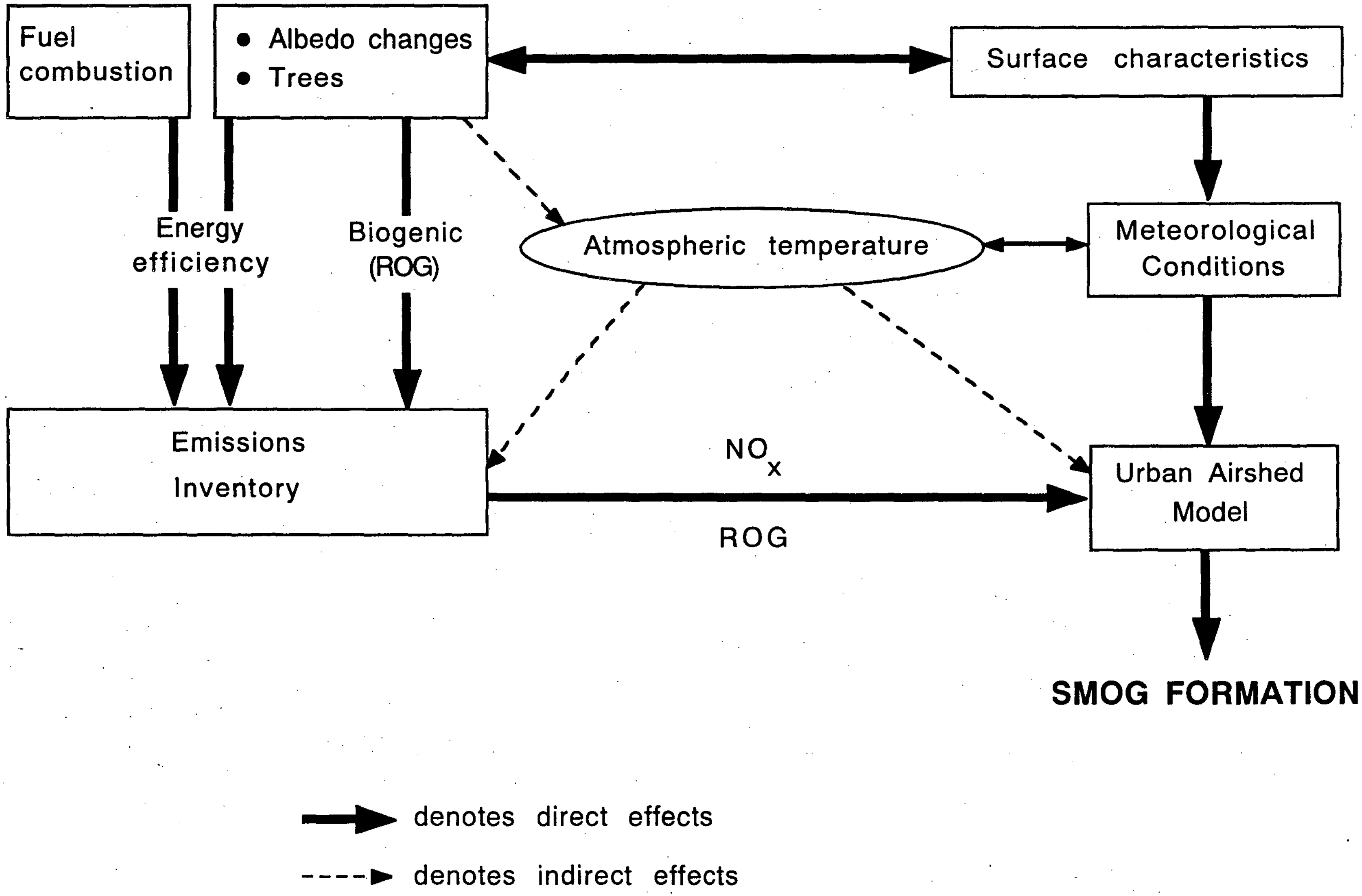
Winer, A.M., Arey, J., Aschmann, S.M., Atkinson, R., Long, W.D., Morrison, L.C. and Olszyk, D.M. 1992. Emission rates of organic compounds from agricultural and natural vegetation found in California's Central Valley. Atmospheric Environment 26A (14):2647-2659.

Woodland, D.W. 1991. Contemporary Plant Systematics. Prentice Hall Publishers, Englewood Cliffs, NJ. 582 pp.

Zimmerman, P. R. 1979. Tampa Bay Area Photochemical Oxidant Study: Determination of emission rates of hydrocarbons from indigenous species of vegetation in the Tampa/St. Petersburg, Florida, area. Final Appendix C, February 2, 1979. EPA 904/9-77-028.

Zimmerman, P. R., Greenberg, J. P. and Westberg, C. E. 1988. Measurements of atmospheric hydrocarbons and biogenic emission fluxes in the Amazon boundary layer. J. Geophys. Res., 93, 1407.

Figure 1 Direct and Indirect Ways to Improve Air Quality in the SoCAB



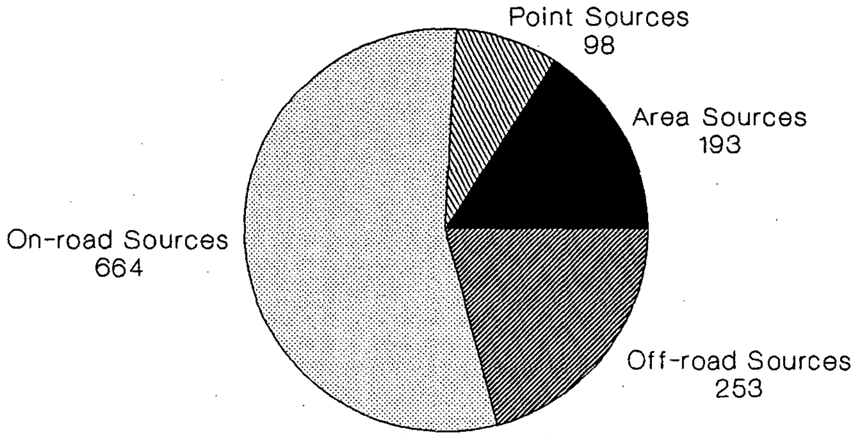


Figure 2 1987 NOx Emissions
Relative Contribution by Source

Total NOx: 1208 tons/day

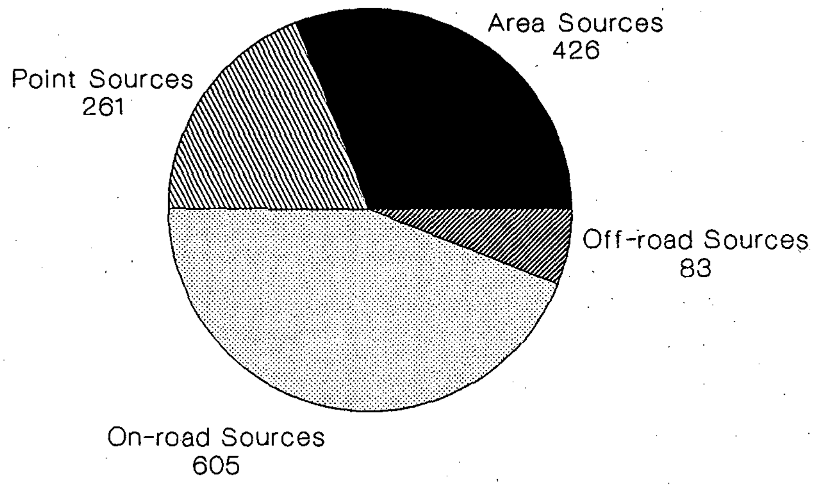


Figure 3 1987 ROG Emissions

Relative Contribution by Source

Total ROG: 1375 tons/day

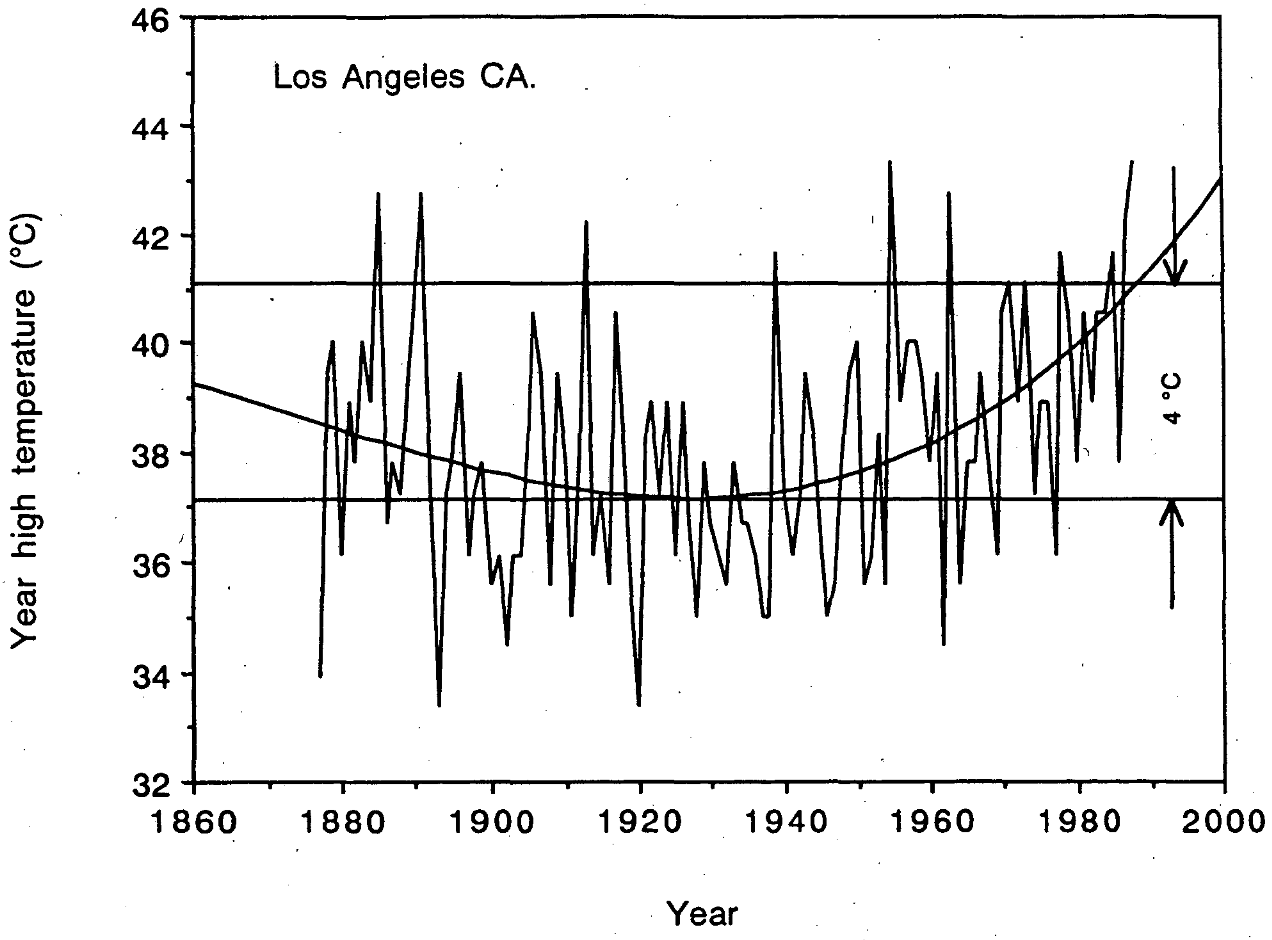
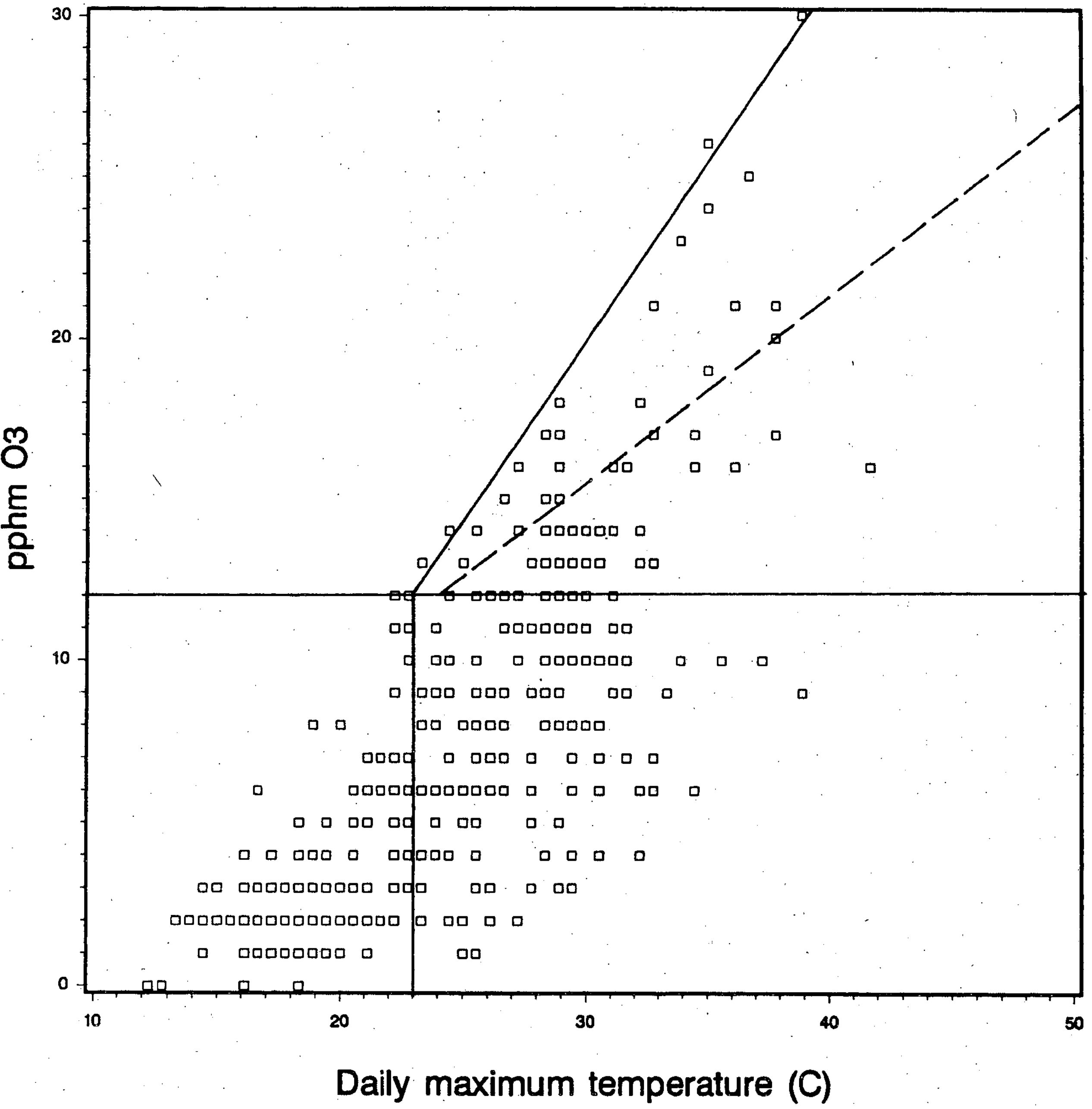


Figure 4. Annual maximum temperatures in downtown Los Angeles.
Based on data from LADWP.

Figure 5. Maximum daily ozone concentration in parts per hundred million (pphm) versus daily maximum urban air temperature (°C) for Los Angeles, 1985. NAAQS is shown as a horizontal line at 12 pphm. The regression line (dashed) indicates that for each 1°C increase in daily maximum temperature, the maximum daily ozone concentration increases by 0.6 pphm. The solid line shows the upper bound of the scatter.



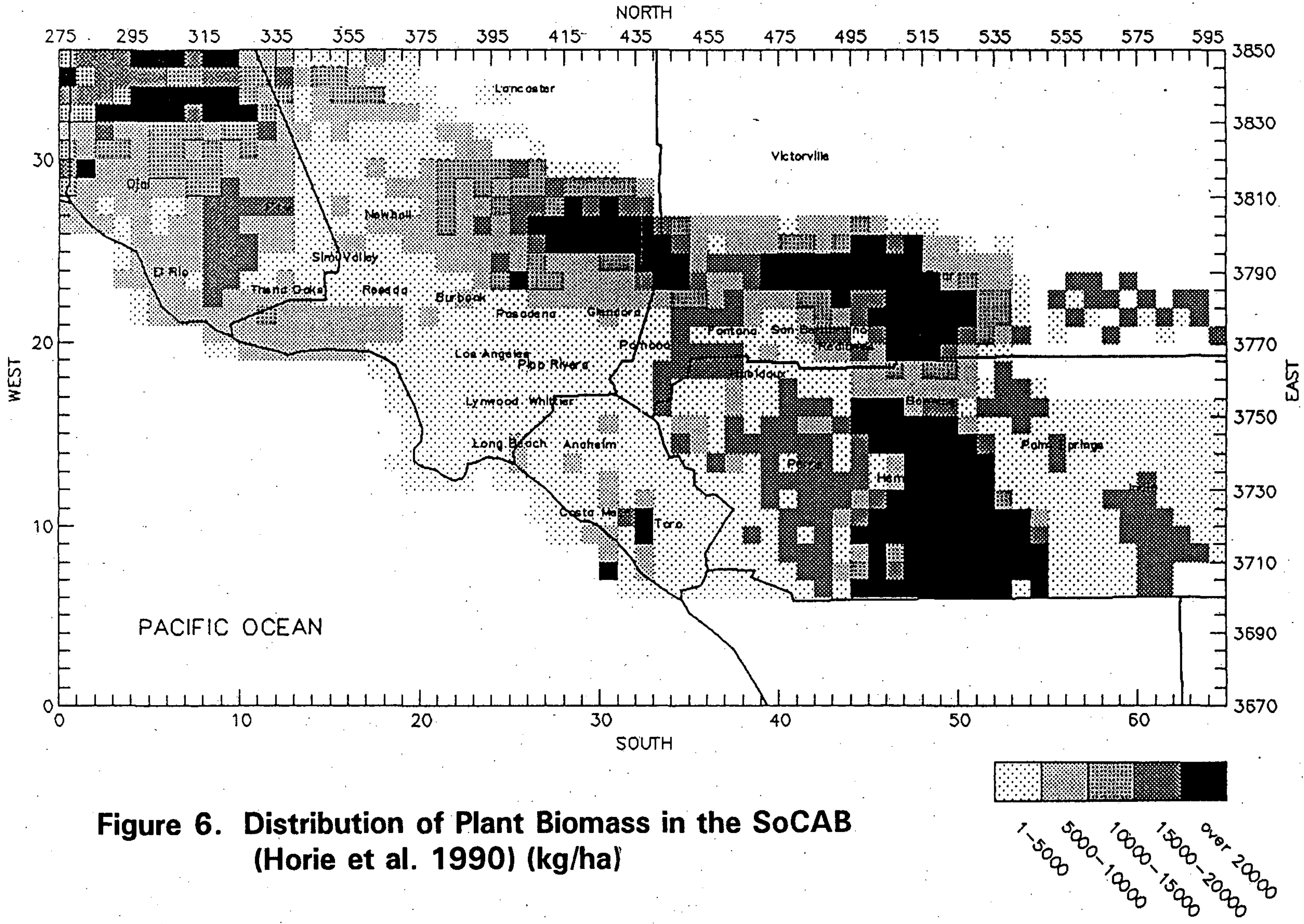


Figure 6. Distribution of Plant Biomass in the SoCAB (Horie et al. 1990) (kg/ha)

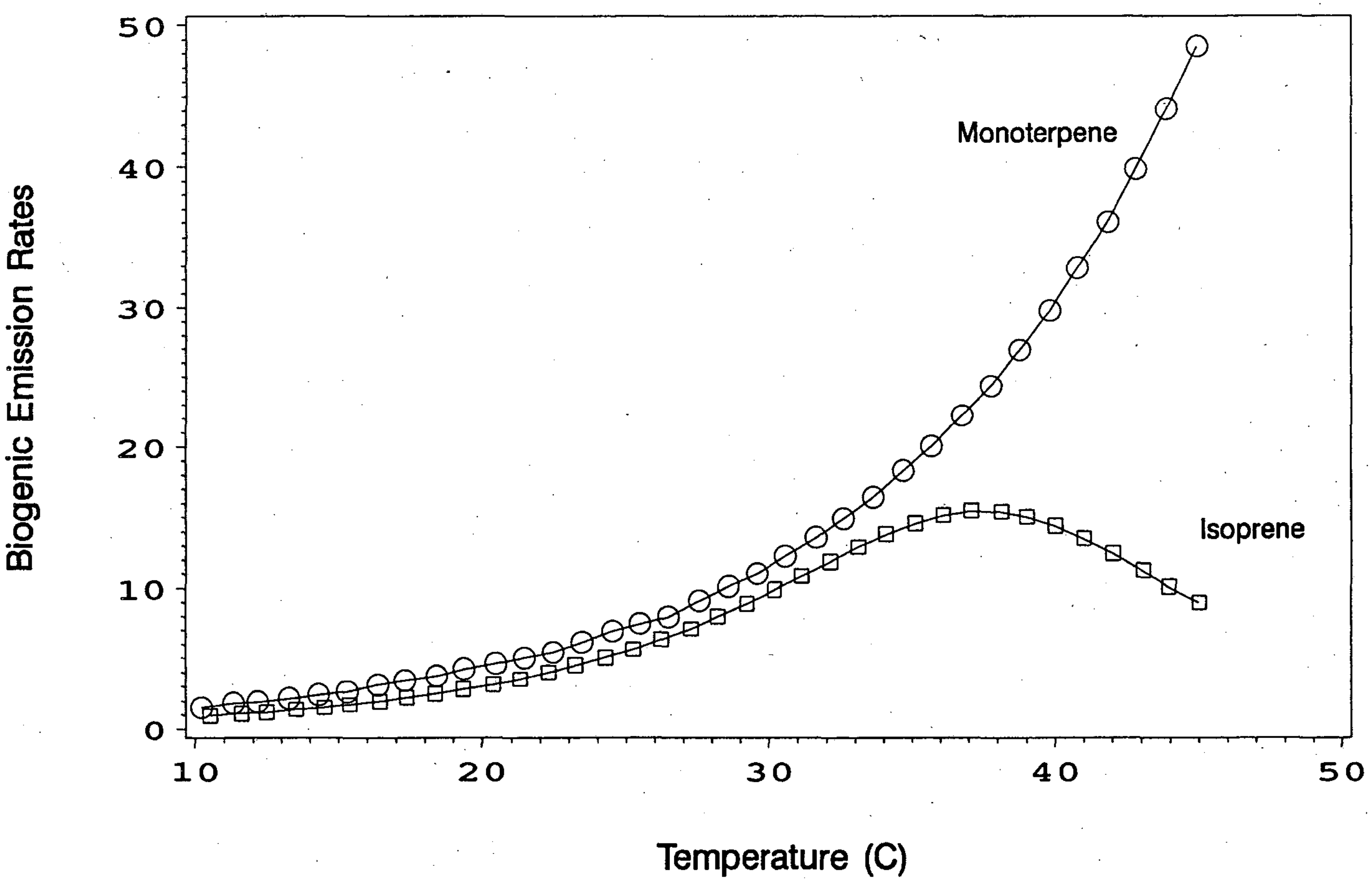


Figure 7. Temperature dependence of biogenic emission rates. From Guenther et al. (1990 and 1991).

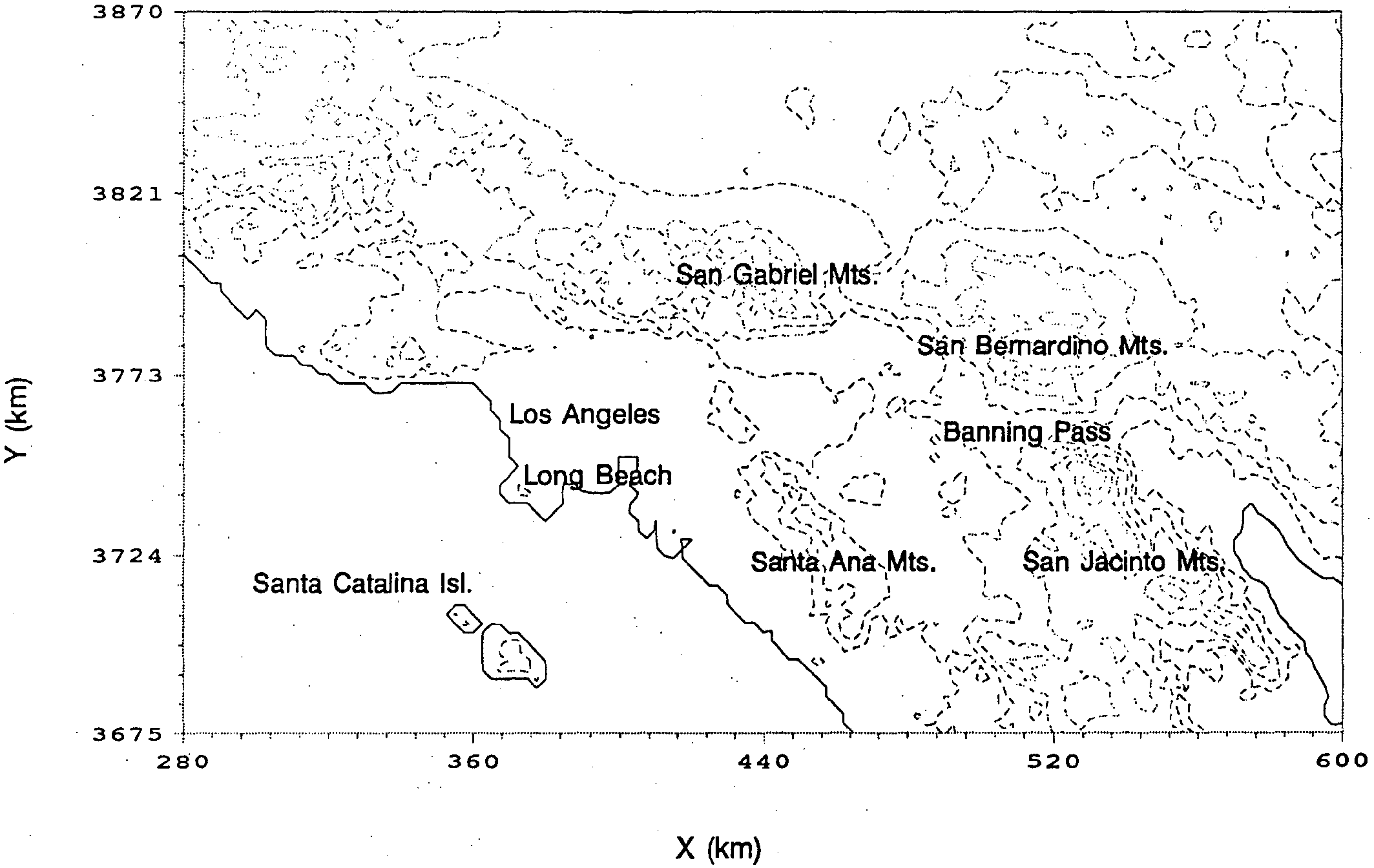


Figure 8. South Coase Air Basin (SoCAB) modeling domain. Terrain contours are every 300 m.

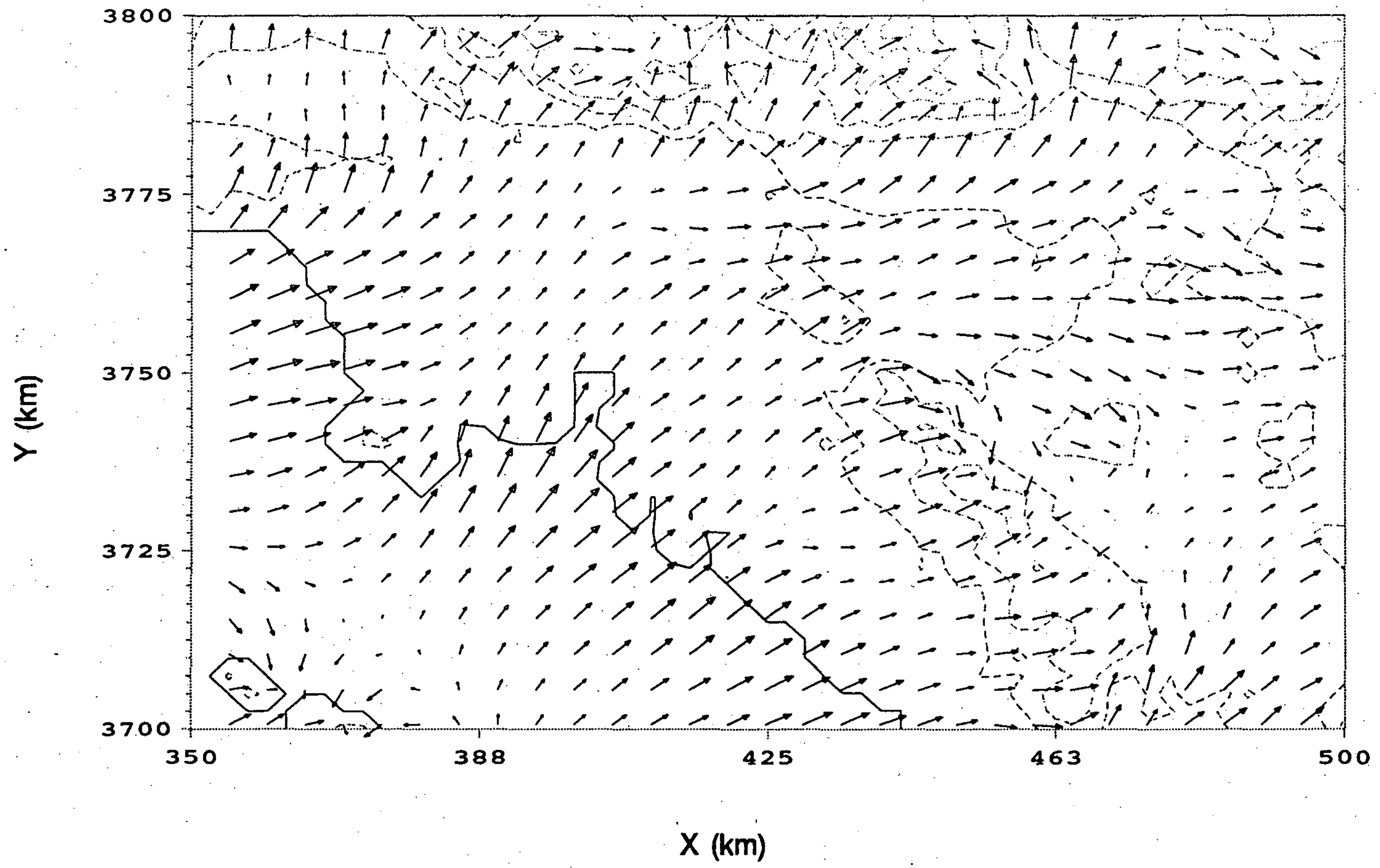


Figure 9. Level horizontal wind vectors for the heterogeneous base case simulation at 1200 LST. Peak velocity is 3.99 m/s.

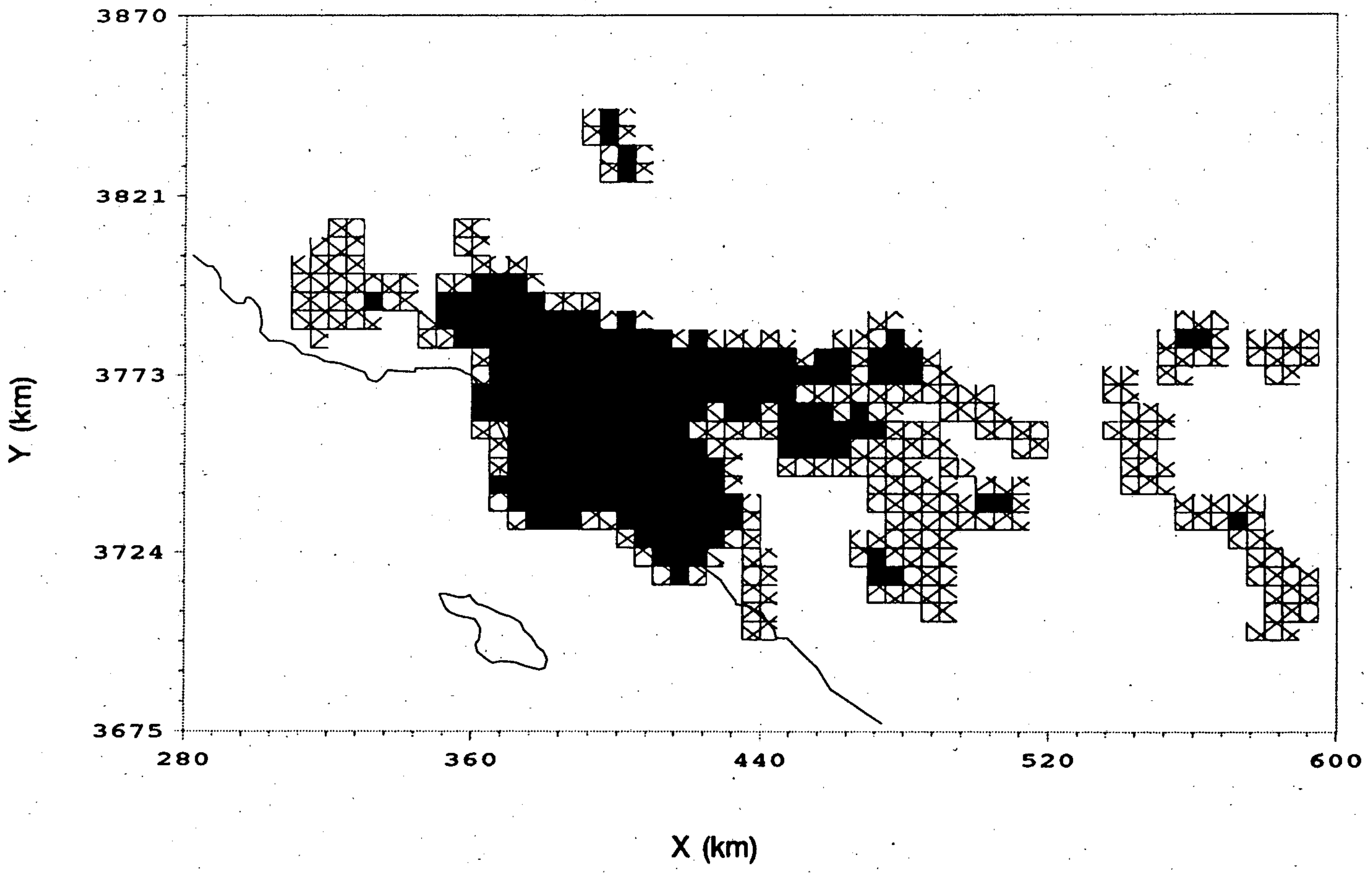


Figure 10. Albedo modification areas. Hashed regions represent modified grid cells. Solid regions are cells where the modification exceeds 0.10

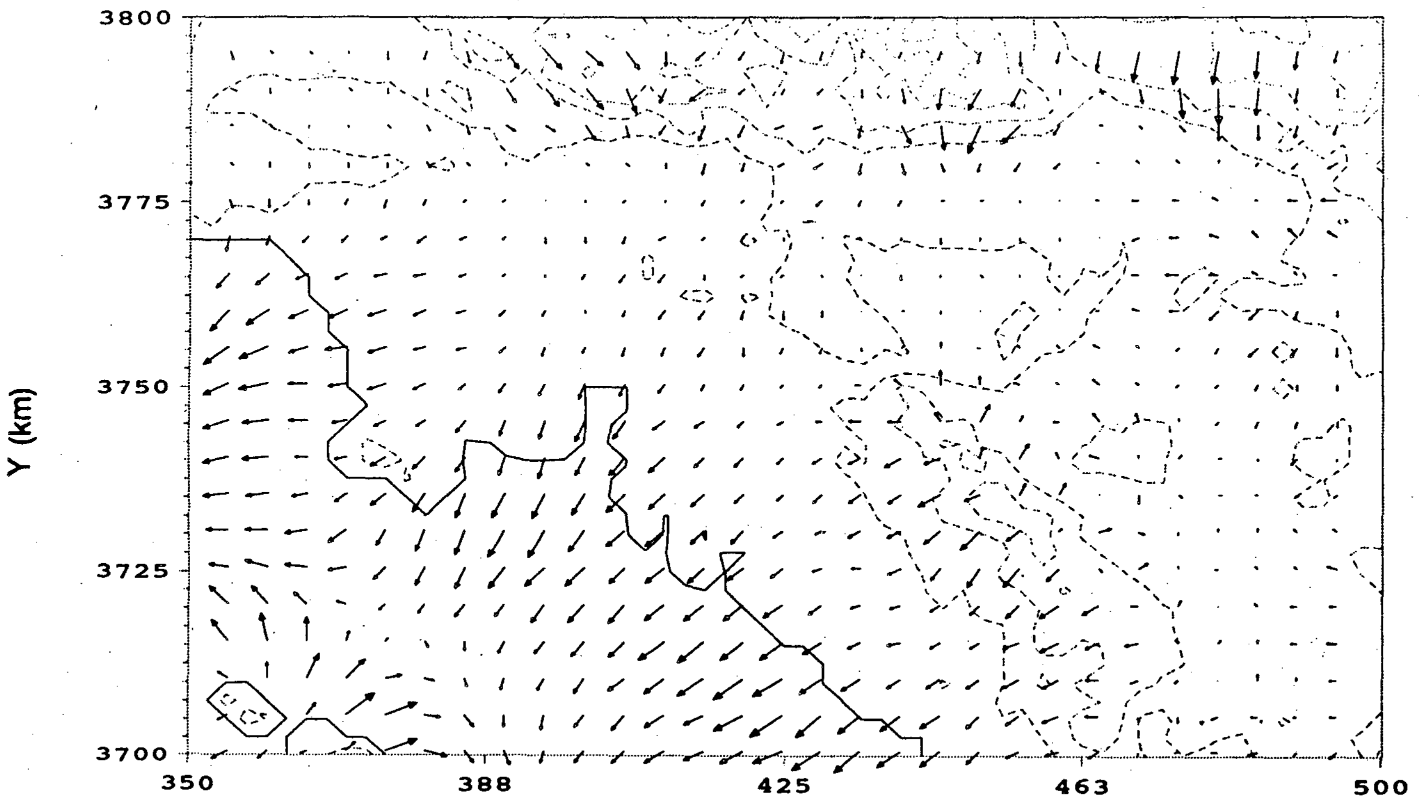


Figure 11. Low-level velocity difference vectors between the albedo modification case and the heterogeneous base case. The peak velocity difference is 1.75 m/s.

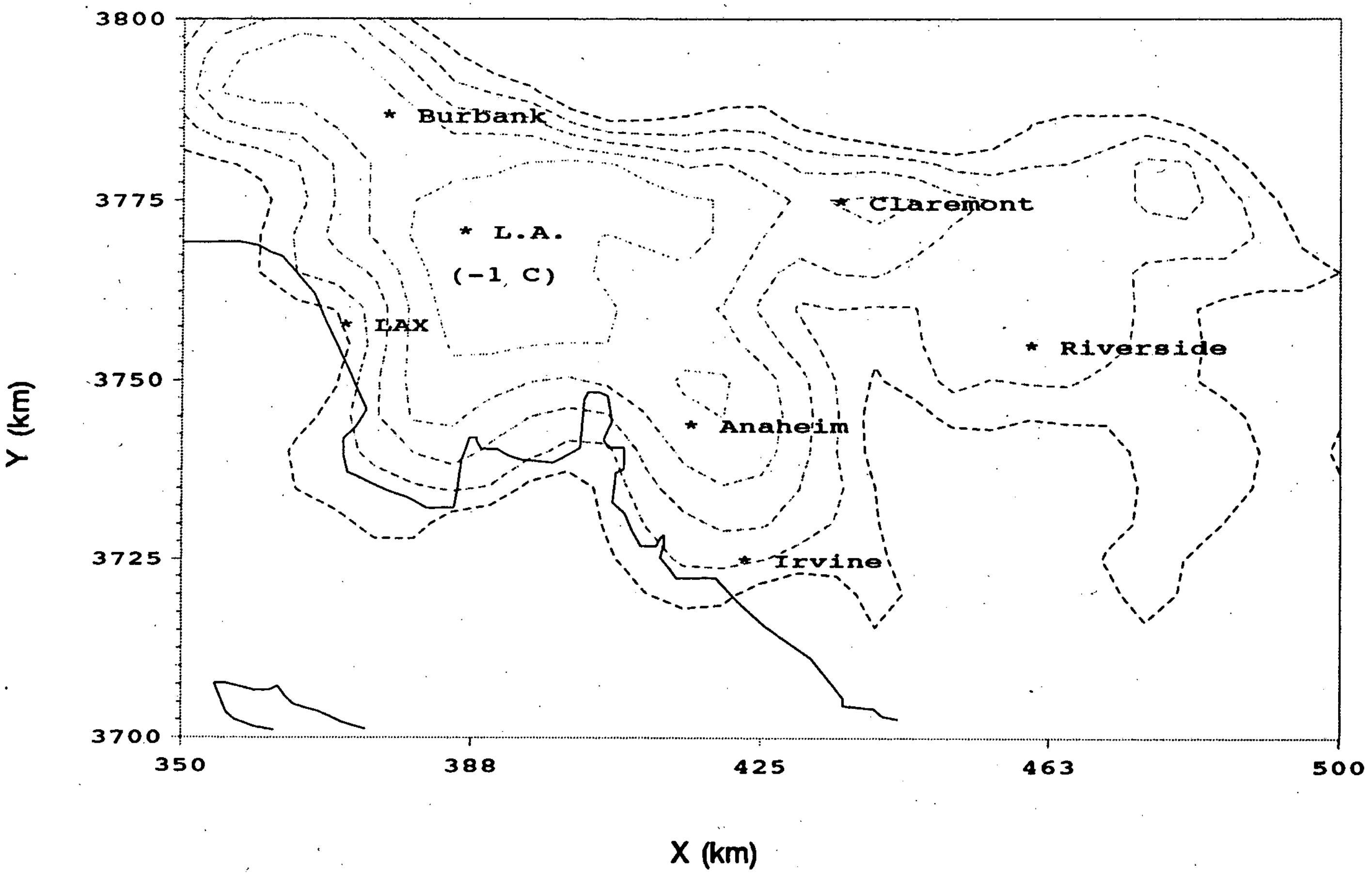


Figure 12. Low-level air temperature difference contours. Temperature for the albedo modification case minus temperature for the heterogeneous base case. Contours are from -0.2 to -1.0 Celsius.

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
TECHNICAL INFORMATION DEPARTMENT
BERKELEY, CALIFORNIA 94720