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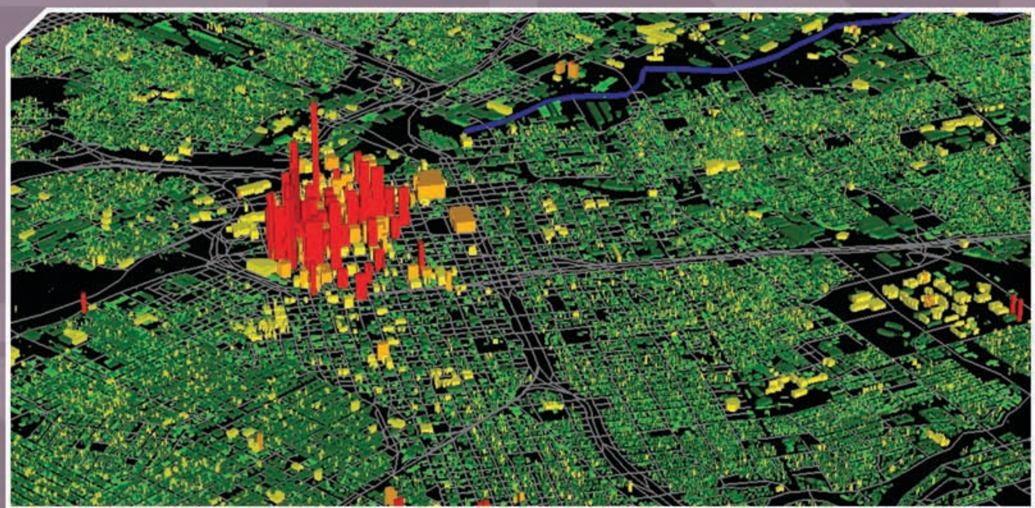

Office of Research and Development
National Exposure Research Laboratory, Atmospheric Modeling and Analyses Division

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Development of Gridded Fields of Urban Canopy Parameters for Advanced Urban Meteorological and Air Quality Models

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Notice

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Abstract

Urban dispersion and air quality simulation models applied at various horizontal scales require different levels of fidelity for specifying the characteristics of the underlying surfaces. As the modeling scales approach the neighborhood level (~1-km horizontal grid spacing), the representation of urban morphological structures requires much greater detail. To provide the most accurate surface characterization possible for an air quality modeling study of Houston, TX, airborne Light Detection and Ranging (LIDAR) data were obtained from TerraPoint LLC at 1-m horizontal grid cell spacing for Harris County, TX, an area of approximately 5800 km^2. The data were managed in the ESRI ArcView 3.3 and ArcGIS 8.2 GIS software packages. Scripts and computer codes were written in Avenue, Visual Basic for Applications, and Fortran to compute 20 urban canopy parameters (UCPs), including building height statistics and histograms, height-to-width ratio, plan area density function, frontal area density function, roughness length, displacement height, mean orientation of streets, and sky view factor. In addition, procedures were developed to approximate several UCPs that could not be determined from the elevation data, including surface cover type, building material fraction, and percent directly connected impervious area.

The modeling phase of the study involved applying an urban energy budget model, DA-SM2-U, the Penn State/National Center for Atmospheric Research Mesoscale Model (MM5), and the U.S. Environmental Protection Agency (EPA) Models-3 Community Multi-scale Air Quality (CMAQ) modeling system. To accommodate the modeler needs, area-weighted UCPs were defined for 82,368 1-km^2 grid cells corresponding to the DA-SM2-U, MM5, and CMAQ modeling domains. Phase I of the UCP computation project focused on a 1653-km^2 section centered on the downtown of the City of Houston. A building footprint data layer was developed and validated using 0.5-m horizontal resolution True Color orthophotos. Using the building footprint data layer refined by the aerial photos and the LIDAR data products, UCPs were calculated for the buildings only, the vegetation only, and the full canopy. The second phase of the project involved computing only full-canopy UCPs for the remaining 3589 km^2 of Harris County not included in Phase I. The third, and final, phase of the UCP computation project involved developing an accurate land use data layer for the 1653-km^2 Phase I study area, correlating the UCPs in the study area to the underlying land use, extrapolating building and vegetation UCPs to the 3589 grid cells in the Phase II study area, and extrapolating all UCPs to the 77,126 grid cells outside of the Phases I and II study areas. In total, the results spreadsheets accompanying this report contain approximately *84 million UCP values.*

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Nomenclature

α	empirical coefficient for Macdonald morphometric roughness equations
β	correction factor for the drag coefficient
Δz	height increment
λ_f	frontal area index
λ_s	building height-to-width ratio
λ_w	building wall-to-plan area ratio
ψ_k	roughness sublayer influence function
ψ_{sky}	sky view factor
θ	wind direction
$\bar{\theta}_{LW}$	length-weighted mean orientation of streets
2D	two dimensional
3D	three dimensional
$A_{fb}(z)$	building frontal area density
$A_{fc}(z)$	canopy frontal area density
$A_{fv}(z)$	vegetation frontal area density
$A_{pb}(z)$	building plan area density
$A_{pc}(z)$	canopy plan area density
A_{proj}	frontal area of roughness elements projected into plane perpendicular to wind
$A_{pv}(z)$	vegetation plan area density
A_T	area of grid cell
$A_{tb}(z)$	building top area density
$A_{tc}(z)$	canopy top area density
$A_{tv}(z)$	vegetation top area density
C_D	drag coefficient
CD	compact disc
c_{dl}	parameter in Raupach morphometric roughness equations
CMAQ	Community Multi-scale Air Quality
COH	City of Houston
c_R	drag coefficient of an isolated roughness element mounted on the surface
CRE	cumulative relative error
c_s	drag coefficient for the substrate surface at height $\bar{h}$
CTG	composite theme grid
DCIA	directly connected impervious area
DEM	digital elevation model
DTM	digital terrain model
EPA	U.S. Environmental Protection Agency
ESRI	Environmental Systems Research Institute
GIRAS	Geographic Information Retrieval Analysis System
GIS	geographic information system
$\bar{h}$	mean height
$\bar{h}_{AW}$	area-weighted mean height
h_c	mean canopy height
HGAC	Houston-Galveston Area Council
k	von Kármán
LIDAR	light detection and ranging
LULC	land use/land cover
L(z)	area index

MM5	Penn State/National Center for Atmospheric Research Mesoscale Model
MrSID	multiresolution seamless image database
NCAR	National Center for Atmospheric Research
NLCD	National Land Cover Dataset
RMSE	root mean square error
s_h	standard deviation of height
TIGER	Topographically Integrated Geographic Encoding and Referencing System
TSARP	Tropical Storm Allison Recovery Project
u*	friction velocity
U	large-scale wind speed
UCP	urban canopy parameter
USGS	U.S. Geological Survey
z_d	displacement height
z_{dpl}	in-plane sheltering displacement
z_o	roughness length

1. Project Overview

Urban morphological characteristics are required to accurately run many mesoscale meteorological, surface energy budget, and air quality models. Traditionally, best guess estimates of urban morphological parameters were made based on literature values and an underlying base dataset (e.g., land use/land cover) that typically had coarse horizontal resolution. However, currently the state-of-the-practice is to analyze three-dimensional (3D) digital datasets of buildings and trees integrated with two-dimensional (2D) digital datasets of land use/land cover, infrastructure, aerial photographs, and satellite imagery to derive the necessary urban canopy parameters. The tools used in the analyses include geographic information system (GIS), image analysis, database management software, and computer programming of the numerical algorithms.

1.1 Project Objectives

The objectives of this project were as follows.

(1) Compile and manage the digital datasets necessary to compute urban canopy parameters for a selected Community Multi-scale Air Quality (CMAQ)/Penn State/National Center for Atmospheric Research Mesoscale Model (MM5)/DA-SM2-U modeling domain, including the City of Houston (COH), TX.

(2) Write computer codes in Avenue, Visual Basic for Applications, and Fortran to process digital data to compute a set of requested urban canopy parameters (UCPs).

(3) Execute the computer codes to calculate the following urban canopy parameters.
- *Building-specific parameters:* mean height, standard deviation of height, mean height weighted by plan area, wall-to-plan area ratio, height histograms, plan area density, top area density, frontal area density, and height-to-width ratio
- *Vegetation-specific parameters:* mean height weighted by plan area, plan area density, top area density, and frontal area density
- *Canopy-specific parameters:* mean height weighted by plan area, plan area density, top area density, and frontal area density
- *General morphological parameters:* roughness length, displacement height, sky view factor, and mean orientation of streets
- *Surface cover parameters:* building material fraction, land cover fraction, land use fraction, and percent directly connected impervious area

(4) Compile the results into spreadsheets and summarize in a final report.

The project required the following data to be supplied: (1) a database consisting of the bald earth elevation, building rooftop elevation, and vegetation (trees and large shrubs) elevation data collected using airborne light detection and ranging (LIDAR) scanning system (in raster form) at both 1- and 5-m horizontal resolutions; (2) a set of derived building polygons (in vector form) with elevation as an attribute based on the data for Harris County, TX; and (3) the grid mesh for Harris County of the nested computational domains in the MM5. As described below, conditions 1 and 2 were not met satisfactorily, and adjustments had to be made to complete the project with an acceptable level of quality.

1.2 Houston Study Area

The CMAQ/MM5/DA-SM2-U modeling domain for this project is centered on the Houston Metropolitan Area in Southeast Texas (see Figure 1). The modeling domain covers an 82,368-km^2 area, including approximately two-thirds land surface and one-third water surface (primarily the Gulf of Mexico). This project involved the computation of requested UCPs for the entire

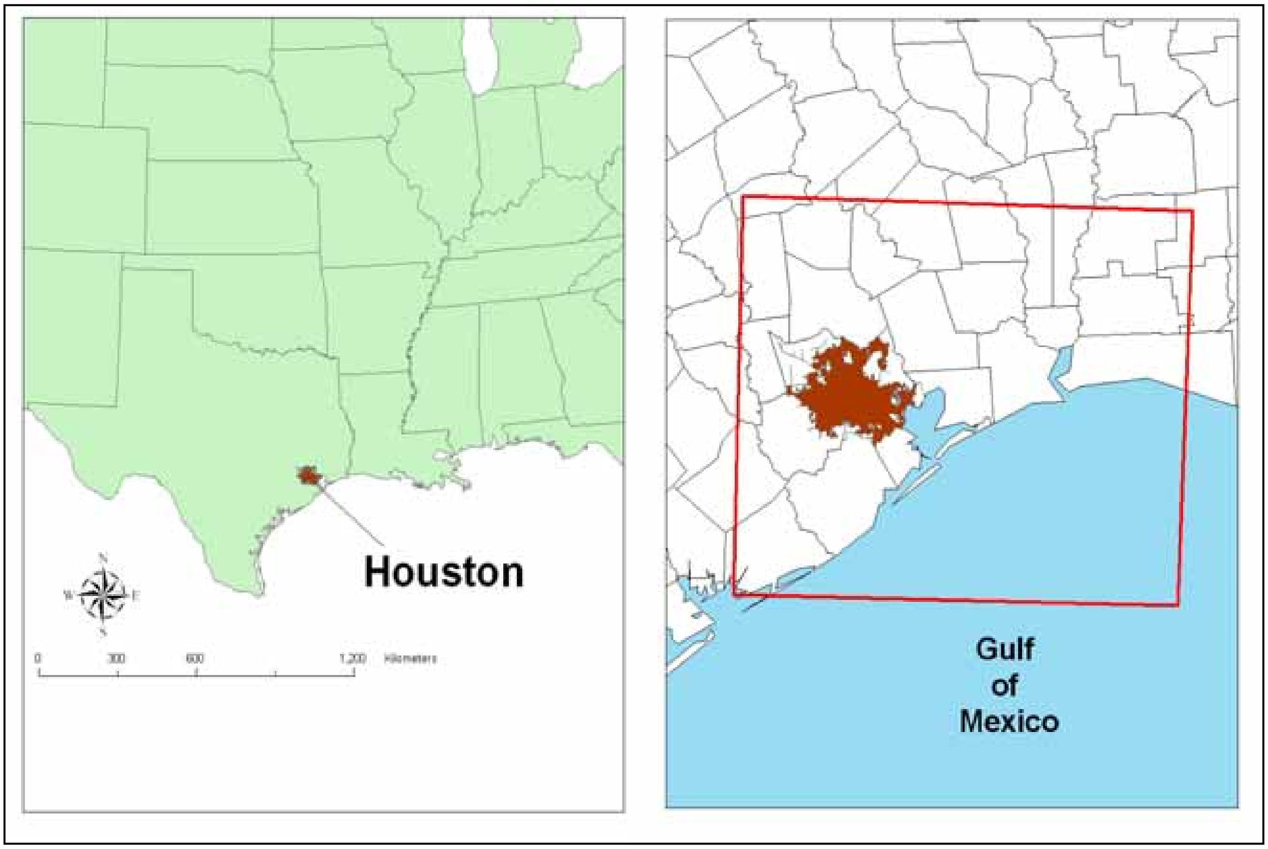

Figure 1. Houston vicinity map and modeling domain. The location of Houston within the State of Texas is shown on the left and the innermost grid of the modeling domain is shown as a red box surrounding the Houston Metropolitan Area on the right.

82,368-km^2 modeling domain. The modeling domain is subdivided into a modeling grid mesh with 1-km horizontal spatial resolution. Each 1-km^2 grid cell (82,368 total) must have all UCPs defined. The land use/land cover (LULC) for the modeling domain is shown in Figure 2. Overall, the land surfaces of the modeling domain are predominantly rural, consisting of significant fractions of Cropland and Pasture and Forest Land. The highest concentration of urban land use is in the Houston Metropolitan Area located at the left center of Figure 2.

The data processing task was divided into three phases, as illustrated in Figure 3. Phase I of the UCP computations focused on a 1653-km^2 section of the COH and surrounding areas. A building footprint data layer was developed and validated using 0.5-m horizontal resolution digital orthophotos. Using the building footprint data layer and refined by the digital orthophotos, UCPs were calculated for the buildings only, the vegetation only, and the full canopy. Phase II of the project involved computing only full canopy UCPs for the remaining 3589-km^2 of Harris County not included in Phase I. Phase III of the project involved developing an accurate land use data layer for the 1653-km^2 Phase I study area, correlating the UCPs in the study area to the underlying land use, extrapolating building and vegetation UCPs to the 3589 grid cells in the Phase II study area, and extrapolating all UCPS to the 77,126 grid cells outside of the Phase I and II study areas (labeled as Phase III in Figure 3).

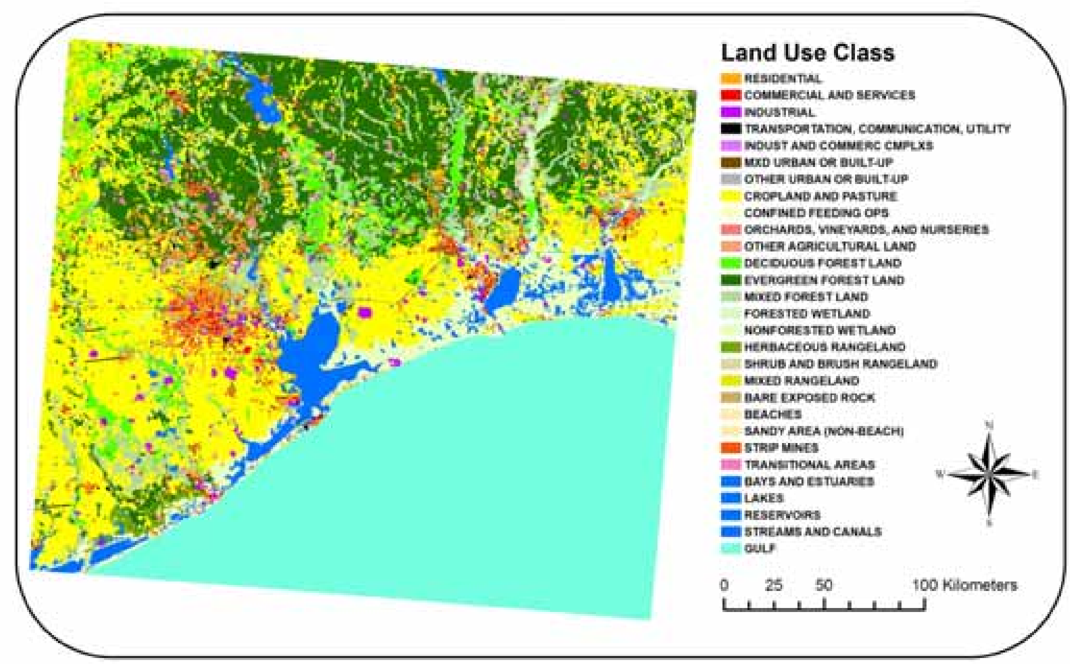

Figure 2. Land use/land cover of the modeling domain inner grid. Land use data based on the USGS dataset, classified according to the Anderson level 2 scheme.

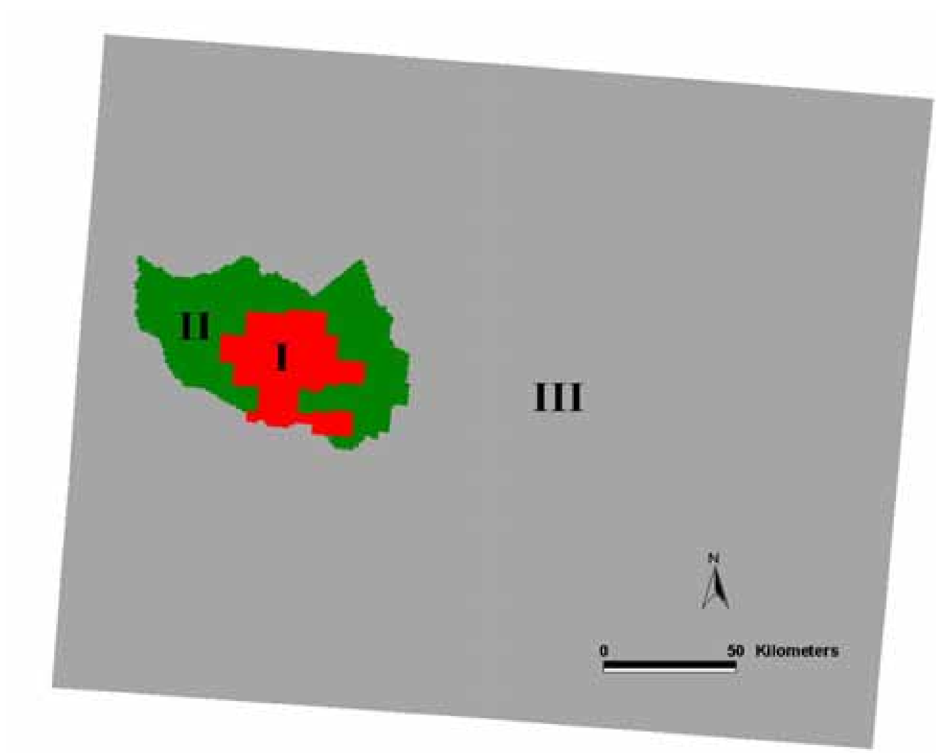

Figure 3. Three phases of UCP computation project.

2. Houston Urban Database

The Houston GIS Urban Database includes multiple surface topography and surface cover digital datasets that were purchased for the project and several derivative data products created during the project. Table 1 lists all datasets that were obtained or created. The data name, format, and source are given, and a brief description of the dataset is included.

2.1 TerraPoint Elevation Data

TerraPoint LLC provided the base layer of elevation data for this project. The elevation data products were derived from data collected using LIDAR technology. LIDAR technology produces x, y, z representation of topography via airborne lasers. Data products are created as an even distribution of data points in evenly spaced grids. The TerraPoint data products were spaced at intervals of 1 and 5 m, with a horizontal accuracy of 15 to 20 cm and a vertical accuracy of 5 to 10 cm.

The following seven data products were included in the delivery from TerraPoint.
(1) Digital Elevation Model (DEM)—full feature (raster)
(2) Digital Terrain Model (DTM)—bare earth (raster)
(3) Ground—ground feature (raster)
(4) Nonground—nonground feature (raster)
(5) Building—building feature (raster)
(6) Vegetation—vegetation feature (raster)
(7) Building Polygons—building footprint shapefile (vector)

The Building, Vegetation, and Building Polygons were found to be inadequate or unnecessary for the present project. The data layers did not cover enough area, and the data itself was found to contain significant errors when cross-referenced with aerial photos taken at approximately the same time as the LIDAR fly over. The TerraPoint algorithm for separating buildings from vegetation did not provide a building polygon coverage sufficiently accurate or extensive for the present project. The most significant deficiency was the incorrect placement of building polygons or missing polygons. Thus, the Building and Vegetation raster datasets and the Building Polygon datasets obtained from TerraPoint were not used in the calculations described below. Instead, other datasets were obtained, derived, and created to meet the project needs.

The UCP calculation algorithms operate with absolute heights of the canopy and objects (as opposed to top elevations relative to mean sea level). The required canopy height data product was derived by subtracting the DTM data layer from the Nonground data layer. The Ground and DEM data products were not needed for this project.

2.2 Building Footprints

Because the TerraPoint building polygon dataset was inadequate to establish accurate building footprints, other options had to be explored. A building footprint dataset was obtained from the City of Houston (COH), but the dataset dated to 1983, with small updates in the mid 1990s. Comparison of the COH building dataset with a recent aerial photo indicated that significant parts of the dataset were outdated. Buildings were not shown in areas of recent development and buildings were shown in areas that had been redeveloped. Approximately 2 person-months were invested in checking and correcting the COH building footprint dataset for a 1653-km^2 area. The 1653-km^2 area was chosen to include the downtown core area of Houston, the ship channel industrial district, and extensive coverage of the level 2 U.S. Geological Survey (USGS)

Table 1. Digital Datasets Obtained or Created for UCP Computations

Dataset	Format	Source	Description
Digital Elevation Model (DEM)	ArcInfo Export	TerraPoint	Full feature; LIDAR gridded data product with 1- and 5-m horizontal spatial resolution
Digital Terrain Model (DTM)	ArcInfo Export	TerraPoint	Bare earth; LIDAR gridded data product with 1- and 5-m horizontal spatial resolution
Ground	ArcInfo Export	TerraPoint	Ground feature; LIDAR gridded data product with 1- and 5-m horizontal spatial resolution
Nonground	ArcInfo Export	TerraPoint	Nonground feature; LIDAR gridded data product with 1- and 5-m horizontal spatial resolution
Buildings	ArcInfo Export	TerraPoint	Building feature; LIDAR gridded data product with 1- and 5-m horizontal spatial resolution
Vegetation	ArcInfo Export	TerraPoint	Vegetation feature; LIDAR gridded data product with 1- and 5-m horizontal spatial resolution
Building Polygons	ESRI shapefile	TerraPoint	Polygons of building footprint derived by TerraPoint for selected areas where buildings are distinct from vegetation
Building Polygons	ESRI map library	City of Houston	Building footprints in the City of Houston dating to 1983
Building Polygons	ESRI shapefile	Created	Building footprint coverage for 1653-km^2 area of the City of Houston. Dataset based on City of Houston building polygon dataset; dataset corrected and improved using 0.5-m digital orthophotos dating to 2000.
Street Centerlines	ESRI shapefile	U.S. Census TIGER files	Downloaded from www.esri.com
Aerial Photos	MrSID	Houston-Galveston Area Council (HGAC)	0.5-m True Color Geo-referenced Digital Orthophotos
Land Use/Land Cover	ESRI shapefile	USGS	Standard USGS land use digital dataset with Level 2 land use classification
Land Use/Land Cover	ESRI shapefile	Created	The USGS dataset was modified using aerial photos as base map for Phase I study area (1653 km^2). Major improvement was the addition of newly developed areas—affected more than 50% of the Phase I and II study areas.
Modeling Grid Cells	ESRI shapefile	Created	1-km^2 horizontal resolution grid cell coverage of modeling domain; coordinates and projection of grid cell coverage specified by EPA
Parcel	ESRI map library	City of Houston	Multiple CD set of data from City of Houston containing a great amount of parcel level information
Elevation Contours	ESRI shapefile	Tropical Storm Allison Recovery Project (TSARP) and Harris County Flood Control District	2-ft elevation contours

land use types. The original COH building dataset within the 1653-km^2 Phase I study area included 523,920 building footprints. The modified building dataset contained 664,861 building footprints.

2.3 Land Use/Land Cover

After comparing several LULC datasets for possible use in this project, the LULC dataset made available by USGS eventually was chosen. The USGS dataset contained a more detailed classification system for urban areas than the National Land Cover Dataset (NLCD), although it was more outdated (1970s versus 1990s). The COH land use parcel data is also available, and it is the most accurate and current compared with the USGS and the NLCD. But, the coverage is limited to the COH and would not be available for extrapolation of UCPs to the entire modeling domain.

The USGS is the Federal agency primarily responsible for development, maintenance, and distribution of a nationwide LULC dataset. The land use and cover is classified according to the level 2 classification scheme described by Anderson et al. (1976) (see Table 2). The level 2 classification scheme has relatively coarse detail but permits finer classification to level 3 or 4. The basic sources of land use compilation data are National Aeronautics and Space Administration (NASA) high-altitude aerial photographs and National High-Altitude Photography (NHAP) program photographs, usually at scales smaller than 1:60,000 (USGS, 1990).

USGS LULC datasets can be downloaded in two formats. The first format was developed as part of the Geographic Information Retrieval Analysis System (GIRAS) and is polygon based. Each polygon represents a contiguous area of homogeneous land use/cover. The minimum size of polygons depicting all “urban or built-up land” (categories 11-17); “water” (51-54); “confined feeding operations” (23); “other agricultural land” (24); “strip mines, quarries, and gravel pits” (75); and urban “transitional areas” (76) is 4 ha. All other categories have a minimum polygon size of 16 ha (USGS, 1990). In the urban or built-up land and water categories, the minimum width of a feature to be shown is 200 m. Although the minimum-width consideration precludes the delineation of very narrow and very long 4 ha polygons, triangles or other polygons are acceptable if the base of the triangle or minimum width of the polygon is 200 m in length, and if the area of the polygon is 4 ha. Exceptions to this specification are limited access highways (14) and all double-line rivers (51) on the 1:250,000-scale base, which have a minimum width of 92 m. For categories other than urban or built-up land and water, the 16-ha minimum size for delineation requires a minimum-width polygon of 400 m. The second data format is termed Composite Theme Grid (CTG). The CTG data are grid cell based. The grid cells are actually based on a regular point sampling, where the center point of each cell is 200 m apart from other center points in adjacent cells (USGS, 1990). The GIRAS-polygon-based dataset was chosen for use in this project.

Table 3 summarizes the amounts of each level 2 land use type within the MM5/CMAQ/DA-SM2-U modeling domain. The majority of the domain is comprised of water (Gulf of Mexico), Cropland and Pasture, Forestland, and Wetlands. Less than 5% of the modeling domain is classified as urban, but that area is, for the most part, concentrated within and adjacent to the COH. UCPs will be computed for each land use type primarily based on an analysis of the 1653-km^2 Phase I study area. Following UCP derivation, the land-use-specific UCPs will be extrapolated to the entire innermost (i.e., finest spatial resolution) grid of the modeling domain using an area-weighted averaging approach based on the underlying USGS land use dataset. More details of the UCP extrapolation are provided in Section 3 of this report.

Table 2. Anderson Classification System Used in USGS LULC Datasets

Level I	Level 2
1. Urban or Built-Up Land	11. Residential 12. Commercial and Services 13. Industrial 14. Transportation, Communication, and Utility 15. Industrial and Commercial Complexes 16. Mixed Urban or Built-Up Land 17. Other Urban or Built-Up Land
2. Agricultural Land	21. Cropland and Pasture 22. Orchards, Groves, Vineyards, Nurseries, and Ornamental Horticultural Areas 23. Confined Feeding Operations 24. Other Agricultural Land
3. Rangeland	31. Herbaceous Rangeland 32. Shrub and Brush Rangeland 33. Mixed Rangeland
4. Forest Land	41. Deciduous Forest Land 42. Evergreen Forest Land 43. Mixed Forest Land
5. Water	51. Streams and Canals 52. Lakes 53. Reservoirs 54. Bays and Estuaries
6. Wetland	61. Forested Wetland 62. Nonforested Wetland
7. Barren Land	71. Dry Salt Flats 72. Beaches 73. Sandy Areas Other Than Beaches 74. Bare Exposed Rock 75. Strip Mines, Quarries, and Gravel Pits 76. Transitional Areas 77. Mixed Barren Land
8. Tundra	81. Shrub and Brush Tundra 82. Herbaceous Tundra 83. Bare Ground 84. Wet Tundra 85. Mixed Tundra
9. Perennial Snow or Ice	91. Perennial Snowfields 92. Glaciers

Table 3. Anderson Level 2 Land Use Types in Modeling Domain

USGS Level 2 Land Use Name	Area (km^2)	Percent of Area
Residential	1867	2.3
Commercial and Services	309	0.4
Industrial	543	0.7
Transportation, Communications, and Utility	236	0.3
Mixed Industrial and Commercial	2	0.0
Mixed Urban or Built-Up Land	110	0.1
Other Urban or Built-Up Land	157	0.2
Cropland and Pasture	19,113	23.2
Orchards, Groves, Vineyards, and Nurseries	13	0.0
Confined Feeding Operations	3	0.0
Other Agricultural Land	28	0.0
Herbaceous Rangeland	466	0.6
Shrub and Brush Rangeland	132	0.2
Mixed Rangeland	446	0.5
Deciduous Forest Land	2951	3.6
Evergreen Forest Land	14,737	17.9
Mixed Forest Land	5025	6.1
Streams and Canals	322	0.4
Lakes	1019	1.2
Reservoirs	671	0.8
Bays and Estuaries	1624	2.0
Gulf of Mexico	27,091	32.9
Forested Wetlands	791	1.0
Nonforested Wetlands	4142	5.0
Beaches	16	0.0
Sandy Areas Other Than Beaches	36	0.0
Bare Exposed Rock	1	0.0
Strip Mines, Quarries, and Gravel Pits	32	0.0
Transitional Areas	494	0.6

3. Urban Canopy Parameters

The Models-3/CMAQ/MM5/DA-SM2-U modeling framework requires many UCPs to be defined to adequately represent the urban effect in the simulations. Table 4 lists the UCPs computed for this project and the name of the Excel spreadsheet that contains the results from the computations (all spreadsheets are available on the accompanying compact disc [CD] set). In addition, a gridded coverage of land use is provided on the CD set. Following the table, a brief review of the parameter calculation procedures is given for each parameter.

Table 4. Urban Canopy Parameters Computed for This Project

Urban Canopy Parameter	Results
Mean Building Height	GridCellUCPs.xls
Standard Deviation of Building Height	GridCellUCPs.xls
Mean Building Height Weighted by Footprint Plan Area	GridCellUCPs.xls
Wall-to-Plan Area Ratio	GridCellUCPs.xls
Building Height-to-Width Ratio (λ_s)	GridCellUCPs.xls
Building Height Histograms	BuildingHeightHistograms.xls
Mean Vegetation Height Weighted by Plan Area	GridCellUCPs.xls
Mean Canopy Height Weighted by Plan Area	GridCellUCPs.xls
Mean Orientation of Street	GridCellUCPs.xls
Building Plan Area Density Function [$A_{pb}(z)$]	BuildingPlanAreaDensity.xls
Vegetation Plan Area Density Function [$A_{pv}(z)$]	VegetationPlanAreaDensity.xls
Canopy Plan Area Density Function [$A_{pc}(z)$]	CanopyPlanAreaDensity.xls
Building Rooftop Area Density Function [$A_{tb}(z)$]	BuildingRooftopAreaDensity.xls
Vegetation Top Area Density Function [$A_{tv}(z)$]	VegetationTopAreaDensity.xls
Canopy Top Area Density Function [$A_{tc}(z)$]	CanopyTopAreaDensity.xls
Building Frontal Area Density Function [$A_{fb}(z)$]	BuildingFrontalAreaDensity.xls
Vegetation Frontal Area Density Function [$A_{fv}(z)$]	VegetationFrontalAreaDensity.xls
Canopy Frontal Area Density Function [$A_{fc}(z)$]	CanopyFrontalAreaDensity.xls
Roughness Length and Displacement Height (Raupach, 1994)	GridCellUCPs.xls
Roughness Length and Displacement Height (Macdonald, et al. 1998)	GridCellUCPs.xls
Roughness Length and Displacement Height (Bottema, 1997)	GridCellUCPs.xls
Sky View Factor	GridCellUCPs.xls
Plan Area Fraction of Buildings, Roadways/Pavement, Vegetation, Open Water, and Other Cover	LandCoverFraction.xls
Building Material Fraction	GridCellUCPs.xls
Percent Directly Connected Impervious Area (DCIA)	GridCellUCPs.xls

3.1 Building Height Characteristics

For the Phase I study area, all building height parameters were computed using either the building footprint shapefile dataset digitized during this project or based on the extrapolation of the land use sample values (described later).

The *mean and standard deviation of building height* were calculated using the following equations:

$$\bar{h} = \frac{\sum_{i=1}^{N} h_i}{N} \qquad (1)$$

$$s_h = \sqrt{\frac{\sum_{i=1}^{N}\left(h_i - \bar{h}\right)^2}{N-1}}, \tag{2}$$

where $\bar{h}$ is the mean building height, s_h is the standard deviation of building height, h_i is the height of building i, and N is the total number of buildings in the area. The *mean building height weighted by building plan area* was calculated using the following equation:

$$\bar{h}_{AW} = \frac{\sum_{i=1}^{N} A_i h_i}{\sum_{i=1}^{N} A_i}, \tag{3}$$

where $\bar{h}_{AW}$ is the mean building height weighted by building plan area, and A_i is the plan area at ground level of building i.

The *wall-to-plan area ratio* is defined as the summed surface area of building walls divided by the grid cell plan area,

$$\lambda_W = \frac{A_W}{A_T}, \tag{4}$$

where A_W is the combined surface area of the building walls, and A_T is the plan area of the grid cell.

The *building height-to-width ratio (λ_S)* is calculated for two buildings by dividing the average height by the distance between the two buildings,

$$\lambda_S = \frac{\left(H_1 + H_2\right)/2}{S_{12}}, \tag{5}$$

where H_1 is the height of the upwind building, H_2 is the height of the downwind building, and S_{12} is the horizontal distance between the two buildings (i.e., the canyon width). The calculation of λ_S can be performed for each pair of adjacent elements in a building array, which can be very tedious for the complex building shapes and patterns in a city. Instead, λ_S is computed along linear traverses across the city at different angles using equation 5. The calculation strategy involved converting the urban building database into a raster DEM (a matrix of numbers representing building height). Then, traversing along each row or column of grid cells, the height-to-width ratio was calculated between each pair of buildings. Because this approach yields λ_S values in nonpreferred directions (e.g., running along a street, not across a street), the matrices of traverses done at different angles are superimposed and the largest height-to-width ratio within each grid cell is selected.

Building height histograms for each grid cell were derived at 5-m height bin sizes.

3.2 Vegetation Height Characteristics

The *mean vegetation height weighted by plan area* was calculated using the following equation:

$$\overline{h}_{AW} = \frac{\sum_{i=1}^{N} A_i h_i}{\sum_{i=1}^{N} A_i}, \tag{6}$$

where $\overline{h}_{AW}$ is the mean vegetation height weighted by plan area, h_i is the vegetation height in raster cell i, and A_i is the plan area of raster cell i.

3.3 Canopy Height Characteristics

The *mean canopy height weighted by plan area* was calculated using the following equation:

$$\overline{h}_{AW} = \frac{\sum_{i=1}^{N} A_i h_i}{\sum_{i=1}^{N} A_i}, \tag{7}$$

where $\overline{h}_{AW}$ is the mean canopy height weighted by plan area, h_i is the canopy height in raster cell i, and A_i is the plan area of raster cell i.

3.4 Plan Area Density Function

The *plan area density function [$A_P(z)$]* is defined as the average roughness element plan area within a height increment divided by the volume of the height increment,

$$A_p(z) = \frac{\frac{1}{\Delta z}\int_{z-\frac{1}{2}\Delta z}^{z+\frac{1}{2}\Delta z} A_P(z')dz'}{A_T \Delta z}, \tag{8}$$

where $A_p(z')$ is the plan area of roughness elements at height z', A_T is the plan area of the site, and Δz is the height increment for the calculation. Because A_T is not a function of height, we can bring it into the integral in the numerator and obtain,

$$A_p(z) = \frac{\frac{1}{\Delta z}\int_{z-\frac{1}{2}\Delta z}^{z+\frac{1}{2}\Delta z} \frac{A_P(z')}{A_T}dz'}{\Delta z}. \tag{9}$$

Knowing $\lambda_P(z') = A_P(z')/A_T$ and assuming that the roughness element plan area does not change appreciably within a height increment Δz, equation 9 can be approximated by,

$$A_p(z) \cong \frac{\lambda_P(z)}{\Delta z} \quad . \tag{10}$$

The plan area density function is computed for buildings only, vegetation only, and canopy.

3.5 Top Area Density Function

The roughness element top plan area within a height increment Δz can be approximated by the difference between the top plan areas at two heights,

$$A_t(z) = A_p\left(z - \frac{\Delta z}{2}\right) - A_p\left(z + \frac{\Delta z}{2}\right), \tag{11}$$

where $A_p(z)$ is the top plan area of roughness elements at the specified height (flat-roofed and canopy top assumption has been made). The *top area density function* [$A_t(z)$] can then be defined as the top plan area of roughness elements per height increment Δz divided by the volume of the height increment,

$$A_t(z) = \frac{A_r(z)}{A_T \cdot \Delta z} = \frac{A_p\left(z - \frac{\Delta z}{2}\right) - A_p\left(z + \frac{\Delta z}{2}\right)}{A_T \cdot \Delta z}, \tag{12}$$

where A_T is the total grid cell area. Analogous to the leaf area index used in the plant canopy community, the integration of $A_t(z)$ from a specified elevation above ground (z) to the height of the canopy (h_c) is equal to the area index [$L(z)$],

$$L(z) = \int_z^{h_c} a_r(z')dz' . \tag{13}$$

The integration of $A_t(z)$ from ground elevation to the canopy height (h_c) is equal to $\lambda_{P,}$

$$L(0) = \lambda_P = \int_0^{h_c} A_t(z')dz' \quad . \tag{14}$$

The top area density function is computed for buildings only, vegetation only, and canopy.

3.6 Frontal Area Density Function

The *frontal area density function [$A_f(z)$]* is defined as,

$$A_f(z,\theta) = \frac{A(\theta)_{proj(\Delta z)}}{A_T \Delta z}, \tag{15}$$

where $A(\theta)_{proj(\Delta z)}$ is the area of roughness surfaces projected into the plane normal to the approaching wind direction for a specified height increment (Δz), θ is the wind direction angle, and A_T is the total plan area of the grid cell. For a specified wind direction, the integral of $A_f(z)$ over the canopy height equates to the frontal area index (λ_f).

The frontal area index is defined as the total area of roughness elements projected into the plane normal to the approaching wind direction (A_{proj}) divided by the plan area of the study site (A_T),

$$\lambda_f\ (\theta) = \frac{A_{proj}}{A_T}, \tag{16}$$

where θ is the wind direction.

The frontal area density function is computed for buildings only, vegetation only, and canopy. For this project, the frontal area density was determined for each grid cell for an approach wind from four directions: north, northeast, east, and southeast. Roughness elements were assumed to be rectangular solids in all cases (i.e., their width does not change with height for a single polygon or grid cell). This, of course is not true for trees and other objects that have a changing width with height, but the data used to find the UCPs did not represent the variable width of objects.

3.7 Sky View Factor

The ratio of radiation received (or emitted) from a planar surface to the radiation emitted (or received) by the entire hemispheric environment is called the sky view factor (ψ_{sky}). ψ_{sky} varies from 0 to 1, where $\psi_{sky} = 0$ means the sky is completely obstructed by obstacles and $\psi_{sky} = 1$ means that there are no obstructions. To expedite the processing, the raster data product was resampled to 3-m horizontal resolution, and the sky view factor was determined for each ground level 9-m^2 grid cell by finding the fraction of visible sky for rays directed in eight azimuths. As an approximation, the average visible sky fraction is computed and set as the sky view for that grid cell. Sky view factor is computed using the canopy dataset only (building- or vegetation-specific sky view factors are not calculated).

3.8 Displacement Height and Roughness Length

The displacement height (z_d) and roughness length (z_o) are computed using three sets of equations reviewed by Grimmond and Oke (1999). The first set of equations was developed by Raupach (1994),

$$\frac{z_d}{z_H} = 1 - \left\{ \frac{1 - \exp\left[-\left(c_{d1} 2\lambda_f \right)^{0.5} \right]}{\left(c_{d1} 2\lambda_f \right)^{0.5}} \right\} \tag{17}$$

and

$$\frac{z_o}{z_H} = \left(1 - \frac{z_d}{z_H} \right) \exp\left(-k \frac{U}{u_*} + \psi_k \right), \tag{18}$$

where

$$\frac{u_*}{U} = \min\left[\left(c_S + c_R \lambda_f\right)^{0.5}, \left(\frac{u_*}{U}\right)_{\max} \right], \tag{19}$$

and ψ_k is the roughness sublayer influence function, U and u_* are the large-scale wind speed and the friction velocity, respectively; c_S and c_R are drag coefficients for the substrate surface at height z_H in the absence of roughness elements and of an isolated roughness element mounted on the surface, respectively; and c_{d1} is a free parameter. Raupach (1994) suggested ψ_k = 0.193, $(u_*/U)_{max}$ = 0.3, c_S = 0.003, c_R = 0.3, and c_{d1} = 7.5.

The second set of equations was derived by Macdonald et al. (1998). These equations incorporate the drag coefficient and displacement height into the expression for roughness length (z_o),

$$\frac{z_d}{\overline{\overline{z_H}}} = 1 + \alpha^{-\lambda_p}\left(\lambda_p - 1\right) \tag{20}$$

and

$$\frac{z_o}{\overline{\overline{z_H}}} = \left(1 - \frac{z_d}{\overline{\overline{z_H}}}\right) \exp\left\{ - \left(0.5\beta \frac{C_D}{k^2} \left(1 - \frac{z_d}{\overline{\overline{z_H}}}\right) \lambda_f \right)^{-0.5} \right\}, \tag{21}$$

where α is an empirical coefficient, C_D is a drag coefficient, k is the von Kármán constant, and β is a correction factor for the drag coefficient (the net correction for several variables, including velocity profile shape, incident turbulence intensity, turbulence length scale, and incident wind angle, and for rounded corners). Macdonald et al. (1998) recommended for staggered arrays of cubes that $\alpha \approx$ 4.43 and $\beta \approx$ 1.0. These values were used by Grimmond and Oke (1999) and are also used here. The drag coefficient C_D was set to 1.2, and the von Kármán constant (k) is equal to 0.4.

The third set of equations was developed by Bottema (1997),

$$\frac{z_o}{\overline{\overline{z_H}}} = \frac{\overline{z_H} - z_{dpl}}{\overline{z_H}} \exp\left[- \frac{k}{\left(0.5 \lambda_f C_{dh}\right)^{0.5}} \right], \tag{22}$$

where z_{dpl} is an in-plane sheltering displacement height calculated based on the density and pattern of the building arrangement (normal or staggered), and C_{dh} = 1.2 max[1 – 0.15(L_x/z_H), 0.82] min[0.65 + 0.06(L_y/z_H), 1.0]. Bottema (1997) provides additional equations to compute z_d and z_{dpl} that are dependent on the arrangement and density of buildings. For the study area, a repeatable calculation method that can be automated must be used. Therefore, the building arrangement is assumed to be staggered arrays of buildings with high densities for all areas. This is a reasonable assumption for most of the land uses, except for the low-density residential areas on the outskirts of the Phase I study area. All roughness lengths and displacement heights are determined for four wind directions: north, northeast, east, and southeast.

3.9 Mean Orientation of Streets

The mean orientation of all streets in a grid cell is computed by finding the length-weighted average,

$$\bar{\theta}_{LW} = \frac{\sum_{i=1}^{N} L_i \theta_i}{\sum_{i=1}^{N} L_i} \quad , \tag{23}$$

where $\bar{\theta}_{LW}$ is the mean orientation weighted by street length, θ_i is the angle of street segment i, and L_i is the length of street segment i. The numeric angles in the range of 0 to 179.99 are defined in Table 5.

Table 5. Numeric Angles Corresponding to Street Orientations

Street Orientation	Angle (degrees)
North-South	0 (179.99 is nearly north-south)
Northeast-Southwest	45
East-West	90
Northwest-Southeast	135

3.10 Building Material

Information on building material of commercial and residential structures is available through the COH Planning and Development Department Tax Roll Records. These parcel level datasets include information on commercial structure type, residential exterior type, and residential exterior masonry description. This tax roll information was used as guidance to develop a matrix to define the fraction of building material used in each Level 2 land use type. The five building materials possible were

(1) concrete,
(2) wood,
(3) steel,
(4) brick, and
(5) combination.

The assumed building material fraction for each land use type is included in the spreadsheet UCP Land Use Averages and shown later in this report**.** Values for all land uses except Residential and Commercial and Services were estimated from assessment of the digital orthophotos.

3.11 Percent Directly Connected Impervious Area

The percent directly connected impervious area (DCIA) in each grid cell is estimated using roadway pavement, building footprint, and uncovered parking data to estimate the total impervious area. Roadways and parking areas are assumed directly connected to the drainage system. This is a very reasonable assumption for most urban areas given that roadway drainage is most likely mandated by local ordinances. Single-family residential rooftops are assumed disconnected from the drainage system because most downspouts from houses are probably directed to pervious areas (e.g., yards). Multifamily rooftops are assumed connected. Commercial and industrial building rooftops are assumed directly connected to the drainage system. A summary of the assumed DCIA values for each land use are included in the spreadsheet UCP Land Use Averages and shown later in this report.

3.12 Fraction Land Cover

The fraction ground cover type was determined by integrating several datasets in GIS. The vegetation, the building footprint, roadway pavement, and open water datasets were used to find the fraction of each grid cell covered by the following land covers.

- Building
- Roadway/Pavement (includes sidewalks and driveways)
- Vegetation
- Open water
- Other (includes gravel, bare soil, rock, beach, railroad lines, and other built structures that are not buildings or roadways)

The values used in the UCP extrapolations are contained in the spreadsheet UCP Land Use Averages and shown later in this report.

4. Urban Canopy Parameter Extrapolation Based on Underlying Land Use

The building dataset covers only 1653 km^2 of the 82,368 km^2 modeling domain (primarily the COH and adjacent areas). The LIDAR data covers only 5242 km^2 of the 82,368 km^2-modeling domain. Clearly, the elevation, building, and surface cover data extent is not enough to provide coverage for UCP computation in each grid cell of the entire modeling domain. Therefore, average UCPs were calculated for each USGS level 2 land use type, and area-weighted averages then were determined for each grid cell that did not have data coverage (i.e., UCPs were extrapolated from the area of data to the area lacking data using the land use). A random spot check of the USGS land use dataset within the 1653-km^2 Phase I study area against the 0.5-m color ortho images from the Houston-Galveston Area Council indicated that the dataset was inaccurate and not acceptable for UCP derivation and validation because of recent unrepresented urbanization. Therefore, the land use dataset was modified using the aerial photos as a base map. Figure 4 shows the final land use dataset used for UCP derivation and validation. Table 6 lists the amount of each level 2 land use type found within the Phase I study area boundary according to the original USGS dataset and according to the modified dataset. The amount of urban land use increases substantially, although the amount of Cropland and Pasture decreases about the same amount. This is expected because the area has urbanized significantly during the 20+ years since the USGS dataset originally was derived. There are also several areas of potential classification differences (e.g., Reservoirs, Strip Mines, and Transitional Areas) between the original dataset and the modified dataset. All land use types with potential large percent changes caused by classification differences do not have a significant effect on the project. For example, many smaller reservoirs would have been too small to be noted in the original dataset but were included in the revised dataset.

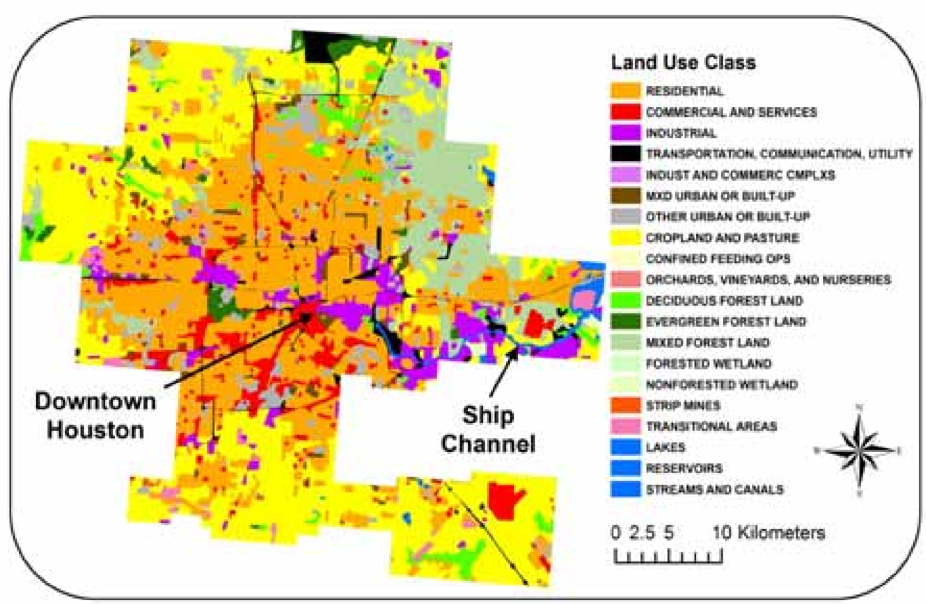

Figure 4. Land use of the Phase I building study area. Land use classified according to the Anderson level 2 categories.

For most parameters, a 1235-km^2 section of the 1653-km^2 Phase I study area was used to derive the average UCP for each land use type, whereas the remaining 418 km^2 was used for validation (see Figure 5). Table 7 contains the land use areas within the derivation area and the

Table 6. Comparison of Land Use Distribution in the 1653-km^2 Phase I Study Area for Original USGS Land Use Dataset and Revised Dataset

USGS Level 2 Land Use Name	Original Area (km^2)	Revised Area (km^2)	Percent Change (%)
Residential	533.7	633.1	+19
Commercial and Services	85.9	115.2	+34
Industrial	79.9	156.6	+96
Transportation, Communications, and Utility	53.3	61.9	+16
Mixed Industrial and Commercial	2.0	1.0	-50
Mixed Urban or Built-Up Land	16.7	19.4	+16
Other Urban or Built-Up Land	67.1	88.5	+32
Cropland and Pasture	532.9	297.5	-44
Orchards, Groves, Vineyards, and Nurseries	0.7	0.0	—
Confined Feeding Operations	0.1	0.0	—
Other Agricultural Land	0.0	1.1	—
Herbaceous Rangeland	0.0	0.0	—
Shrub and Brush Rangeland	0.0	0.0	—
Mixed Rangeland	0.0	0.0	—
Deciduous Forest Land	46.7	68.6	+47
Evergreen Forest Land	22.3	12.7	-43
Mixed Forest Land	172.6	147.5	-15
Streams and Canals	14.3	21.8	+53
Lakes	1.0	0.6	-40
Reservoirs	2.8	7.7	+175
Bays and Estuaries	0.0	0.0	—
Gulf of Mexico	0.0	0.0	—
Forested Wetlands	0.8	0.3	-63
Nonforested Wetlands	3.5	3.0	-14
Beaches	0.0	0.0	—
Sandy Areas Other Than Beaches	0.0	0.0	—
Bare Exposed Rock	0.0	0.0	—
Strip Mines, Quarries, and Gravel Pits	2.0	11.0	+450
Transitional Areas	14.7	5.5	-63

validation area for comparison. For some parameters, calculation of values for large areas was not possible because of data, time, or computational limitations. For these situations, five samples of each land use type located within the 1235-km^2 section of the Phase I study area were arbitrarily selected (the same five sample sites were used for all UCPs that had to be calculated in this fashion). Table 8 contains a description and size of each sample site. When necessary, the UCPs were calculated for the five samples, and the average value was used in the extrapolation calculation. Time constraints prevented validation for some of these UCPs.

As a summary of the UCP-land use derivation process, Table 9 lists each UCP and indicates the areas (Phases I, II, III; see Figure 3) that have the parameter value based on actual calculation and the areas that have the value based on the area-weighted averaging of land use specific parameters (i.e., extrapolation). Only eight parameters were based on the samples to compute the average value per land use, and two parameters (mean orientation of streets and land use fraction) were computed for the entire modeling domain. The remaining parameter extrapolations are based on Phase I study area averages. The average UCP values per land

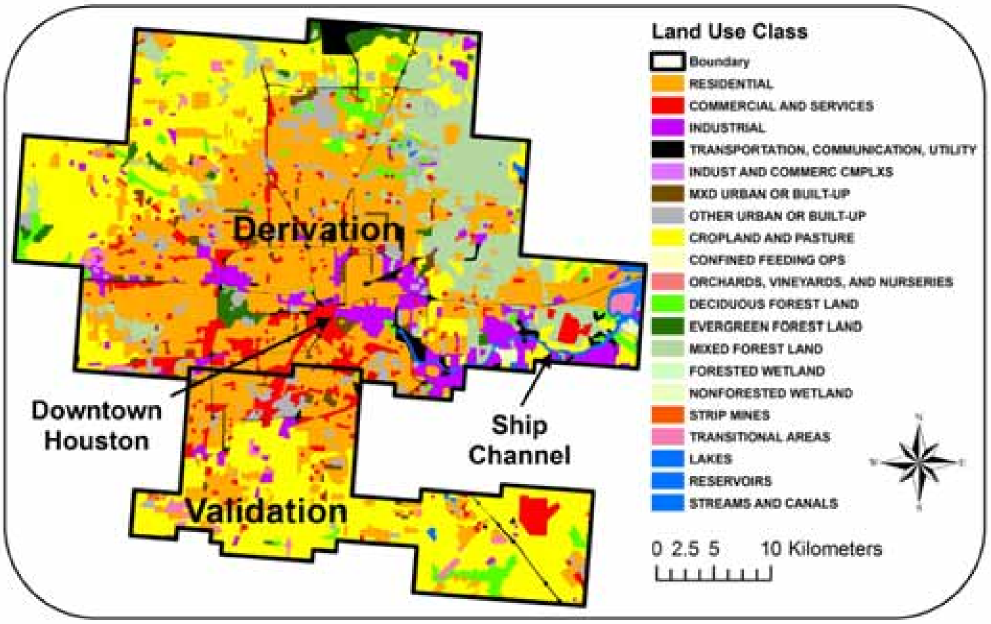

Figure 5. UCP derivation and validation zones overlaying land use.

use and per sample site are included in the UCP Land Use Averages Excel spreadsheet. Only a summary and brief description of the values is given here.

4.1 Average Urban Canopy Parameter Derivation

4.1.1 Building Height Characteristics

Average building height characteristics were determined for the 1235-km^2 UCP derivation section of the Phase I study area. The average values were computed and are listed in Table 10. In some cases, the average values were discarded and other values were assumed (see the UCP Land Use Averages Excel spreadsheet for a full accounting of the assumptions).

Building height histograms were found for each land use based on the buildings contained in the 1235-km^2 UCP derivation section of the Phase I study area. Figure 6 shows the building height histograms for the seven urban land use types. The height histograms are given in terms of number of buildings per square kilometer, which can be used for area-weighted extrapolation. To extrapolate, the number of buildings in each height increment is multiplied by the area of each land use type within each grid cell boundary. The building height histograms for the nonurban land use types are not shown because those land uses contained very few buildings.

The building plan area density, top area density, and frontal area density were also found for the 1235-km^2 UCP derivation section of the Phase I study area. These functions of height are shown in Figures 7, 8, and 9. Figure 7 indicates that the Commercial and Services and Industrial land use types have the highest ground level building plan area fraction on average (0.22 for Commercial and 0.18 for Industrial) and have the most gradual decrease in plan area fraction as height increases.

The building roof area density function shown in Figure 8 clearly shows the concentration of rooftops between 5 and 13 m (predominantly one- to three-story structures). The Commercial and Services, Industrial, and Mixed Urban or Built-Up land use types have the largest roof area

Table 7. Comparison of Areas of Each Land Use Type in the UCP Derivation and Validation Areas

USGS Level 2 Land Use Name	Derivation (km^2)	Validation (km^2)
Residential	481.4	151.5
Commercial and Services	95.6	19.7
Industrial	133.8	22.8
Transportation, Communications, and Utility	46.4	15.5
Mixed Industrial and Commercial	1.0	—
Mixed Urban or Built-Up Land	17.4	1.9
Other Urban or Built-Up Land	71.1	17.4
Cropland and Pasture	148.7	148.7
Orchards, Groves, Vineyards, and Nurseries	—	—
Confined Feeding Operations	—	—
Other Agricultural Land	—	1.1
Herbaceous Rangeland	—	—
Shrub and Brush Rangeland	—	—
Mixed Rangeland	—	—
Deciduous Forest Land	36.7	31.9
Evergreen Forest Land	8.7	—
Mixed Forest Land	147.5	—
Streams and Canals	21.8	—
Lakes	0.6	—
Reservoirs	4.8	2.9
Bays and Estuaries	—	—
Gulf of Mexico	—	—
Forested Wetlands	0.3	—
Nonforested Wetlands	2.7	0.3
Beaches	—	—
Sandy Areas Other Than Beaches	—	—
Bare Exposed Rock	—	—
Strip Mines, Quarries, and Gravel Pits	9.3	1.7
Transitional Areas	4.9	0.6

density values (within the 5- to 9-m increment). Figure 9 indicates that the Commercial and Services, Industrial, and Mixed Urban or Built-Up land use types also have the highest building frontal area densities.

4.1.2 Vegetation Height Characteristics

The mean vegetation height was determined for the five land use samples, and the average is shown in Table 11. As expected, the forest land use types have the highest mean vegetation height. Of the urban land use types, the Residential land use has the highest.

The vegetation plan area density, top area density, and frontal area density were also found for the five land use samples. The average functions for each land use type are shown in Figures 10, 11, and 12. Figure 10 indicates that the two forest land use types have the greatest plan area density at all heights. One other interesting note is the higher plan area density for Residential land use compared to Cropland and Pasture.

Table 8. Sample Site Descriptions (size of area shown in parentheses)

Land Use	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Residential	Older high-density single-family (13 ha)	Older high-density single-family (5 ha)	Newer multifamily apartments (10 ha)	Newer high-density single-family (15 ha)	Older low-density single-family (16 ha)
Commercial and Services	Business and distribution (28 ha)	Office buildings (24 ha)	Shopping mall (58 ha)	Strip commercial (8 ha)	Downtown (28 ha)
Industrial	Mixed warehousing and manufacturing (18 ha)	Manufacturing (25 ha)	Refinery—ship channel (62 ha)	Heavy industrial—ship channel (51 ha)	Warehousing and distribution—ship channel (53 ha)
Mixed Industrial and Commercial	Not enough samples—averaged Commercial and Services and Industrial				
Mixed Urban or Built-Up	Mixed industrial, commercial, and residential (16 ha)	Mixed industrial, commercial, and residential (16 ha)	Industrial, commercial, and multifamily residential (21 ha)	Industrial, warehousing, and mobile and single-family homes (17 ha)	Light industrial, commercial, and mobile and single-family homes (14 ha)
Other Urban or Built-Up	Educational (high school) (21 ha.)	Golf course (43 ha)	New buildings with large tracts of landscaping (19 ha)	Parking area with adjacent landscaping (17 ha)	Industrial-like activity with open pit and open space (18 ha)
Cropland and Pasture	Cropland (56 ha)	Cropland (85 ha)	Mixed cropland and pasture (33 ha)	Mixed cropland and pasture with trees (47 ha)	Mixed cropland and pasture with trees (51 ha)
Orchards, Groves, Vineyards, and Nurseries	No samples—used Cropland and Pasture				
Confined Feeding Operations	No samples—used Cropland and Pasture				
Other Agricultural Land	Not enough land area for sufficient samples—used Cropland and Pasture				
Herbaceous Rangeland	No samples—used Cropland and Pasture				
Shrub and Brush Rangeland	No samples—used Cropland and Pasture				
Mixed Rangeland	No samples—used Cropland and Pasture				
Deciduous Forest Land	Dense forest cover (75 ha)	Dense forest cover (56 ha)	Dense forest cover (96 ha)	Dense forest cover (77 ha)	Dense forest cover (34 ha)
Evergreen Forest Land	Dense forest cover (75 ha)	Dense forest cover (62 ha)	Dense forest cover (21 ha)	Dense forest cover (15 ha)	Dense forest cover (47 ha)
Mixed Forest Land	Dense forest cover (74 ha)	Dense forest cover (32 ha)	Dense forest cover (58 ha)	Dense forest cover (231 ha)	Dense forest cover (88 ha)
Streams and Canals	No samples – parameters easily defined				
Lakes	No samples—parameters easily defined				
Reservoirs	No samples—parameters easily defined				
Bays and Estuaries	No samples—parameters easily defined				
Gulf	No samples—parameters easily defined				
Forested Wetland	Not enough land area for sufficient samples—used Mixed Forest Land				
Nonforested Wetland	Not enough land area for sufficient samples—used Cropland and Pasture				
Beaches	No samples—parameters easily defined				
Sandy Area Non-Beach	No samples—parameters easily defined				
Bare Exposed Rock	No samples—parameters easily defined				
Strip Mines, Quarries, and Gravel Pits	Open pit (75 ha)	Gravel pit (11 ha)	Open pit (185 ha)	Gravel mine (41 ha)	Open pit (51 ha)
Transitional Areas	Not enough land area for sufficient samples—used Strip Mines				

Table 9. Calculation and Extrapolation Extent for Each Urban Canopy Parameter

Urban Canopy Parameter	Calculation[a]	Extrapolation[a]
Mean Building Height	Phase I	Phase II and III
Standard Deviation of Building Height	Phase I	Phase II and III
Mean Building Height Weighted by Footprint Plan Area	Phase I	Phase II and III
Wall-to-Plan Area Ratio	Phase I	Phase II and III
Building Height-to-Width Ratio (λ_s)	Phase I	Phase II and III
Building Height Histograms	Phase I	Phase II and III
Mean Vegetation Height Weighted by Plan Area	Samples	Phase I, II, and III
Mean Canopy Height Weighted by Plan Area	Phase I and II	Phase III
Mean Orientation of Streets	Phase I, II, and III	None
Building Plan Area Density Function [$A_{pb}(z)$]	Phase I	Phase II and III
Vegetation Plan Area Density Function [$A_{pv}(z)$]	Samples	Phase I, II, and III
Canopy Plan Area Density Function [$A_{pc}(z)$]	Phase I	Phase II and III
Building Rooftop Area Density Function [$A_{tb}(z)$]	Phase I	Phase II and III
Vegetation Top Area Density Function [$A_{tv}(z)$]	Samples	Phase I, II, and III
Canopy Top Area Density Function [$A_{tc}(z)$]	Phase I	Phase II and III
Building Frontal Area Density Function [$A_{fb}(z)$]	Phase I	Phase II and III
Vegetation Frontal Area Density Function [$A_{fv}(z)$]	Samples	Phase I, II, and III
Canopy Frontal Area Density Function [$A_{fc}(z)$]	Phase I	Phase II and III
Roughness Length and Displacement Height (Raupach, 1994)	Phase I	Phase II and III
Roughness Length and Displacement Height (Macdonald et al., 1998)	Phase I	Phase II and III
Roughness Length and Displacement Height (Bottema, 1997)	Phase I	Phase II and III
Sky View Factor	Samples	Phase II and III
Plan Area Fraction of Buildings, Roadways/Pavement, Vegetation, Open Water, and Other Cover	Samples	Phase I, II, and III
Land Use Fraction	Phase I, II, and III	None
Building Material Fraction	Samples	Phase I, II, and III
Directly Connected Impervious Area (DCIA)	Samples	Phase I, II, and III

[a]Of the 1653-km^2 Phase I study area, 1235 km^2 were used to derive the average UCP for each land use type, whereas 418 km^2 were used to validate the averaging and extrapolation. The Phase II study area is the 3589-km^2 area of Harris County that has LIDAR data for canopy but no buildings and vegetation. Phase III is the remainder of the modeling domain outside the 5242-km^2 Phases I and II areas of Harris County (see Figure 3).

The vegetation top area density function in Figure 11 clearly shows the concentration of vegetation tops in the 5- to 15-m range. The forest land use types have the largest top area density. Figure 11 indicates that the forest land use types also have the highest vegetation frontal area densities.

4.1.3 Canopy Height Characteristics

The mean canopy height per land use was determined for the 1235 km^2 section of the Phase I study area. Values are listed in Table 12. Note the high canopy height of the forest land, whereas the Residential and Commercial and Services land use types have the highest mean canopy height of the urban land use types.

The canopy plan area density, top area density, and frontal area density also were found for the five land use samples. These functions of height are shown in Figures 13, 14, and 15. Figure 13

Table 10. Average Building Height Characteristics per Land Use in the 1235-km^2 UCP Derivation Area

USGS Level 2 Land Use Name	Number of Buildings	Mean Building Height (m)	Standard Deviation of Building Height (m)	Plan-Area-Weighted Mean Building Height (m)	Wall-to-Plan Area Ratio	Height-to-Width Ratio
Residential	433,811	5.70	3.04	5.49	0.251	0.087
Commercial and Services	28,372	6.05	7.07	8.97	0.214	0.089
Industrial	25,789	6.09	3.73	8.09	0.136	0.054
Transportation, Communications, and Utility	823	4.81	3.54	10.04	0.001	0.013
Mixed Industrial and Commercial	331	4.97	3.42	6.21	0.151	0.060
Mixed Urban or Built-Up Land	11,918	5.72	3.20	6.04	0.246	0.091
Other Urban or Built-Up Land	5246	4.95	2.73	6.00	0.037	0.019
Cropland and Pasture	2187	5.02	3.20	5.50	0.004	0.005
Orchards, Groves, Vineyards, and Nurseries	0	5.02	3.20	5.50	0.004	0.005
Confined Feeding Operations	0	5.02	3.20	5.50	0.004	0.005
Other Agricultural Land	3	5.02	3.20	5.50	0.004	0.005
Herbaceous Rangeland	0	5.02	3.20	5.50	0.004	0.005
Shrub/Brush Rangeland	0	5.02	3.20	5.50	0.004	0.005
Mixed Rangeland	0	5.02	3.20	5.50	0.004	0.005
Deciduous Forest Land	677	7.32	4.42	7.64	0.007	0.006
Evergreen Forest Land	61	5.51	3.45	5.27	0.002	0.003
Mixed Forest Land	1525	6.74	4.13	5.89	0.003	0.004
Streams and Canals	0	—	—	—	—	—
Lakes	0	—	—	—	—	—
Reservoirs	0	—	—	—	—	—
Bays and Estuaries	0	—	—	—	—	—
Gulf of Mexico	0	—	—	—	—	—
Forested Wetlands	0	6.74	4.13	5.89	0.003	0.004
Nonforested Wetlands	0	5.02	3.20	5.50	0.004	0.005
Beaches	0	—	—	—	—	—
Sandy Areas	0	—	—	—	—	—
Bare Exposed Rock	0	—	—	—	—	—
Strip Mines, Quarries, and Gravel Pits	100	4.10	1.83	4.72	0.003	0.004
Transitional Areas	16	—	—	—	—	—

indicates that the two forest land use types have the greatest plan area density near the ground surface (<25 m), whereas, above 25 m, the Commercial and Services land use has the highest plan area density. One other interesting observation is the higher plan area density for Residential land use near the ground level.

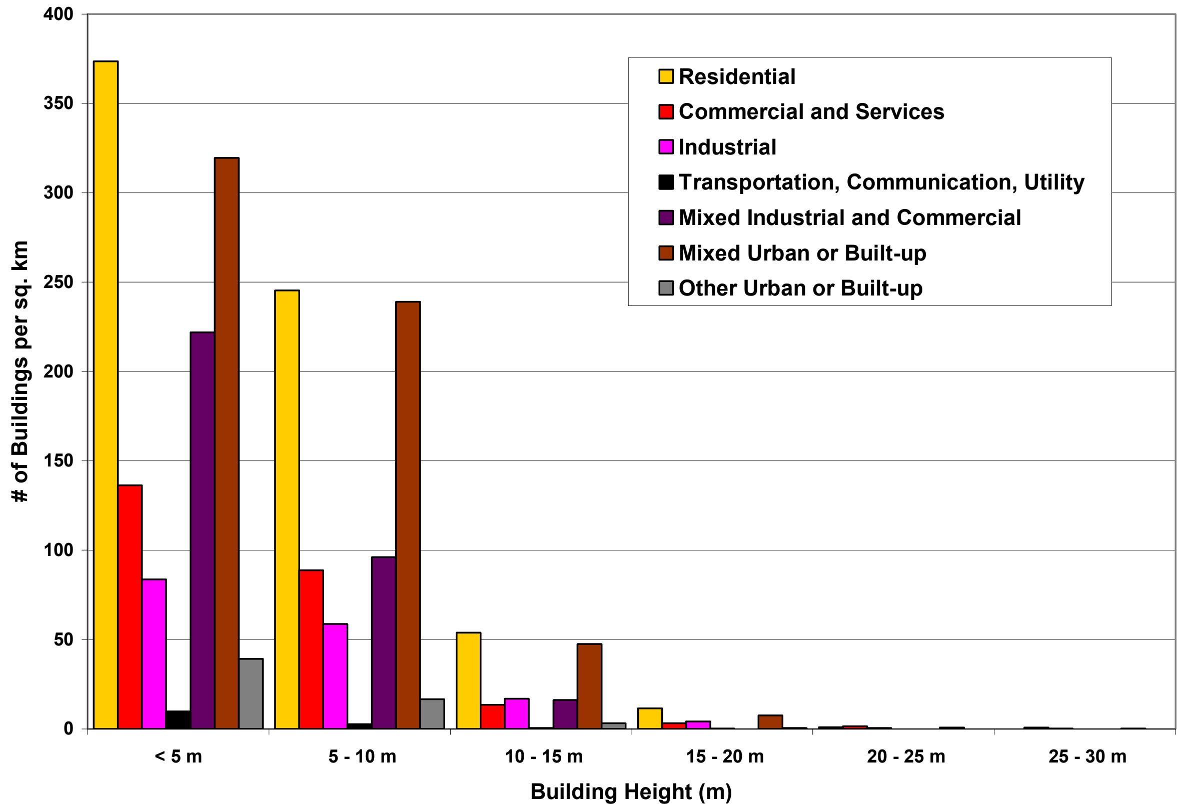

Figure 6. Building height histograms. Number of buildings on average in 5-m height increments for each urban land use type.

The canopy top area density functions in Figure 14 clearly show the concentration of canopy top in the 5- to 10-m range for most land uses, except forested types. The forest land use types have the largest top area density. Figure 15 indicates that the forest land use types also have the highest vegetation frontal area densities near the ground, whereas the Commercial and Services has the highest above 28 m.

4.1.4 Sky View Factor

The mean sky view factor was determined for the five sample sites for each land use type. The average of the five is shown in Table 13.

4.1.5 Displacement Height and Roughness Length

The displacement height and roughness length were determined according to three sets of morphometric equations as described above. The average displacement heights and roughness lengths based on the five land use samples are listed in Tables 14 and 15, respectively. Interestingly, there is significant variability in roughness length and displacement height for the different equation methods used. This discrepancy is being explored further, and the findings will be reported later.

4.1.6 Building Material

Using guidance developed from the COH Planning and Development Department Tax Roll Records, a matrix of assumed fractions of building materials per land use type was developed (see Table 16). These values are by far the most uncertain of the UCPs presented in this report.

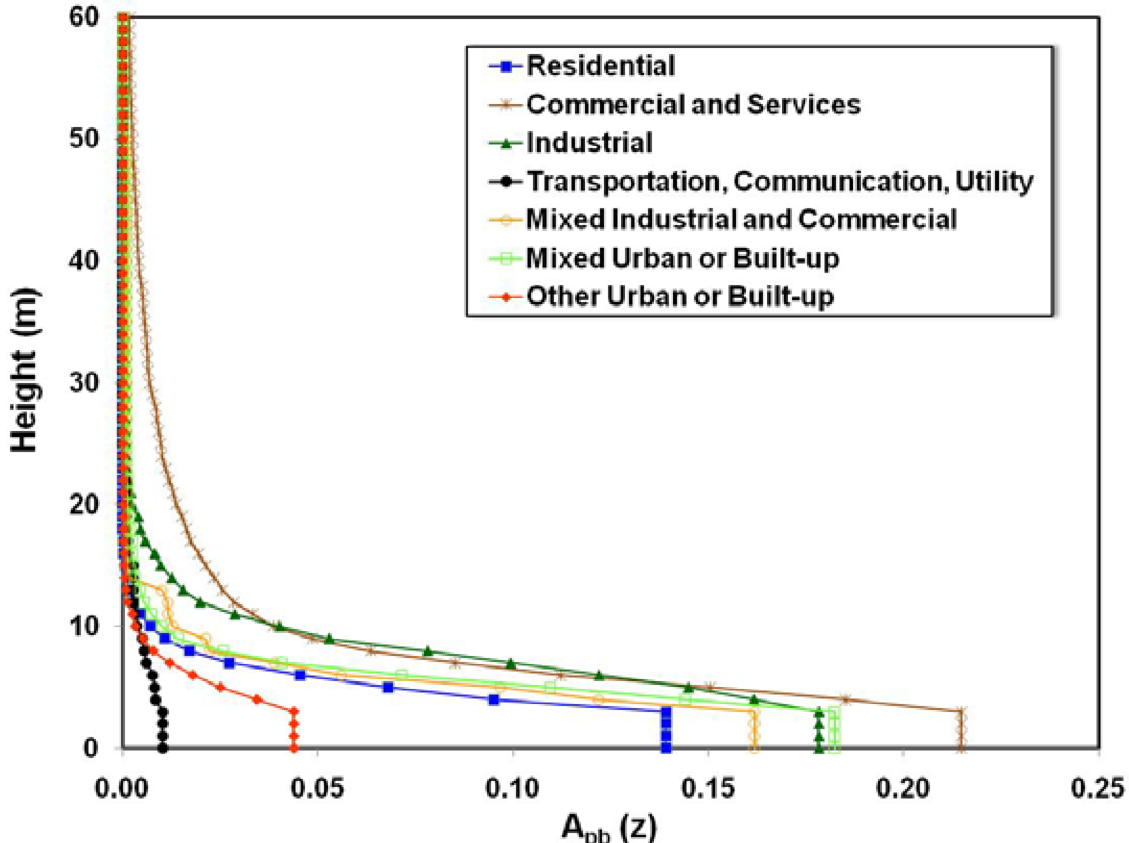

Figure 7. Building plan area density computed for the 1235-km^2 UCP derivation section in Houston (shown are the values for the USGS level 2 urban land use types).

If buildings are not a significant fraction of the land use surface area (i.e., low plan area fractions), then the building material fractions are listed as zero for all materials.

4.1.7 Percent Directly Connected Impervious Area

The percent DCIA was determined for the five sample sites for each land use type. The mean value for each land use type is listed in Table 17. Because of insufficient samples the following assumptions were made.

- The DCIA for Mixed Industrial and Commercial is assumed to be the average of Industrial and Commercial and Services.
- Cropland and Pasture DCIA was used for the following land use types: Orchards, Groves, Vineyards, and Nurseries; Confined Feeding Operations; Other Agricultural Land; Herbaceous Rangeland; Shrub and Brush Rangeland; Mixed Rangeland; Nonforested Wetland. Mixed Forest Land DCIA was used for Forested Wetland.
- All water surfaces were assumed to have a DCIA of zero (this might be modified if downstream water flow is of interest).
- Beaches, Sandy Non-Beach, and Bare Exposed Rock all were assumed to have a zero DCIA; Transitional Areas were assumed to have the same DCIA of Strip Mines.

4.1.8 Fraction Land Cover

The average fraction land cover for each land use is determined from the five sample sites. Table 18 lists the average fractions computed.

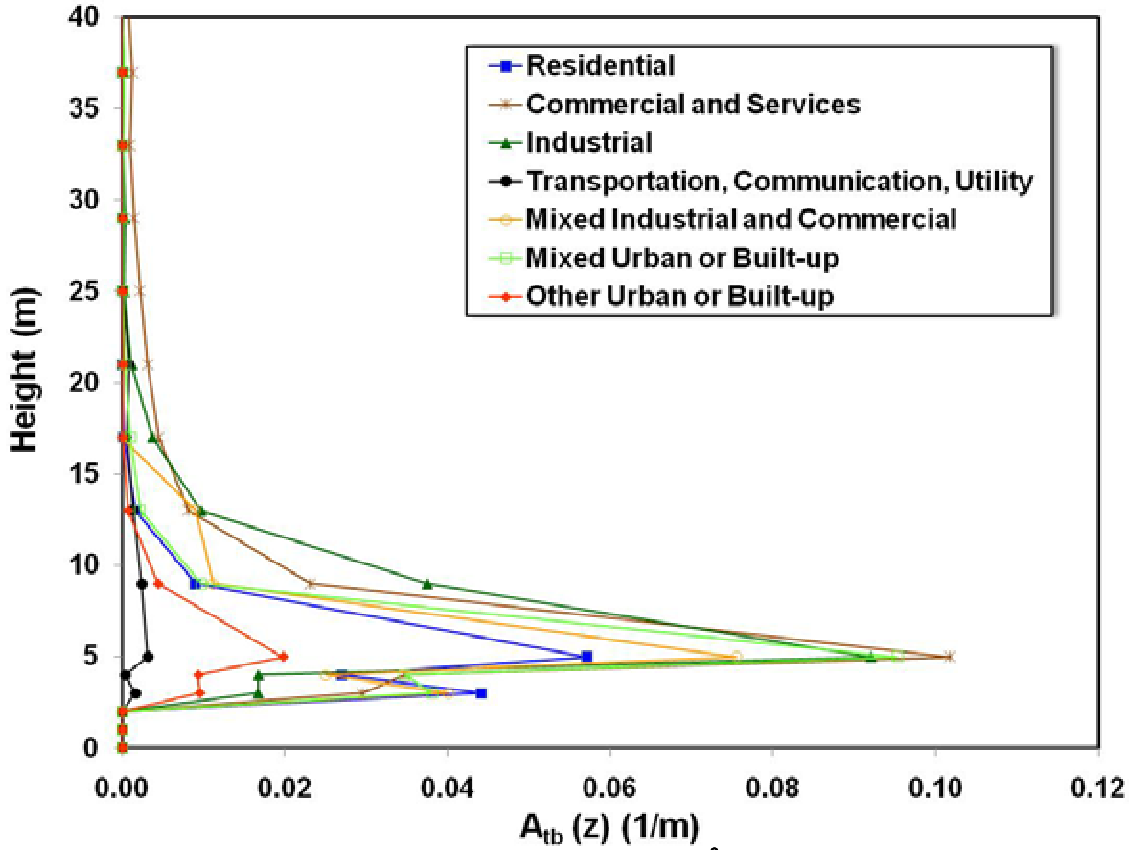

Figure 8. Building top area density computed for the 1235-km^2 UCP derivation section in Houston (shown are the values for the USGS level 2 urban land use types).

4.2 UCP Assessment and Validation

An assessment of the accuracy of the UCP extrapolation procedure was performed for most of the parameters computed. The assessment was conducted by comparing the actual calculated values for each grid cell in the 418-km^2 UCP validation area with the extrapolated values. The validation area is south of the UCP derivation area (see Figure 5) and contains a fairly representative distribution of land use types. In addition, because the validation area is adjacent, much of the styles of the land use development will be similar (e.g., residential subdivisions likely will be fairly similar in form). This assessment will indicate the relative level of confidence for each UCP value.

The relative similarity of the 418 pairs of calculated and extrapolated UCPs is determined through the computation of several summary statistics:

$$\text{Bias} = \frac{1}{n}\sum_{i=1}^{n}\left(UCP_i - \overline{UCP_i}\right), \tag{24}$$

$$\text{Root Mean Square Error (RMSE)} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(UCP_i - \overline{UCP_i}\right)^2}, \text{ and} \tag{25}$$

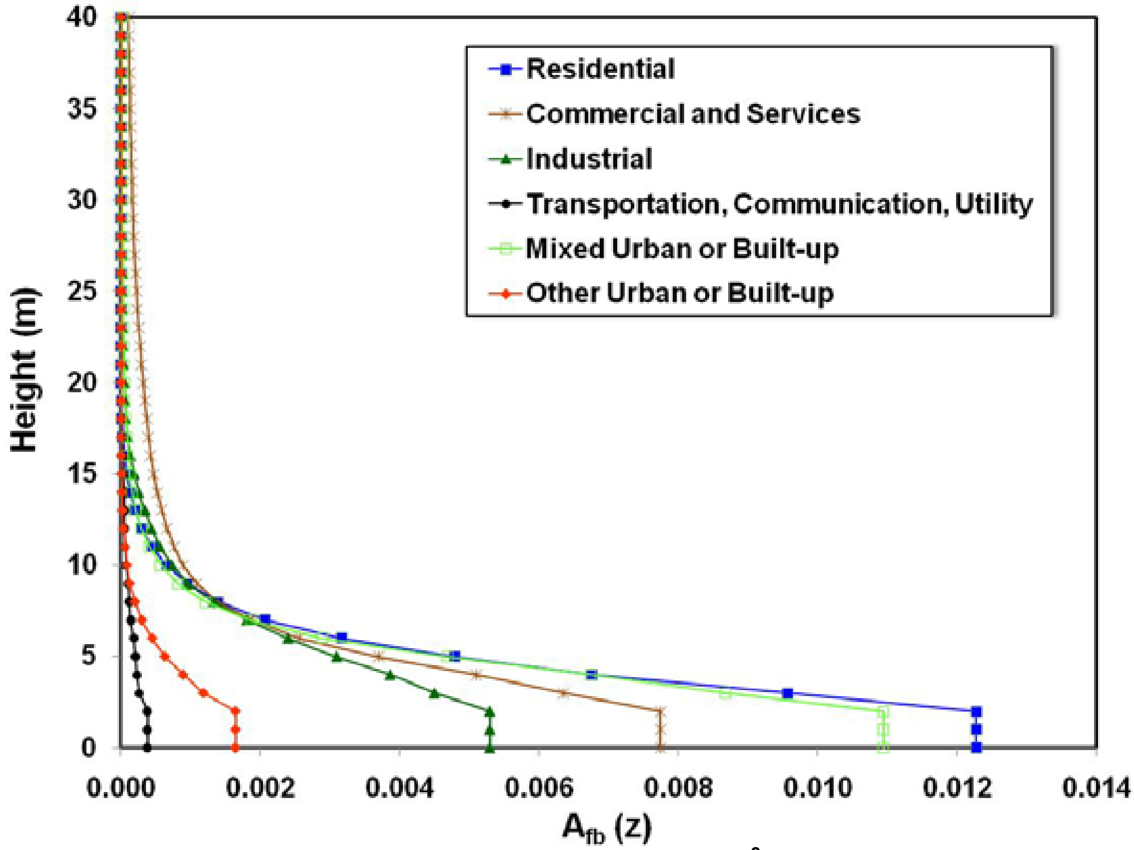

Figure 9. Building frontal area density computed for the 1235-km^2 UCP derivation section in Houston for a wind from the north direction (shown are the values for the USGS level 2 urban land use types).

$$\text{Cumulative Relative Error (CRE)} = 100 \cdot \frac{\sum_{i=1}^{n} \left| UCP_i - \overline{UCP_i} \right|}{\sum_{i=1}^{n} \overline{UCP_i}}, \qquad (26)$$

where UCP_i is the extrapolated UCP for the i^{th} grid cell, $\overline{UCP_i}$ is the calculated UCP for the i^{th} grid cell, and n is the number of grid cells (418). In addition to the calculation of the statistics, scatter plots also were produced to visualize the relative match between the pairs.

4.2.1 Building Height Characteristics

The bias, root mean square error (RMSE), and cumulative relative error (CRE) for the building height characteristics extrapolation are shown in Table 19. The bias column includes a percent change indicating the relative increase or decrease for the extrapolated values compared with the calculated values. For example, the results indicate that the extrapolated mean building height per grid cell is 23% higher on average than the calculated mean building height. The comparison statistics clearly show that, on average, the extrapolation will result in higher building height UCPs compared with calculation from actual data. One possible explanation is the fact that the UCP derivation area included downtown Houston, which would have elevated the average building height characteristics. This was anticipated at the outset of the project but,

Table 11. Mean Vegetation Height per Land Use Type

USGS Level 2 Land Use Name	Mean Vegetation Height (m)	Notes
Residential	4.03	
Commercial and Services	2.90	
Industrial	1.16	
Transportation, Communications, and Utility	0.27	
Mixed Industrial and Commercial	2.03	
Mixed Urban or Built-Up Land	2.77	
Other Urban or Built-Up Land	2.43	
Cropland and Pasture	1.13	
Orchards, Groves, Vineyards, and Nurseries	1.13	Used Cropland and Pasture
Confined Feeding Operations	1.13	Used Cropland and Pasture
Other Agricultural Land	1.13	Used Cropland and Pasture
Herbaceous Rangeland	1.13	Used Cropland and Pasture
Shrub and Brush Rangeland	1.13	Used Cropland and Pasture
Mixed Rangeland	1.13	Used Cropland and Pasture
Deciduous Forest Land	11.83	
Evergreen Forest Land	9.09	
Mixed Forest Land	9.76	
Streams and Canals	—	No vegetation
Lakes	—	No vegetation
Reservoirs	—	No vegetation
Bays and Estuaries	—	No vegetation
Gulf of Mexico	—	No vegetation
Forested Wetlands	9.76	Used Mixed Forest Land
Nonforested Wetlands	1.13	Used Cropland and Pasture
Beaches	—	No vegetation
Sandy Areas Other Than Beaches	—	No vegetation
Bare Exposed Rock	—	No vegetation
Strip Mines, Quarries, and Gravel Pits	3.16	
Transitional Areas	—	Assumed no vegetation

given the small area of the downtown core compared with the entire UCP derivation area, the effect was determined to be small.

For the building height characteristics, it was also feasible to compare parameters as a function of land use type. Table 20 shows the mean building height and standard deviation of building height as calculated in the UCP derivation and validation areas. The Residential and Industrial land uses have the greatest difference in mean building height between the derivation and validation areas. This was unexpected because it was anticipated that the Commercial and Services land use, which included downtown Houston, would have the greatest difference because of the presence of skyscrapers in the derivation area and not in the validation area. The large difference in the Industrial area may be caused by the ship channel industries making up most of the Industrial land use in the derivation area, whereas standard industrial parks made up the Industrial land use in the validation area.

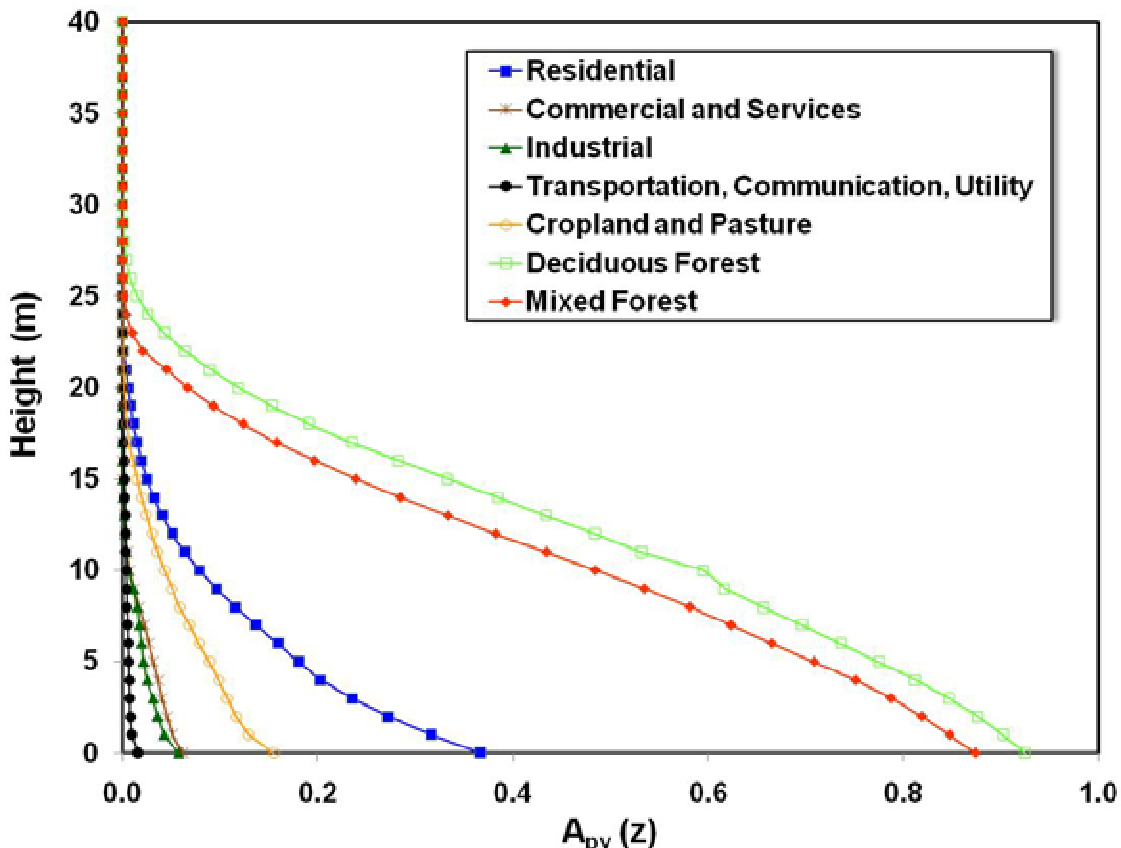

Figure 10. Vegetation plan area density computed for the 1235-km^2 UCP derivation section in Houston (shown are the values for selected USGS level 2 land use types).

Scatter plots were produced to visualize the relative comparison between calculated and extrapolated values in the validation area. Figures 16 and 17 show the scatter plots for the mean and standard deviation of building height, respectively. The figures visualize the increased frequency of overprediction by the extrapolation process, as was shown in the summary statistics above. Another observation that must be explained is the lower threshold for the extrapolated values visible in the plots. This may be occurring because of several reasons. First, the average values for building height characteristics used in the extrapolation assume that buildings will be present in all land uses, even if it is a very small number of buildings. But, some grid cells will not contain buildings. The grid cells with zero calculated height did not contain buildings, and these significantly affect the appearance of the scatter plot (i.e., no points found near 0,0). Another possible reason for the appearance of a lower threshold on extrapolated values is the potential for errors in building heights used to determine the calculated values. Errors in height will be more pronounced in grid cells with a small number of buildings.

The scatter plot for the plan-area-weighted mean building height is shown in Figure 18, which is similar to the mean building height and standard deviation scatter plots. Figures 19 and 20 display the scatter plots of the wall-to-plan area ratio and the height-to-width ratio, respectively. The match between extrapolated and calculated values is much better for these two ratios, except for the extremely large calculated values. But the lower threshold is not noted because the ratio values take into account the density of the buildings (i.e., how many per area and how far apart they are). Therefore, the average values used for extrapolation will include rather small values that accurately can represent the small values calculated in the grid cell. This was not possible for the mean height, standard deviation, and plan-area-weighted height because the

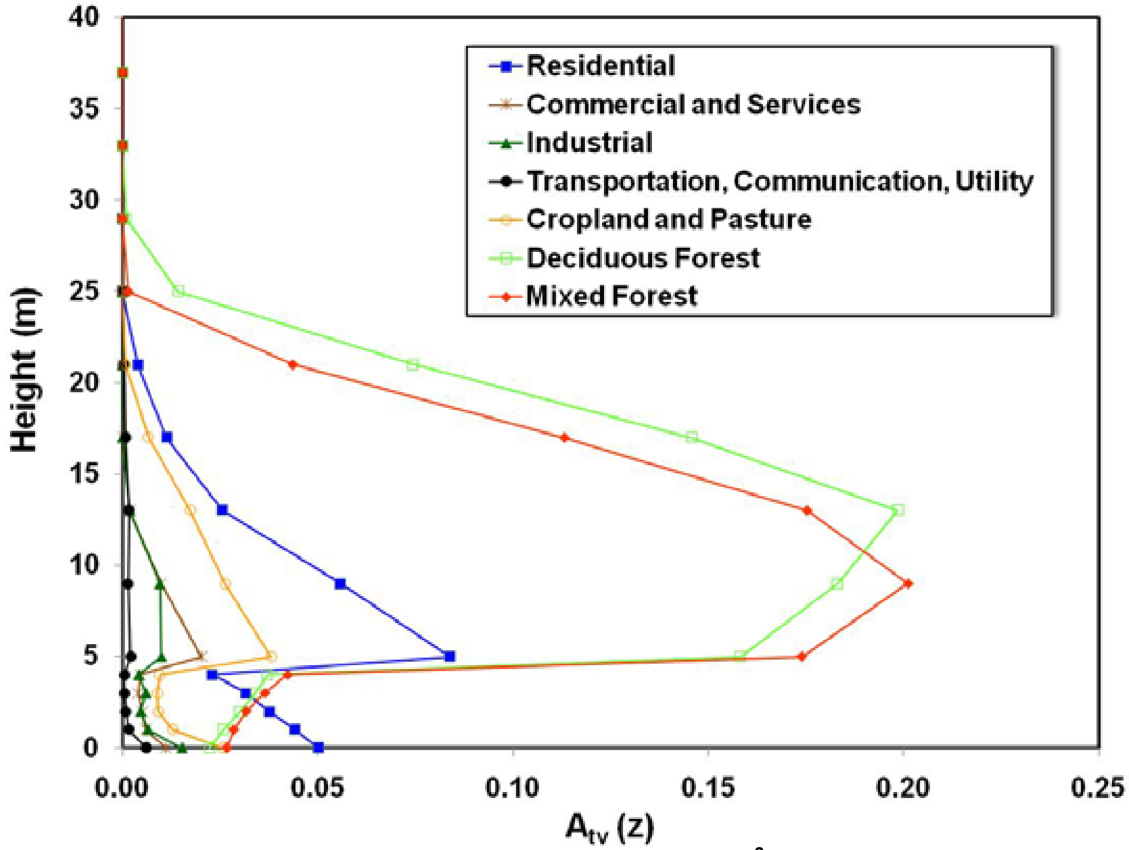

Figure 11. Vegetation top area density computed for the 1235-km^2 UCP derivation section in Houston (shown are the values for selected USGS level 2 land use types).

average values used in the extrapolation did not account for the number of buildings or density. Clearly, the extrapolation will not be able to capture the extremes (small or large calculated values) because average values are used, but, for most parameters, the match will be fair except for the extremely large values. Thus, the average values may be sufficient to provide an acceptable estimation for most of the UCPs.

The accuracy of the extrapolation of the building height histograms, building plan area density, top area density, and frontal area density was assessed by computing the bias, RMSE, and CRE for 25 randomly selected grid cells of the 418 validation cells. The mean, minimum, and maximum bias, RMSE, and CRE are shown in Table 21. The CRE suggests that the building frontal area density and building plan area density are predicted across all elevations with the most accuracy. The building height histograms and building top area density also are predicted fairly well. In most cases, the mean values are affected significantly by the maximum value, and the maximum value is an outlier that is especially poorly predicted.

4.2.2 Canopy Height Characteristics

The Bias, RMSE, and CRE for the canopy height characteristics extrapolation are shown in Table 22. The bias column includes a percent change indicating the relative increase or decrease for the extrapolated values compared with the calculated values. For example, the results indicate that the extrapolated mean canopy height per grid cell is 36% higher, on average, than the calculated mean canopy height. The comparison statistics clearly show that, on average, the extrapolation will result in elevated canopy height UCPs compared with

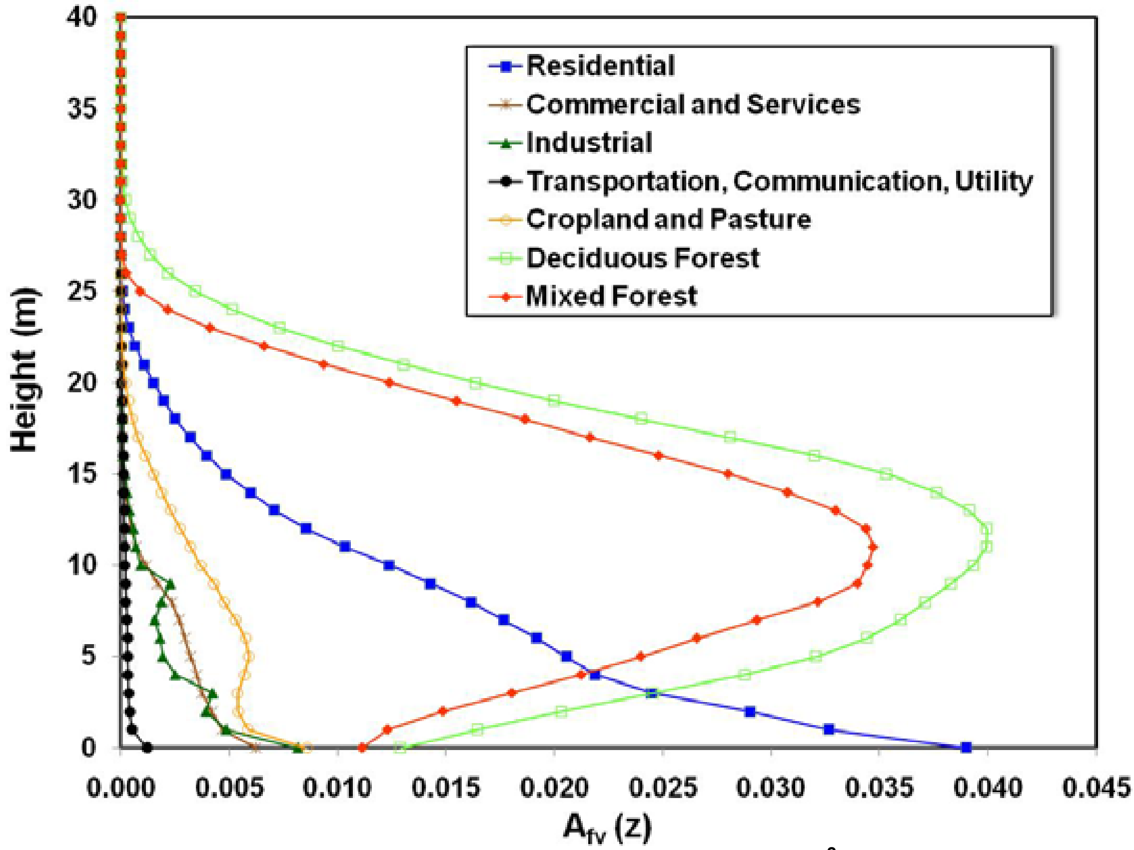

Figure 12. Vegetation frontal area density computed for the 1235-km² UCP derivation section in Houston for a wind from the north direction (shown are the values for selected USGS level 2 land use types).

calculation from actual data. The anticipated overprediction of roughness length and displacement height is expected to be approximately 30% to 40%.

Scatter plots were produced to visualize the relative comparison between calculated and extrapolated values in the validation area. Figure 21 shows the scatter plot for the mean canopy height. The scatter of the data pairs for the mean canopy height is greater than the scatter for the mean building height. Thus, it appears that the mean canopy height extrapolation will produce, on average, less accurate values than the mean building height.

The scatter plots for the roughness length and displacement extrapolations also were prepared. Figures 22 and 23 display the scatter plots for roughness length and displacement height computed using the Macdonald et al. (1998) set of equations, whereas Figures 24 and 25 show z_o and z_d for the Raupach (1994) set of equations. It was not possible to perform the validation for the Bottema (1997) equations because the extrapolation was based on samples. Figures 22 and 23 indicate that the roughness length extrapolation is less accurate than the displacement height extrapolation. In fact, the displacement height extrapolation appears to be very accurate. Figures 24 and 25 indicate that the displacement height calculated by the Raupach (1994) equations is more accurately extrapolated than the roughness length calculated by the Macdonald et al. (1998) equations.

Table 12. Mean Canopy Height per Land Use Type

USGS Level 2 Land Use Name	Mean Canopy Height (m)	Notes
Residential	7.39	
Commercial and Services	7.11	
Industrial	5.59	
Transportation, Communications, and Utility	5.96	
Mixed Industrial and Commercial	4.81	
Mixed Urban or Built-Up Land	6.31	
Other Urban or Built-Up Land	6.15	
Cropland and Pasture	6.02	
Orchards, Groves, Vineyards, and Nurseries	6.02	Used Cropland and Pasture
Confined Feeding Operations	6.02	Used Cropland and Pasture
Other Agricultural Land	6.02	Used Cropland and Pasture
Herbaceous Rangeland	6.02	Used Cropland and Pasture
Shrub and Brush Rangeland	6.02	Used Cropland and Pasture
Mixed Rangeland	6.02	Used Cropland and Pasture
Deciduous Forest Land	11.06	
Evergreen Forest Land	11.79	
Mixed Forest Land	10.51	
Streams and Canals	0.00	
Lakes	0.00	
Reservoirs	0.00	
Bays and Estuaries	0.00	
Gulf of Mexico	0.00	
Forested Wetlands	10.51	Used Mixed Forest Land
Nonforested Wetlands	6.02	Used Cropland and Pasture
Beaches	0.00	
Sandy Areas Other Than Beaches	0.00	
Bare Exposed Rock	0.00	
Strip Mines, Quarries, and Gravel Pits	2.56	
Transitional Areas	0.00	

The accuracy of the extrapolation of the canopy plan are density and top area density was assessed by computing the bias, RMSE, and CRE for 25 randomly selected grid cells of the 418 validation cells (the same 25 that were used for the building height histogram, plan area density, top area density, and frontal area density validation assessments). The mean, minimum, and maximum bias, RMSE, and CRE are shown in Table 23. The results suggest that the extrapolation of the canopy plan and top area densities are fairly accurate. The minimum CRE values indicate that, for some grid cells, the extrapolation produces a density function very close to that calculated, and the mean CRE indicates that only 50% cumulative relative error is to be expected, on average.

Overall, the assessment indicates that, although there may be significant error associated with the extrapolation for individual grid cells, on average, the errors will be moderate and have a minimal impact on model results.

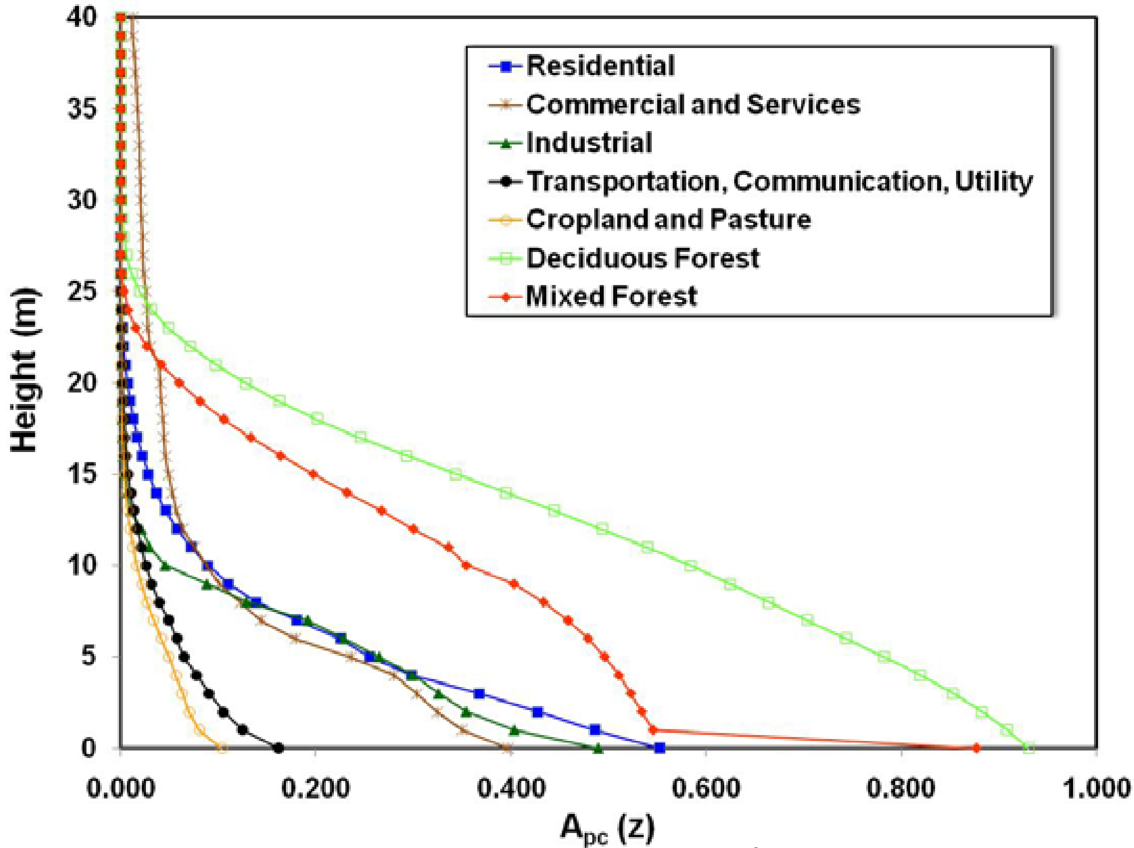

Figure 13. Canopy plan area densities computed for the 1235-km^2 UCP derivation section in Houston (shown are the values for selected USGS level 2 land use types).

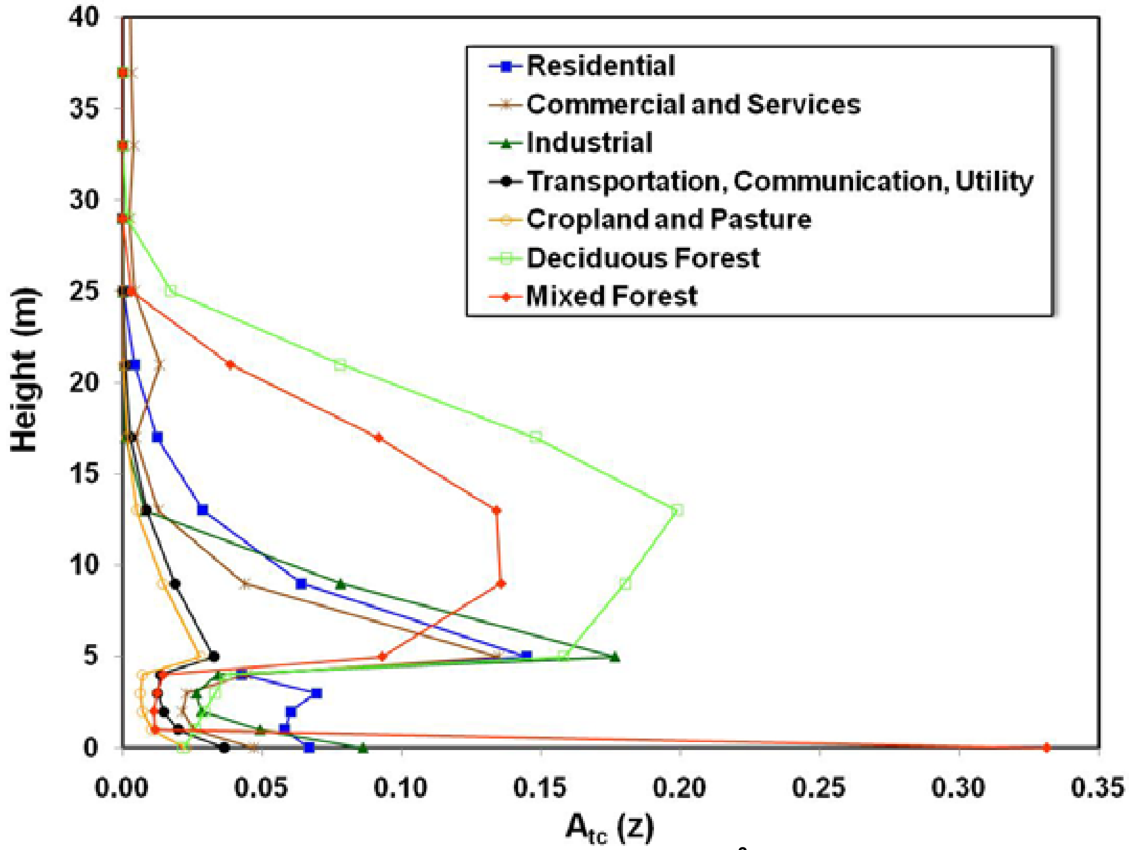

Figure 14. Canopy top area densities computed for the 1235-km^2 UCP derivation section in Houston (shown are the values for selected USGS level 2 land use types).

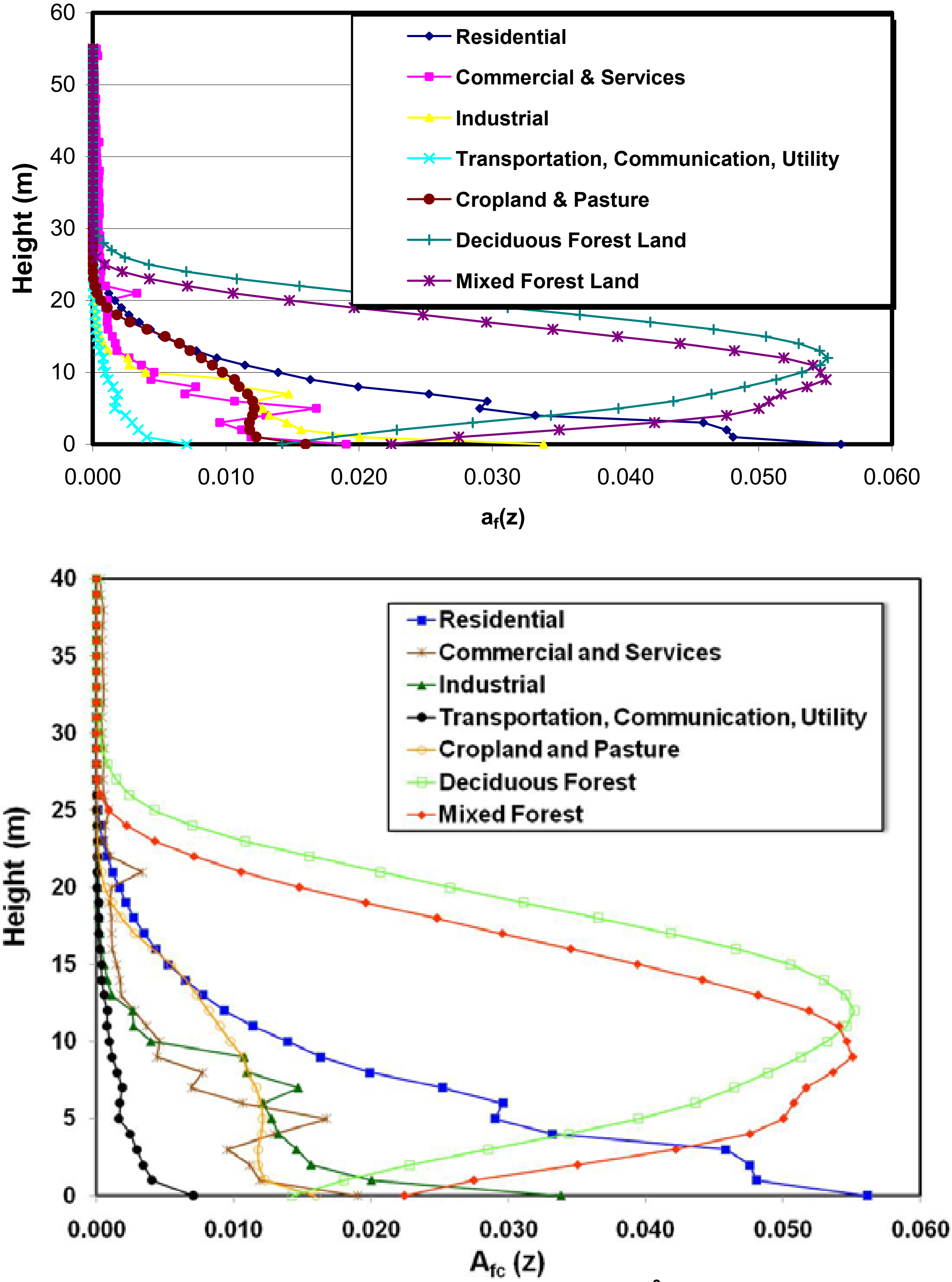

Figure 15. Canopy frontal area densities computed for the 1235-km^2 UCP derivation section in Houston for a wind from the north direction (shown are the values for selected USGS level 2 land use types).

Table 13. Mean Sky View Factor per Land Use Type

USGS Level 2 Land Use Name	Mean Sky View Factor
Residential	0.70
Commercial and Services	0.81
Industrial	0.82
Transportation, Communications, and Utility	0.91
Mixed Industrial and Commercial	0.81
Mixed Urban or Built-Up Land	0.78
Other Urban or Built-Up Land	0.84
Cropland and Pasture	0.94
Orchards, Groves, Vineyards, and Nurseries	0.94
Confined Feeding Operations	0.94
Other Agricultural Land	0.94
Herbaceous Rangeland	0.94
Shrub and Brush Rangeland	0.94
Mixed Rangeland	0.94
Deciduous Forest Land	0.61
Evergreen Forest Land	0.65
Mixed Forest Land	0.78
Streams and Canals	1.00
Lakes	1.00
Reservoirs	1.00
Bays and Estuaries	1.00
Gulf of Mexico	1.00
Forested Wetlands	0.78
Nonforested Wetlands	0.94
Beaches	1.00
Sandy Areas Other Than Beaches	1.00
Bare Exposed Rock	1.00
Strip Mines, Quarries, and Gravel Pits	0.96
Transitional Areas	1.00

Table 14. Mean Displacement Height per Land Use Type (for north wind)

USGS Level 2 Land Use Name	Mean Displacement Height—Raupach (m)	Mean Displacement Height—Macdonald (m)	Mean Displacement Height—Bottema (m)
Residential	4.69	5.94	2.89
Commercial and Services	3.42	4.74	3.65
Industrial	2.81	4.21	2.63
Transportation, Communications, and Utility	1.68	2.04	0.17
Mixed Industrial and Commercial	3.13	4.52	3.14
Mixed Urban or Built-Up Land	4.21	4.82	3.02
Other Urban or Built-Up Land	3.90	3.42	2.22
Cropland and Pasture	3.06	1.39	0.18
Orchards, Groves, Vineyards, and Nurseries	3.06	1.39	0.18
Confined Feeding Operations	3.06	1.39	0.18
Other Agricultural Land	3.06	1.39	0.18
Herbaceous Rangeland	3.06	1.39	0.18
Shrub and Brush Rangeland	3.06	1.39	0.18
Mixed Rangeland	3.06	1.39	0.18
Deciduous Forest Land	8.15	10.87	13.23
Evergreen Forest Land	8.02	10.94	11.26
Mixed Forest Land	7.69	10.16	10.36
Streams and Canals	0.00	0.00	0.00
Lakes	0.00	0.00	0.00
Reservoirs	0.00	0.00	0.00
Bays and Estuaries	0.00	0.00	0.00
Gulf of Mexico	0.00	0.00	0.00
Forested Wetlands	7.69	10.16	10.36
Nonforested Wetlands	3.06	1.39	0.18
Beaches	0.00	0.00	0.00
Sandy Areas Other Than Beaches	0.00	0.00	0.00
Bare Exposed Rock	0.00	0.00	0.00
Strip Mines, Quarries, and Gravel Pits	1.08	0.82	0.02
Transitional Areas	0.00	0.00	0.00

Table 15. Mean Roughness Length per Land Use Type (for north wind)

USGS Level 2 Land Use Name	Mean Roughness Length—Raupach (m)	Mean Roughness Length—Macdonald (m)	Mean Roughness Length—Bottema (m)
Residential	0.86	0.24	1.05
Commercial and Services	0.72	0.24	0.98
Industrial	0.61	0.11	0.74
Transportation, Communications, and Utility	0.15	0.12	0.17
Mixed Industrial and Commercial	0.67	0.17	0.86
Mixed Urban or Built-Up Land	0.67	0.35	1.10
Other Urban or Built-Up Land	0.72	0.83	1.84
Cropland and Pasture	0.67	1.15	1.01
Orchards, Groves, Vineyards, and Nurseries	0.67	1.15	1.01
Confined Feeding Operations	0.67	1.15	1.01
Other Agricultural Land	0.67	1.15	1.01
Herbaceous Rangeland	0.67	1.15	1.01
Shrub and Brush Rangeland	0.67	1.15	1.01
Mixed Rangeland	0.67	1.15	1.01
Deciduous Forest Land	0.93	0.00	0.48
Evergreen Forest Land	1.21	0.07	0.54
Mixed Forest Land	0.90	0.02	0.29
Streams and Canals	0.00	0.00	0.00
Lakes	0.00	0.00	0.00
Reservoirs	0.00	0.00	0.00
Bays and Estuaries	0.00	0.00	0.00
Gulf of Mexico	0.00	0.00	0.00
Forested Wetlands	0.90	0.02	0.29
Nonforested Wetlands	0.67	1.15	1.01
Beaches	0.00	0.00	0.00
Sandy Areas Other Than Beaches	0.00	0.00	0.00
Bare Exposed Rock	0.00	0.00	0.00
Strip Mines, Quarries, and Gravel Pits	0.20	0.24	0.48
Transitional Areas	0.00	0.00	0.00

Table 16. Assumed Building Material Fraction per Land Use Type

USGS Level 2 Land Use Name	Concrete	Wood	Steel	Brick	Mixed
Residential	0.10	0.30	0.00	0.30	0.30
Commercial and Services	0.30	0.10	0.30	0.10	0.20
Industrial	0.10	0.05	0.60	0.05	0.20
Transportation, Communications, and Utility	—	—	—	—	—
Mixed Industrial and Commercial	0.20	0.08	0.45	0.07	0.20
Mixed Urban or Built-Up Land	0.20	0.20	0.20	0.20	0.20
Other Urban or Built-Up Land	0.50	0.10	0.00	0.30	0.10
Cropland and Pasture	—	—	—	—	—
Orchards, Groves, Vineyards, and Nurseries	—	—	—	—	—
Confined Feeding Operations	—	—	—	—	—
Other Agricultural Land	—	—	—	—	—
Herbaceous Rangeland	—	—	—	—	—
Shrub and Brush Rangeland	—	—	—	—	—
Mixed Rangeland	—	—	—	—	—
Deciduous Forest Land	—	—	—	—	—
Evergreen Forest Land	—	—	—	—	—
Mixed Forest Land	—	—	—	—	—
Streams and Canals	—	—	—	—	—
Lakes	—	—	—	—	—
Reservoirs	—	—	—	—	—
Bays and Estuaries	—	—	—	—	—
Gulf of Mexico	—	—	—	—	—
Forested Wetlands	—	—	—	—	—
Nonforested Wetlands	—	—	—	—	—
Beaches	—	—	—	—	—
Sandy Areas Other Than Beaches	—	—	—	—	—
Bare Exposed Rock	—	—	—	—	—
Strip Mines, Quarries, and Gravel Pits	—	—	—	—	—
Transitional Areas	—	—	—	—	—

Table 17. Mean Percent DCIA per Land Use Type

USGS Level 2 Land Use Name	Mean DCIA (%)
Residential	26.5
Commercial and Services	86.4
Industrial	74.1
Transportation, Communications, and Utility	70.3
Mixed Industrial and Commercial	80.3
Mixed Urban or Built-Up Land	49.7
Other Urban or Built-Up Land	24.5
Cropland and Pasture	1.2
Orchards, Groves, Vineyards, and Nurseries	1.2
Confined Feeding Operations	1.2
Other Agricultural Land	1.2
Herbaceous Rangeland	1.2
Shrub and Brush Rangeland	1.2
Mixed Rangeland	1.2
Deciduous Forest Land	2.3
Evergreen Forest Land	0.0
Mixed Forest Land	1.2
Streams and Canals	0.0
Lakes	0.0
Reservoirs	0.0
Bays and Estuaries	0.0
Gulf of Mexico	0.0
Forested Wetlands	1.2
Nonforested Wetlands	1.2
Beaches	0.0
Sandy Areas Other Than Beaches	0.0
Bare Exposed Rock	0.0
Strip Mines, Quarries, and Gravel Pits	3.3
Transitional Areas	0.0

Table 18. Fraction Land Cover per Land Use Type

USGS Level 2 Land Use Name	Roadway /Parking	Building	Vegetation	Open Water	Other
Residential	0.210	0.219	0.570	0.000	0.001
Commercial and Services	0.610	0.255	0.135	0.000	0.000
Industrial	0.471	0.240	0.230	0.002	0.057
Transportation, Communications, and Utility	0.507	0.007	0.267	0.000	0.219
Mixed Industrial and Commercial	0.541	0.248	0.182	0.001	0.028
Mixed Urban or Built-Up Land	0.356	0.219	0.424	0.000	0.000
Other Urban or Built-Up Land	0.184	0.070	0.725	0.005	0.017
Cropland and Pasture	0.022	0.002	0.975	0.001	0.000
Orchards, Groves, Vineyards, and Nurseries	0.022	0.002	0.975	0.001	0.000
Confined Feeding Operations	0.022	0.002	0.975	0.001	0.000
Other Agricultural Land	0.022	0.002	0.975	0.001	0.000
Herbaceous Rangeland	0.022	0.002	0.975	0.001	0.000
Shrub and Brush Rangeland	0.022	0.002	0.975	0.001	0.000
Mixed Rangeland	0.022	0.002	0.975	0.001	0.000
Deciduous Forest Land	0.023	0.000	0.977	0.000	0.000
Evergreen Forest Land	0.000	0.000	1.000	0.000	0.000
Mixed Forest Land	0.012	0.000	0.988	0.000	0.000
Streams and Canals	0.000	0.000	0.000	1.000	0.000
Lakes	0.000	0.000	0.000	1.000	0.000
Reservoirs	0.000	0.000	0.000	1.000	0.000
Bays and Estuaries	0.000	0.000	0.000	1.000	0.000
Gulf of Mexico	0.000	0.000	0.000	1.000	0.000
Forested Wetlands	0.012	0.000	0.988	0.000	0.000
Nonforested Wetlands	0.022	0.002	0.975	0.001	0.000
Beaches	0.000	0.000	0.000	0.000	1.000
Sandy Areas Other Than Beaches	0.000	0.000	0.000	0.000	1.000
Bare Exposed Rock	0.000	0.000	0.000	0.000	1.000
Strip Mines, Quarries, and Gravel Pits	0.034	0.008	0.079	0.027	0.851
Transitional Areas	0.000	0.000	0.000	0.000	1.000

Table 19. Comparison Statistics for the Calculated and Extrapolated Building Height Characteristics

	Bias	RMSE	CRE
Mean Building Height	1.024 (+23%)	1.643	28%
Standard Deviation of Building Height	1.471 (+75%)	1.849	83%
Footprint Area-Weighted Mean Height	1.153 (+23%)	2.392	34%
Wall-to-Plan Area Ratio	0.009 (+9%)	0.052	31%
Height-to-Width Ratio	0.004 (+11%)	0.022	37%

Table 20. Comparison of Mean Building Height and Standard Deviation for Selected USGS Level 2 Land Use Types (Note: The derivation area is 1235 km^2 and the validation area is 418 km^2.)

USGS Level 2 Land Use Name	Mean Building Height (m)–Derivation	Mean Building Height (m)–Validation	Standard Deviation (m)–Derivation	Standard Deviation (m)–Validation
Residential	5.70	4.74	3.04	2.06
Commercial and Services	6.05	5.85	7.07	5.81
Industrial	6.09	4.95	3.73	2.24
Transportation, Communications, and Utility	4.81	4.17	3.54	2.26
Other Urban or Built-Up Land	4.95	4.68	2.73	2.80
Cropland and Pasture	5.02	4.94	3.20	2.78
Deciduous Forest Land	7.32	5.67	4.42	3.32

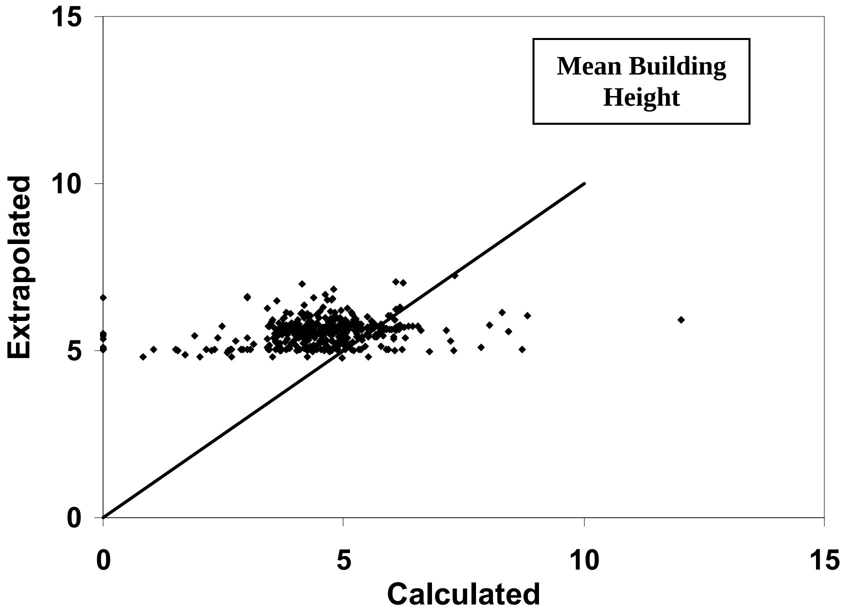

Figure 16. Scatter plot of extrapolated versus calculated mean building height (m) for the 418 grid cells in the validation area.

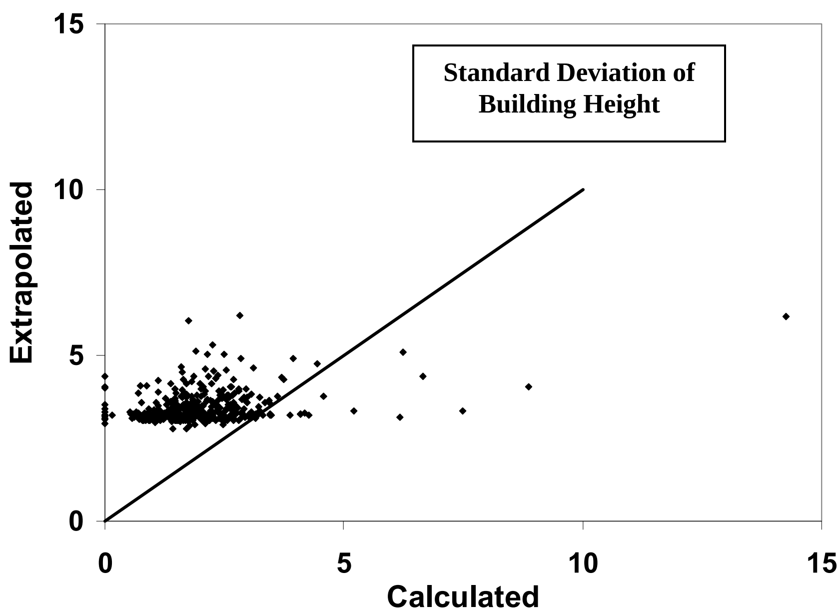

Figure 17. Scatter plot of extrapolated versus calculated standard deviations of building height (m) for the 418 grid cells in the validation area.

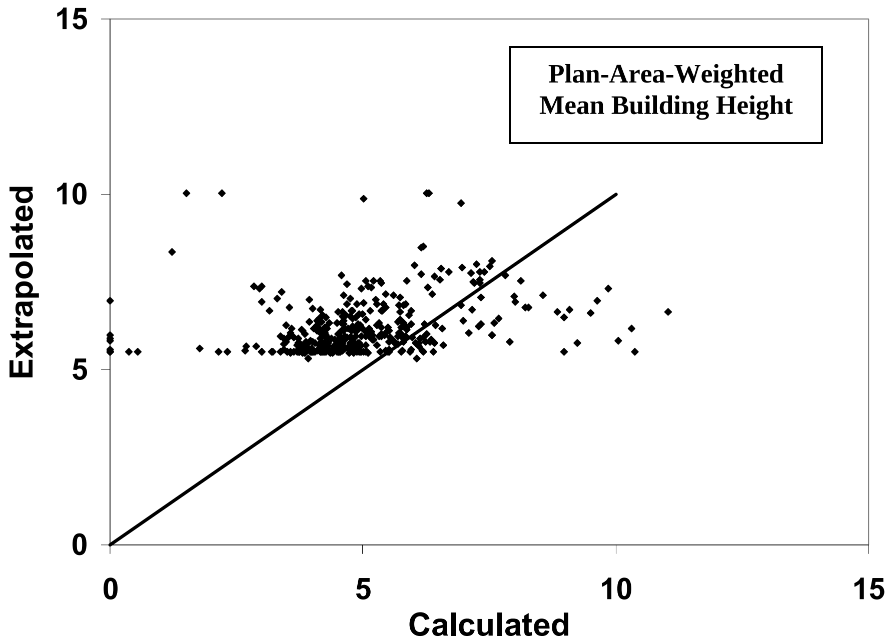

Figure 18. Scatter plot of extrapolated versus calculated plan-area-weighted mean building height (m) for the 418 grid cells in the validation area.

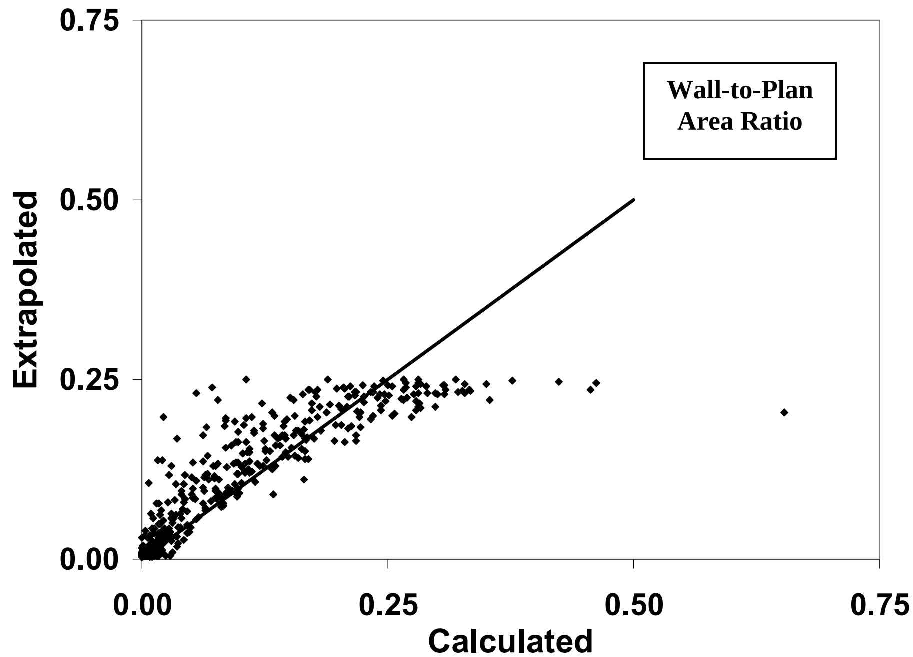

Figure 19. Scatter plot of extrapolated versus calculated wall-to-plan area ratio for the 418 grid cells in the validation area.

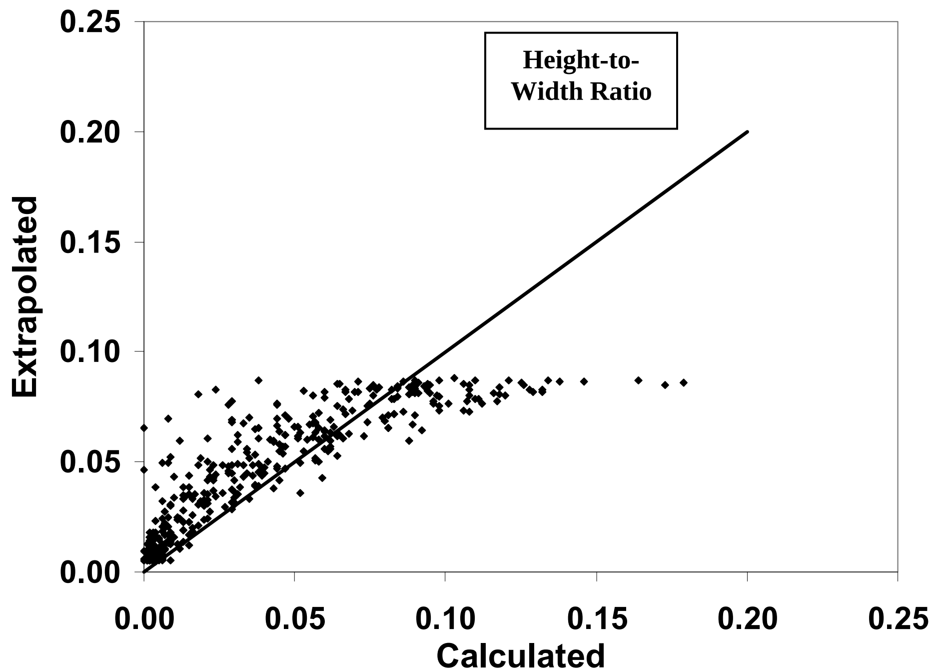

Figure 20. Scatter plot of extrapolated versus calculated Height-to-Width Ratio for the 418 grid cells in the validation area.

Table 21. Comparison Statistics for the Calculated and Extrapolated Building Height Histograms, Plan Area Density, Top Area Density, and Frontal Area Density

	Mean Bias	Min. Bias	Max. Bias	Mean RMSE	Min. RMSE	Max. RMSE	Mean CRE	Min. CRE	Max. CRE
Building Height Histograms	-6.02	-41.52	22.42	39.35	1.55	130.44	80%	26%	576%
Building Plan Area Density	0.0035	-0.0129	0.0406	0.0143	0.0003	0.0669	65%	23%	193%
Building Top Area Density	0.0002	-0.0031	0.0063	0.0046	0.0003	0.0119	88%	45%	178%
Building Frontal Area Density	0.0002	-0.0010	0.0012	0.0008	0.0001	0.0019	55%	25%	185%

Table 22. Comparison Statistics for the Calculated and Extrapolated Canopy Height Characteristics

	Bias	RMSE	CRE
Mean Canopy Height	1.81 (+36%)	2.48	42%
z_o, North Wind, Macdonald et al., 1998	0.29 (+107%)	0.44	125%
z_d, North Wind, Macdonald et al., 1998	0.61 (+17%)	1.79	38%
z_o, North Wind, Raupach, 1994	0.14 (+23%)	0.24	33%
z_d, North Wind, Raupach, 1994	1.00 (+33%)	1.43	40%

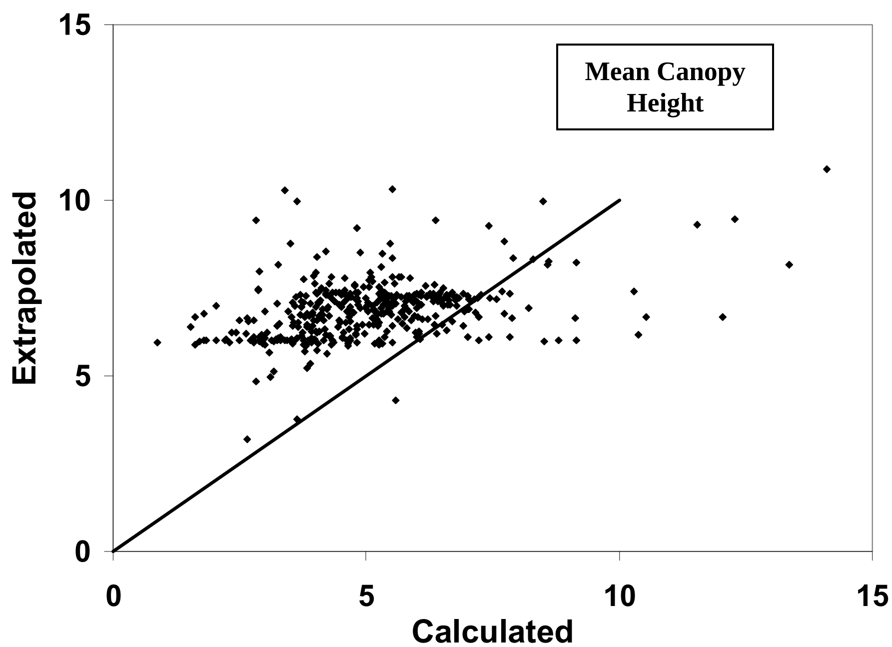

Figure 21. Scatter plot of extrapolated versus calculated mean canopy height (m) for the 418 grid cells in the validation area.

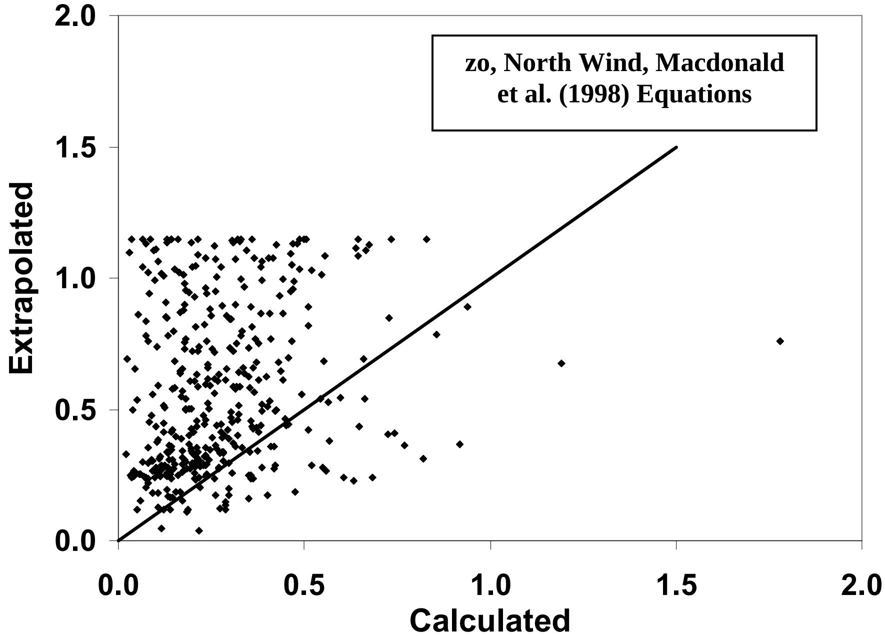

Figure 22. Scatter plot of extrapolated versus calculated roughness lengths (m) for the 418 grid cells in the validation area using the Macdonald et al. (1998) equations and a north wind azimuth.

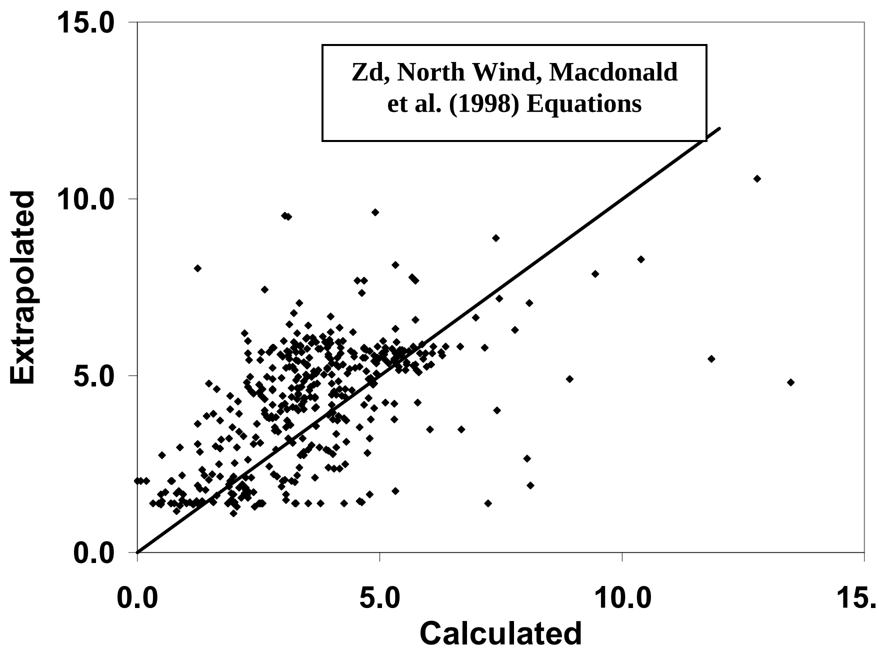

Figure 23. Scatter plot of extrapolated versus calculated displacement heights (m) for the 418 grid cells in the validation area using the Macdonald et al. (1998) equations and a north wind azimuth.

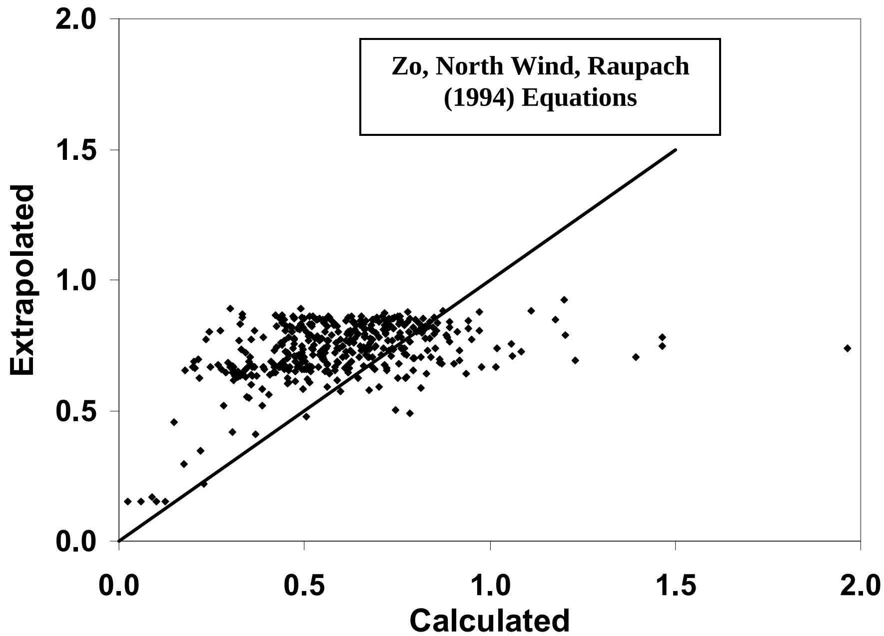

Figure 24. Scatter plot of extrapolated versus calculated roughness lengths (m) for the 418 grid cells in the validation area using the Raupach (1994) equations and a north wind.

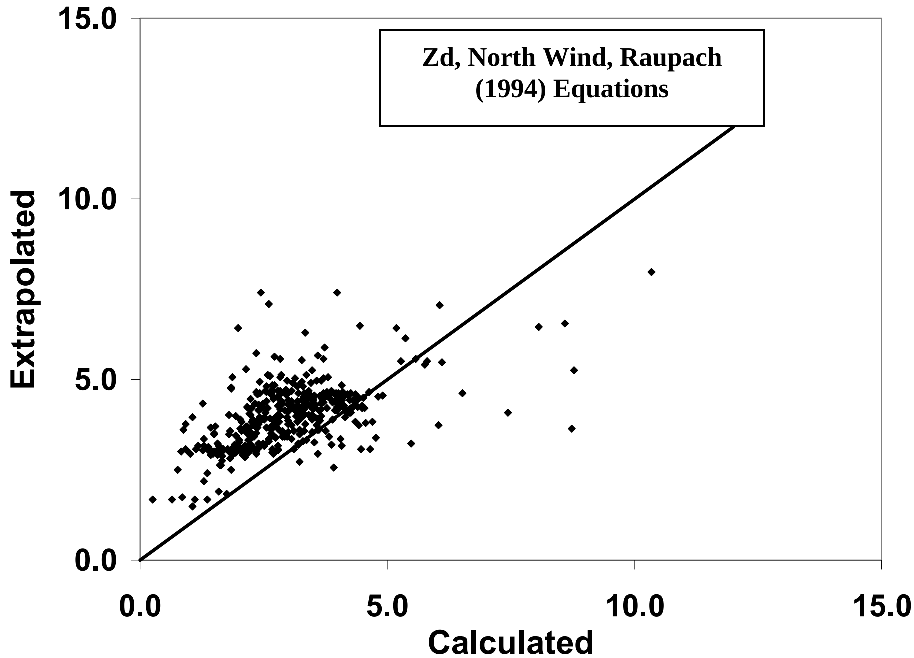

Figure 25. Scatter plot of extrapolated versus calculated displacement heights (m) for the 418 grid cells in the validation area using the Raupach (1994) equations and a north wind.

Table 23. Comparison Statistics for the Calculated and Extrapolated Canopy Plan Area Density and Top Area Density

	Mean Bias	Min. Bias	Max. Bias	Mean RMSE	Min. RMSE	Max. RMSE	Mean CRE	Min. CRE	Max. CRE
Canopy Plan Area Density	0.0194	-0.0492	0.2529	0.0708	0.0107	0.3132	57%	8%	171%
Canopy Top Area Density	-0.0013	-0.0117	0.0101	0.0125	0.0040	0.0356	53%	15%	124%

5. Houston Urban Canopy Parameters

This section contains a brief overview and summary of the Houston UCPs. The figures shown were created to display the final gridded dataset and begin the process of validating the dataset and interpreting the spatial distribution patterns. The complete UCP dataset is included with the accompanying spreadsheets.

5.1 Building Height Characteristics

For the discussion of the building height characteristics, the focus primarily will be the Harris County grid cells because of the concentration of buildings in this region of the modeling domain. Figures 26 and 27 display the spatial distribution of the mean and standard deviation of building height for Harris County. For reference, Figures 28 and 29 show the building count per grid cell for Harris County and the modeling domain, respectively. The building count information probably somehow should be factored into, or paired with, the other building height data when trying to determine drag effects. Some building height characteristics might not accurately represent the entire grid cell if the number of buildings in the cell is small. For example, assume the mean building height in one grid cell is 7.5, but that grid cell only contains three buildings. The overall effect on the wind flow because of those three buildings is small, but may be exaggerated by simply using the mean height without a count of buildings. Note in Figures 26 and 27 the distinct separation between the data contained in Harris A (actual building data) and the other parts of Harris County.

Figures 30 and 31 illustrate the building wall-to-plan area ratio for Harris County and the modeling domain, respectively. Clearly, a trend is noticeable with the building parameters. Houston contains the highest values and a concentration of the highest values of the parameters, with pockets of elevated values spread among the other urbanized areas in Harris County and the modeling domain. Figure 2 contains a figure of the land use for the modeling domain, which follows closely with the building parameter results (for the domain, this is expected because of the UCP-land use correlation). Figures 32 and 33 show the building height-to-width ratio parameter for Harris County and the modeling domain, respectively. The overall spatial pattern is again similar to the other building parameters. One overall observation from the building parameters is the aggregation of elevated values within the Downtown Core Area. High values also are observed in several Commercial and Services and Industrial centers within and near Houston. Some high values are noticed in Residential (multifamily) districts.

Figures 34 and 35 display the building plan area fraction parameter in Harris County and the modeling domain, respectively. One interesting observation is the location of the highest values in the Commercial and Services and Residential districts in the city, in addition to the expected high values within the downtown core area. Industrial areas near the ship channel, however, did not have high building plan area fractions. Similar patterns are noted in Figures 36 and 37, which show the spatial distribution of the building frontal area index parameter for Harris County and the modeling domain, respectively.

5.2 Vegetation Height Characteristics

Figures 38 and 39 illustrate the spatial distribution of mean vegetation height per grid cell in Harris County and the modeling domain. The elevated vegetation heights in the northern part of Harris County correspond to a heavily forested region. This correlation is more noticeable in Figure 39 where the forested regions of the northern part of the modeling domain are delineated clearly. Similar spatial distributions to the vegetation height are noted for the vegetation plan area fraction and frontal area index (see Figures 40-43).

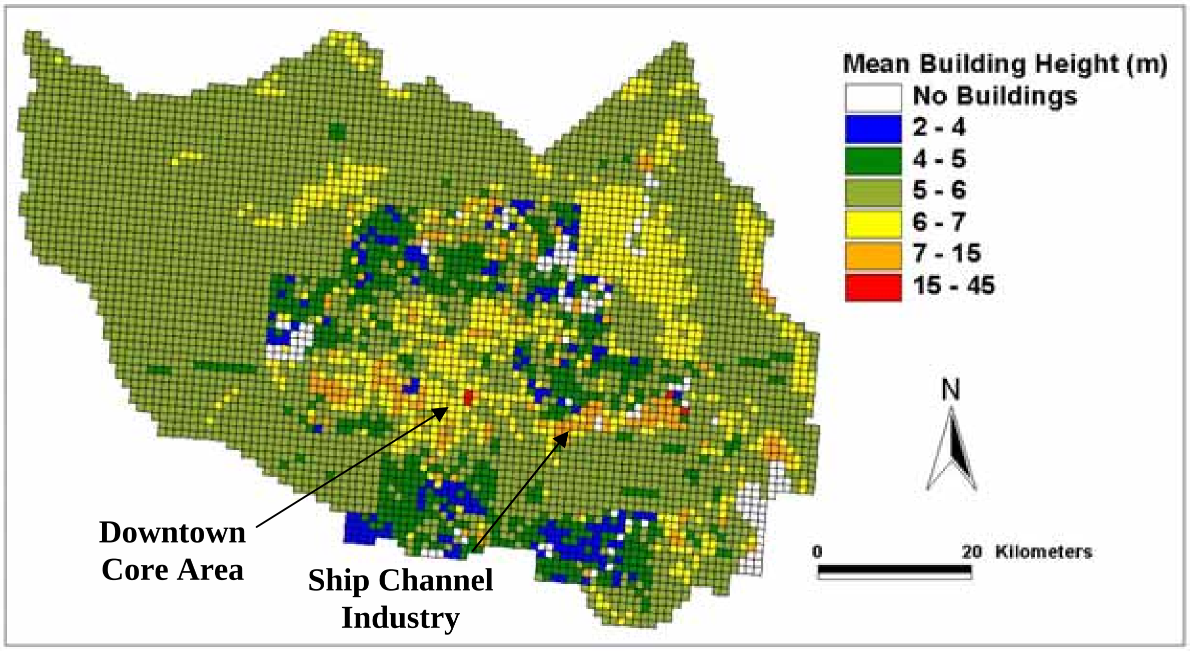

Figure 26. Spatial distribution of mean building height in Harris County.

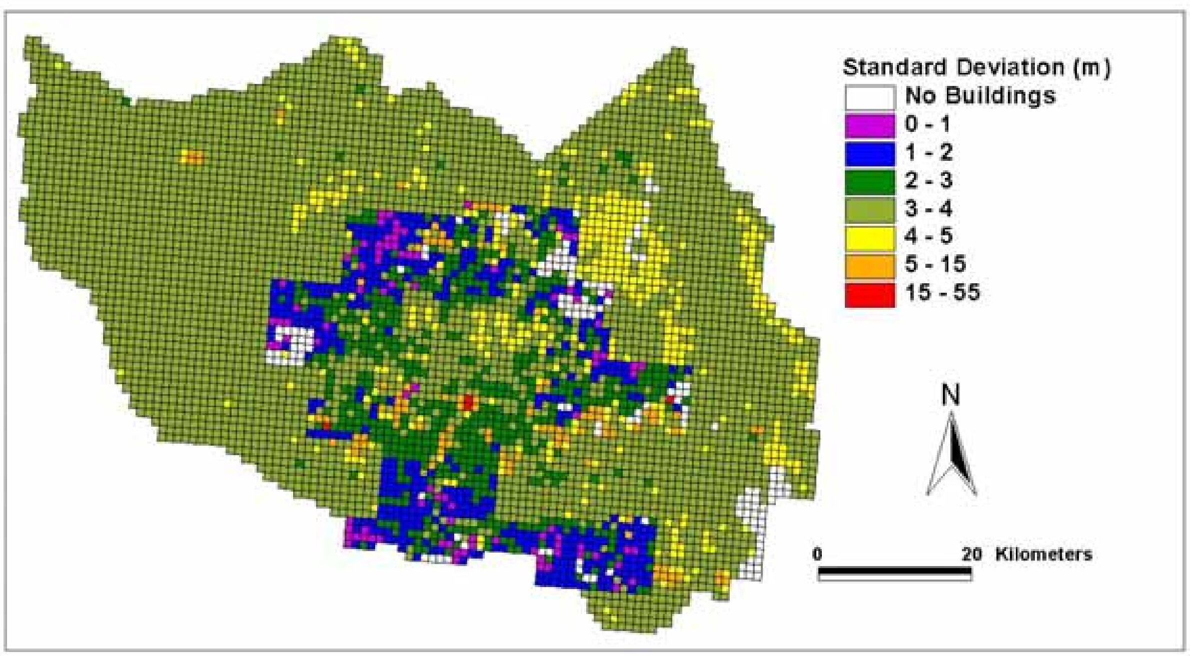

Figure 27. Spatial distribution of standard deviation of building height in Harris County.

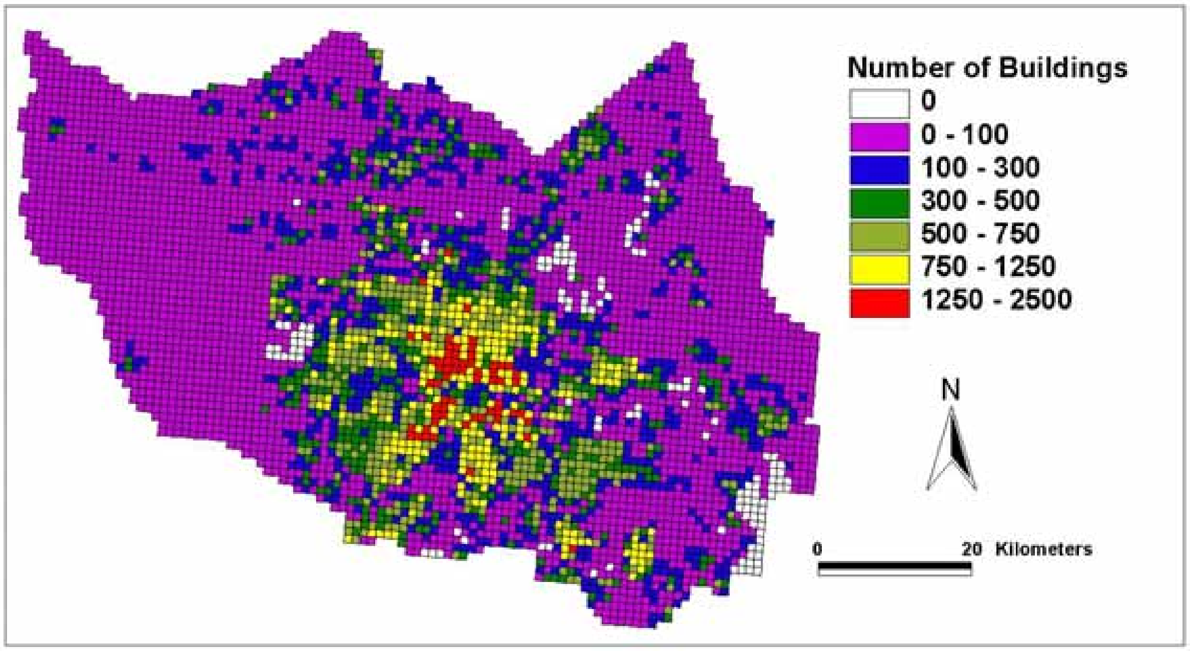

Figure 28. Spatial distribution of number of buildings in Harris County.

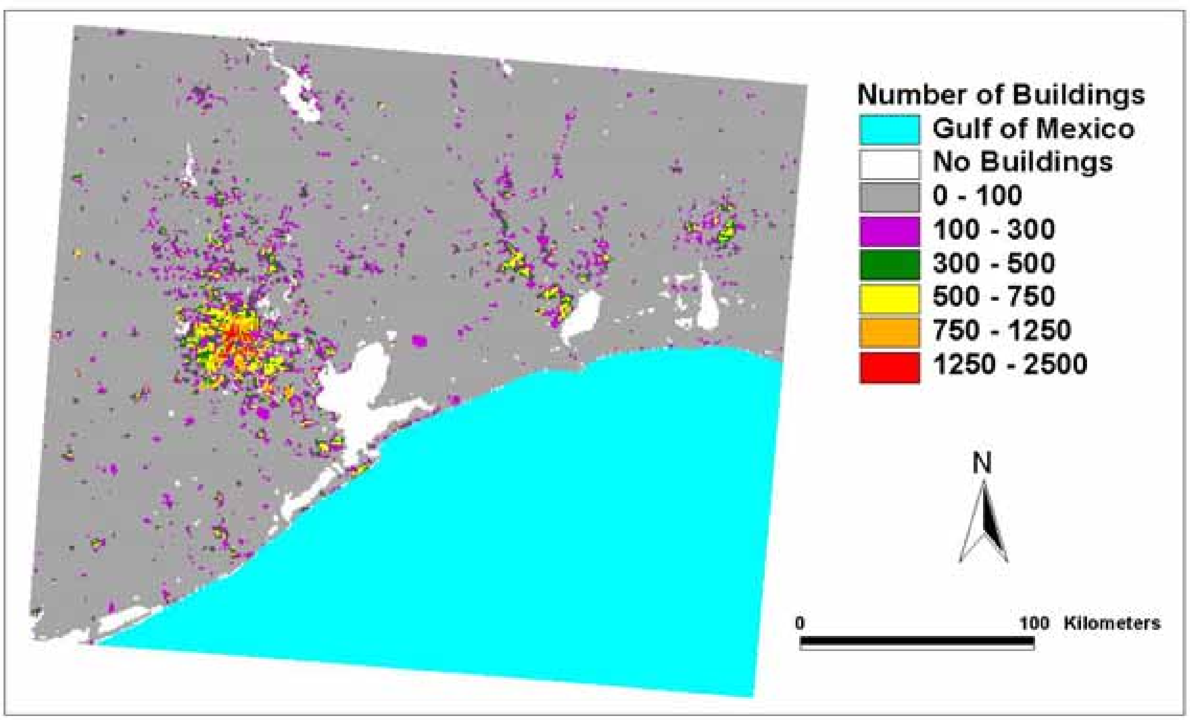

Figure 29. Spatial distribution of number of buildings in the modeling domain.

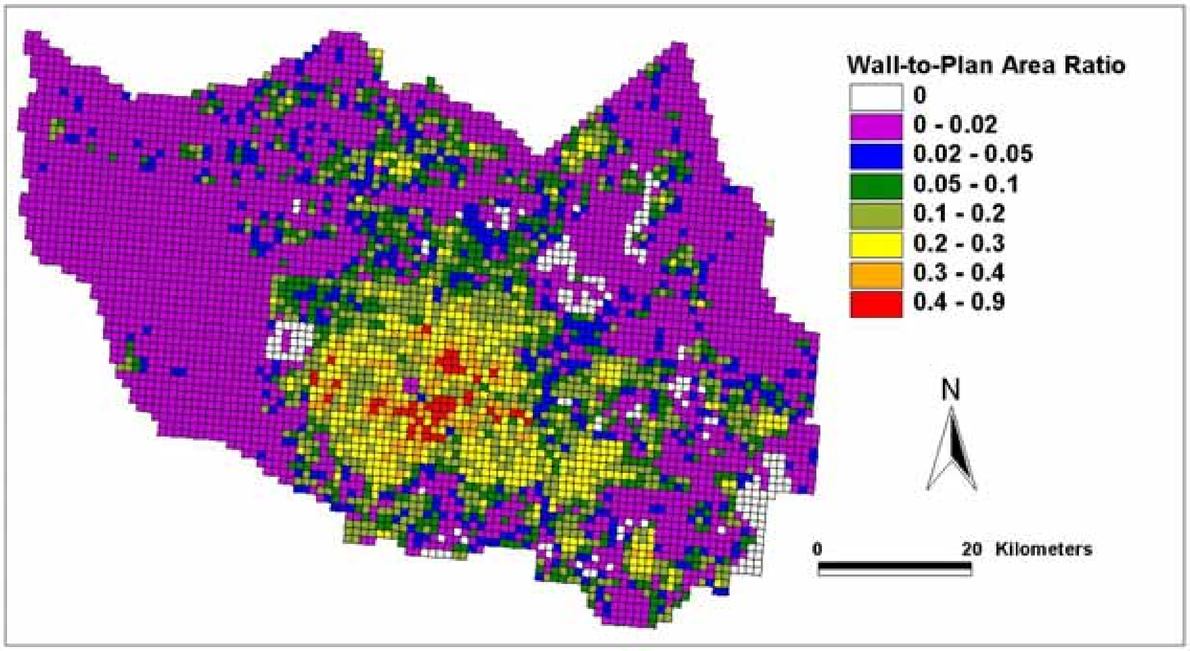

Figure 30. Spatial distribution of average wall-to-plan area ratio in Harris County.

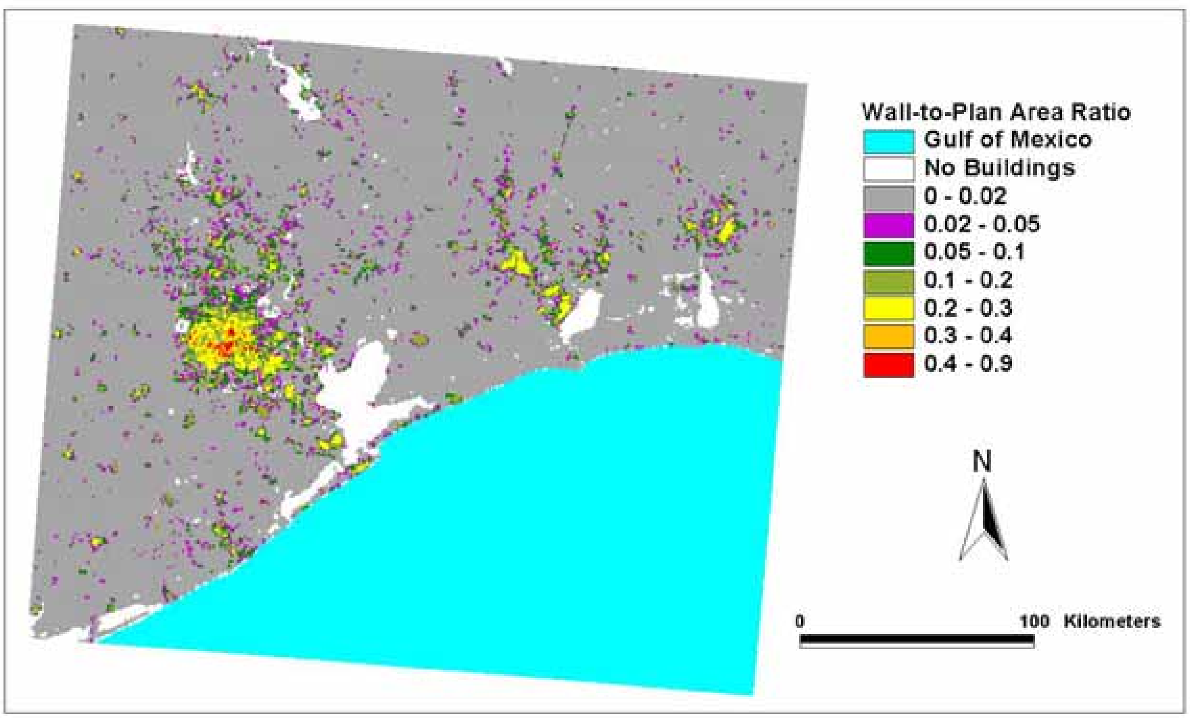

Figure 31. Spatial distribution of average wall-to-plan area ratio in the modeling domain.

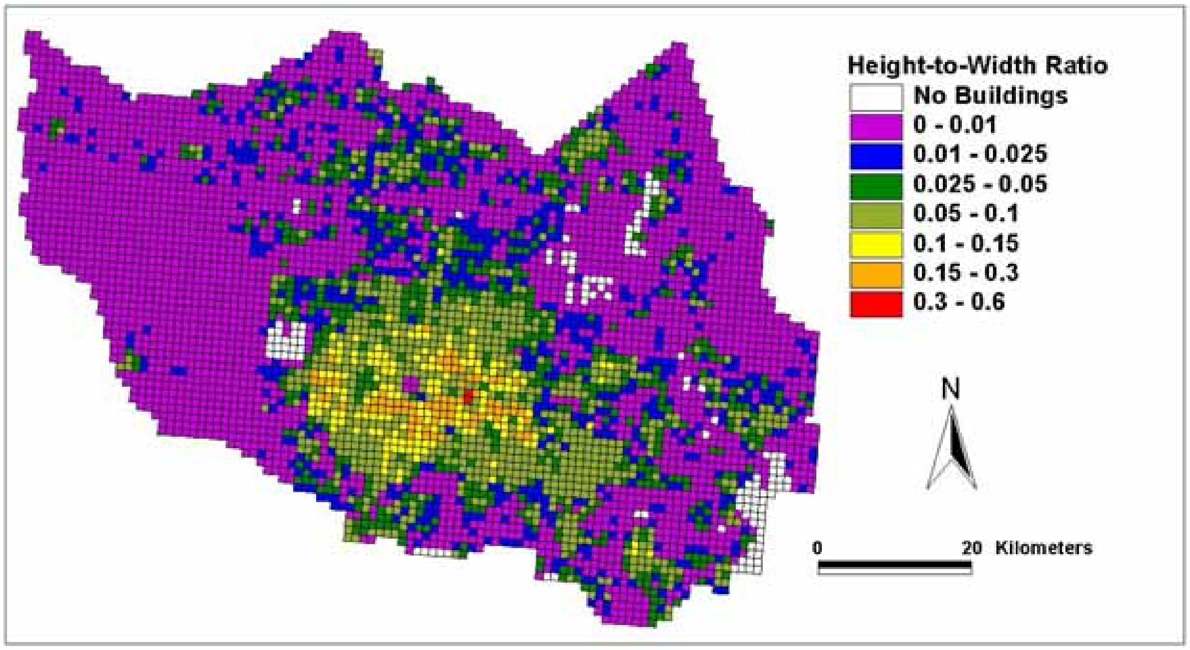

Figure 32. Spatial distribution of average building height-to-width ratio in Harris County.

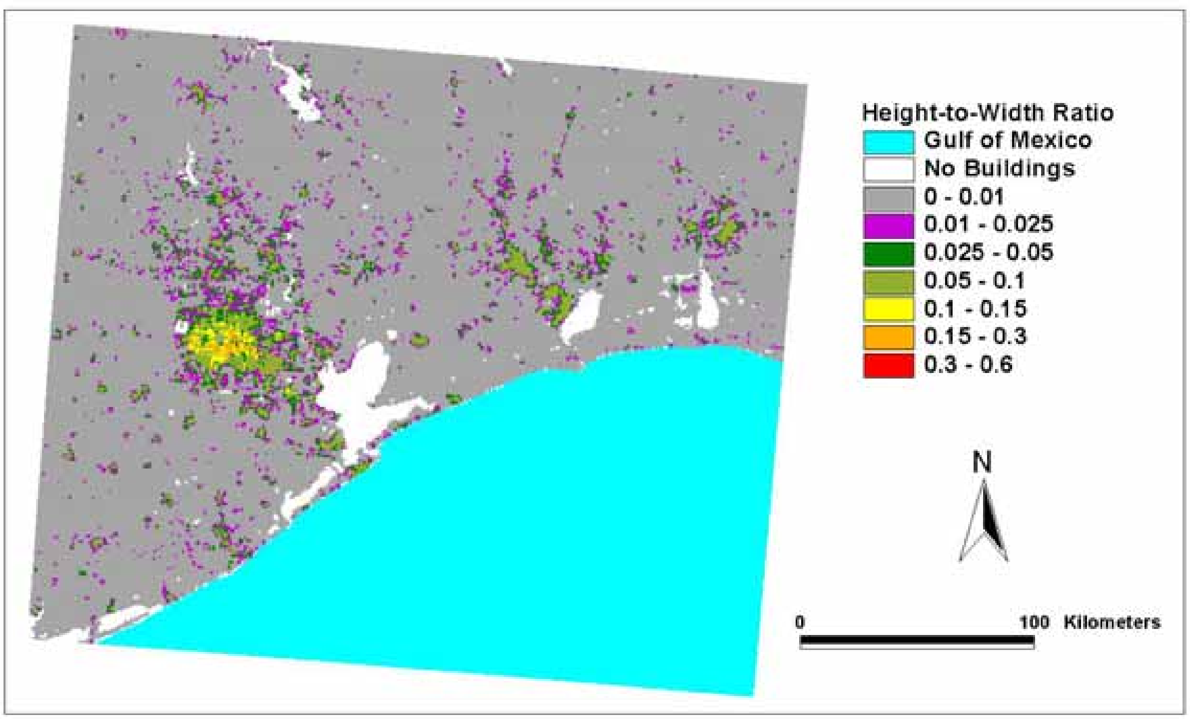

Figure 33. Spatial distribution of average building height-to-width ratio in the modeling domain.

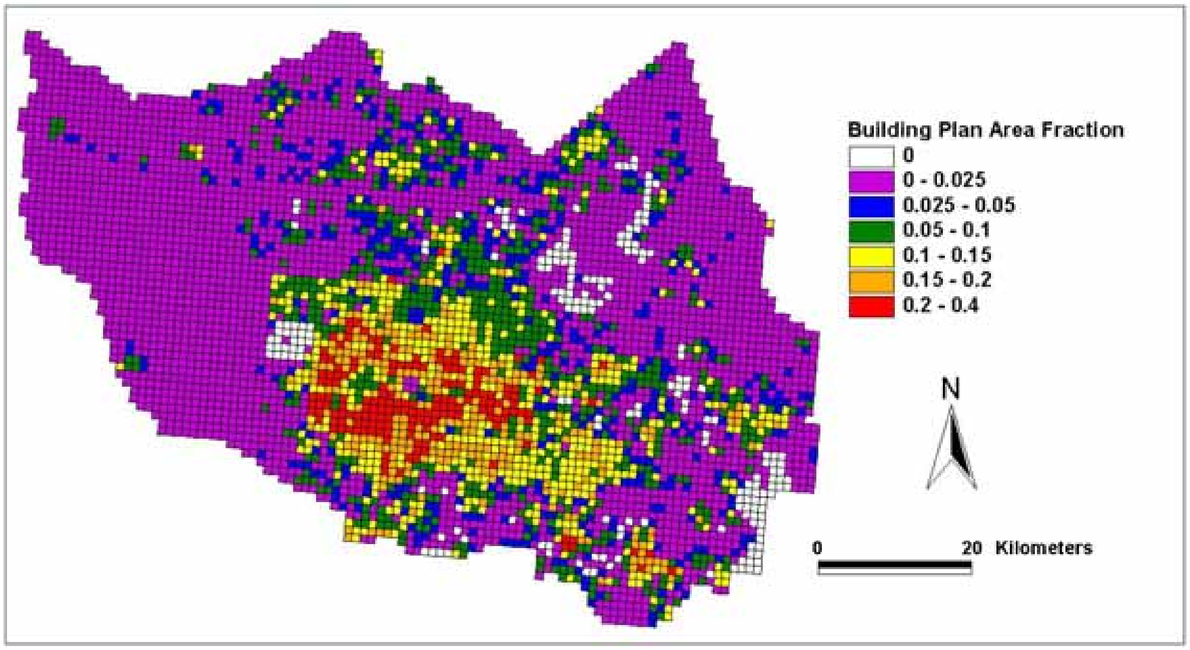

Figure 34. Spatial distribution of building plan area fraction in Harris County.

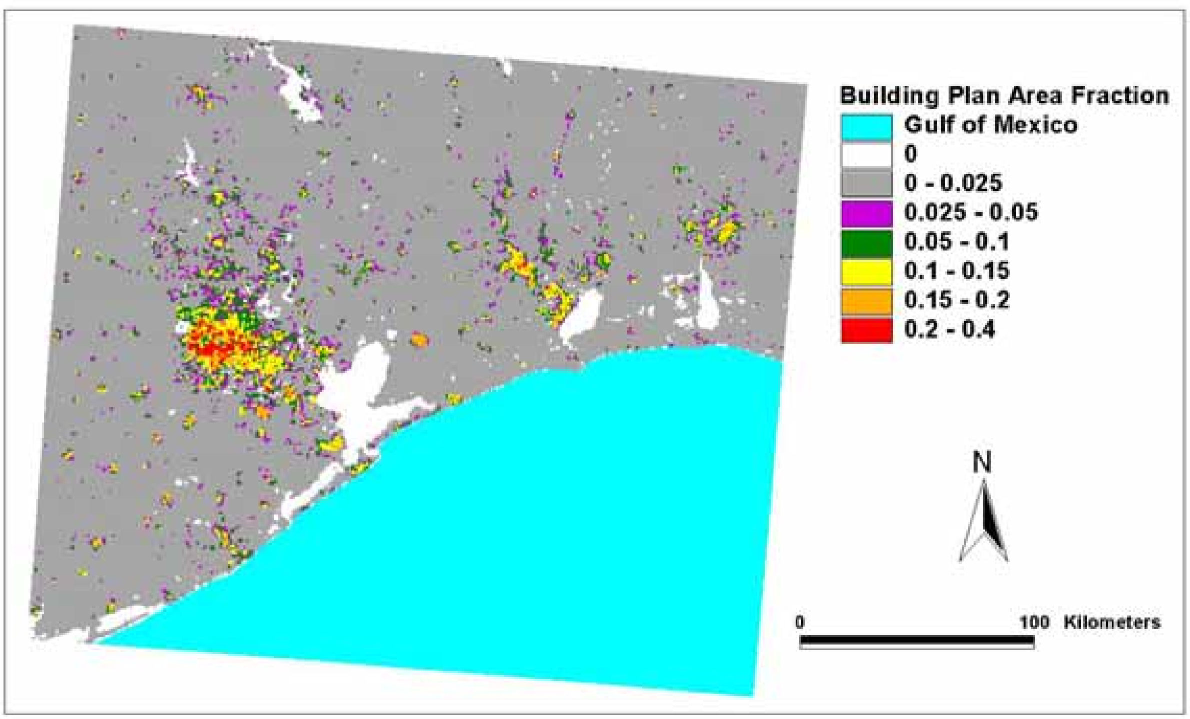

Figure 35. Spatial distribution of building plan area fraction in the modeling domain.

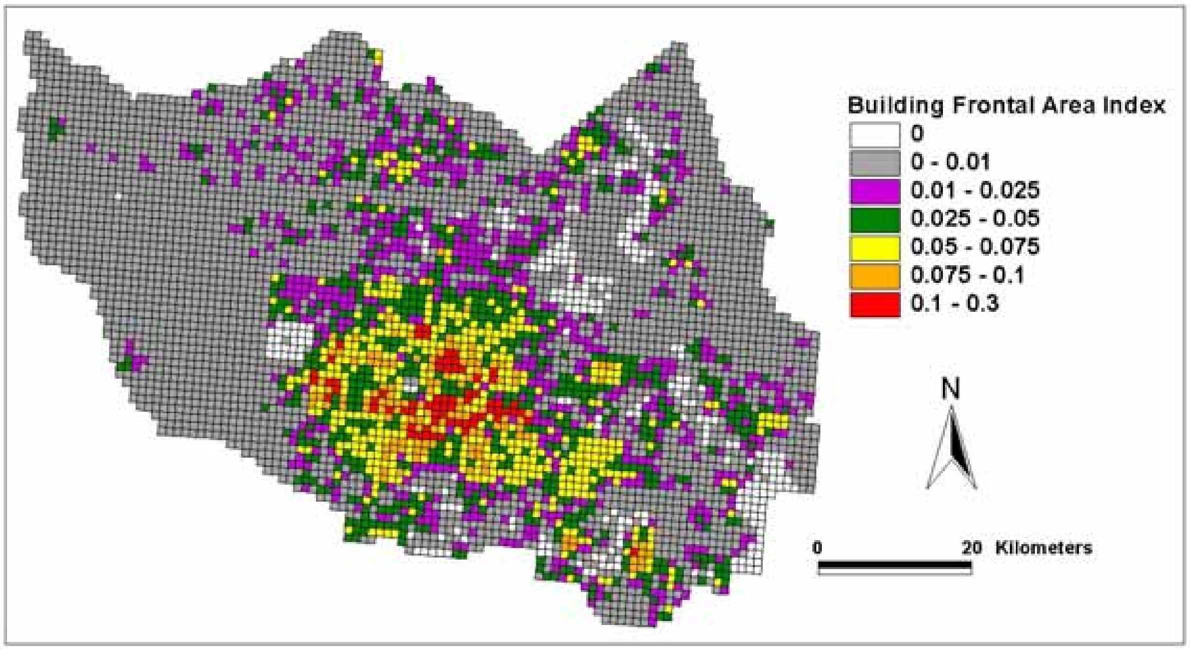

Figure 36. Spatial distribution of building frontal area index in Harris County.

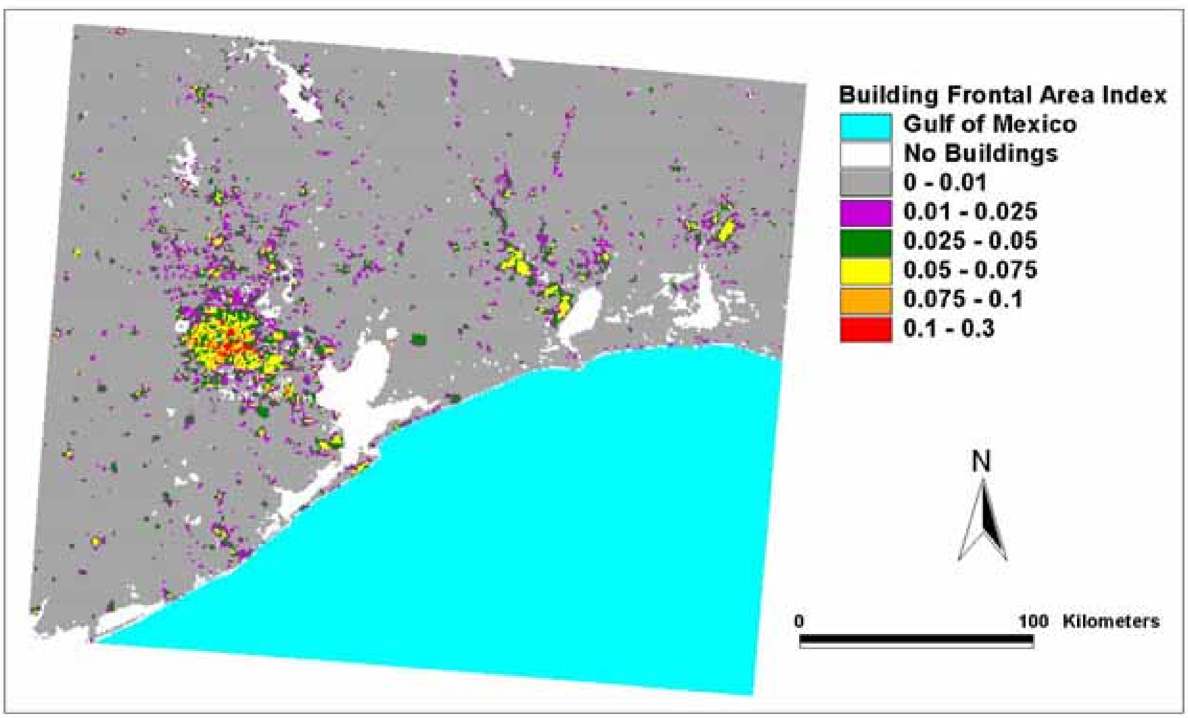

Figure 37. Spatial distribution of building frontal area index in the modeling domain.

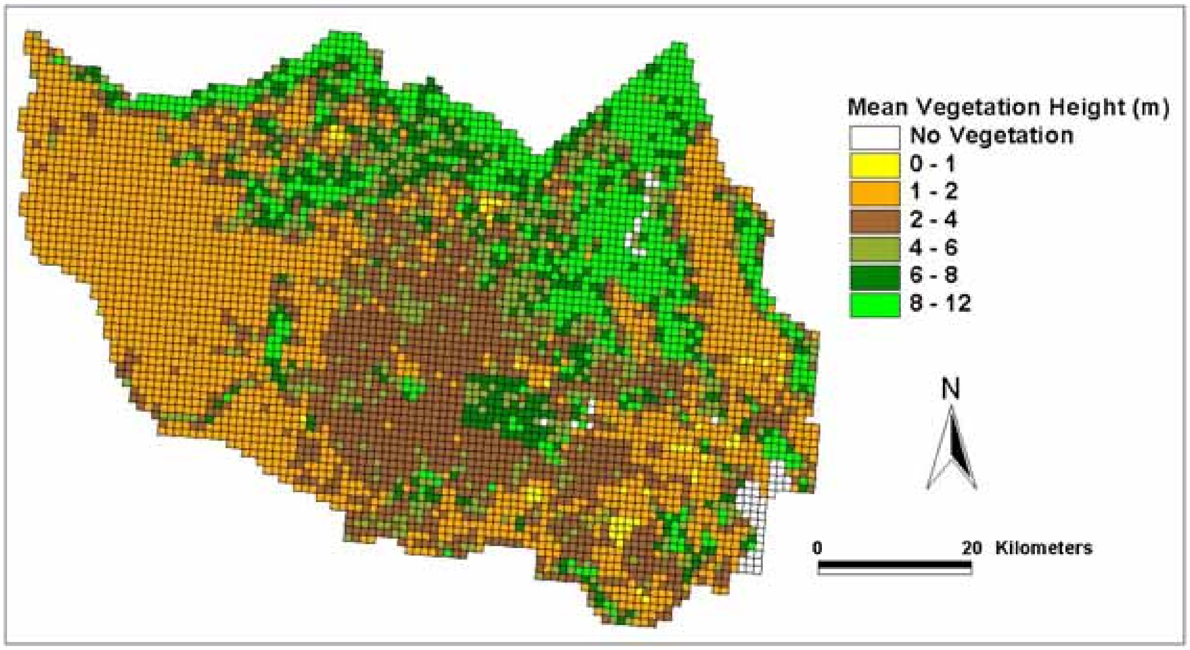

Figure 38. Spatial distribution of mean vegetation height in Harris County.

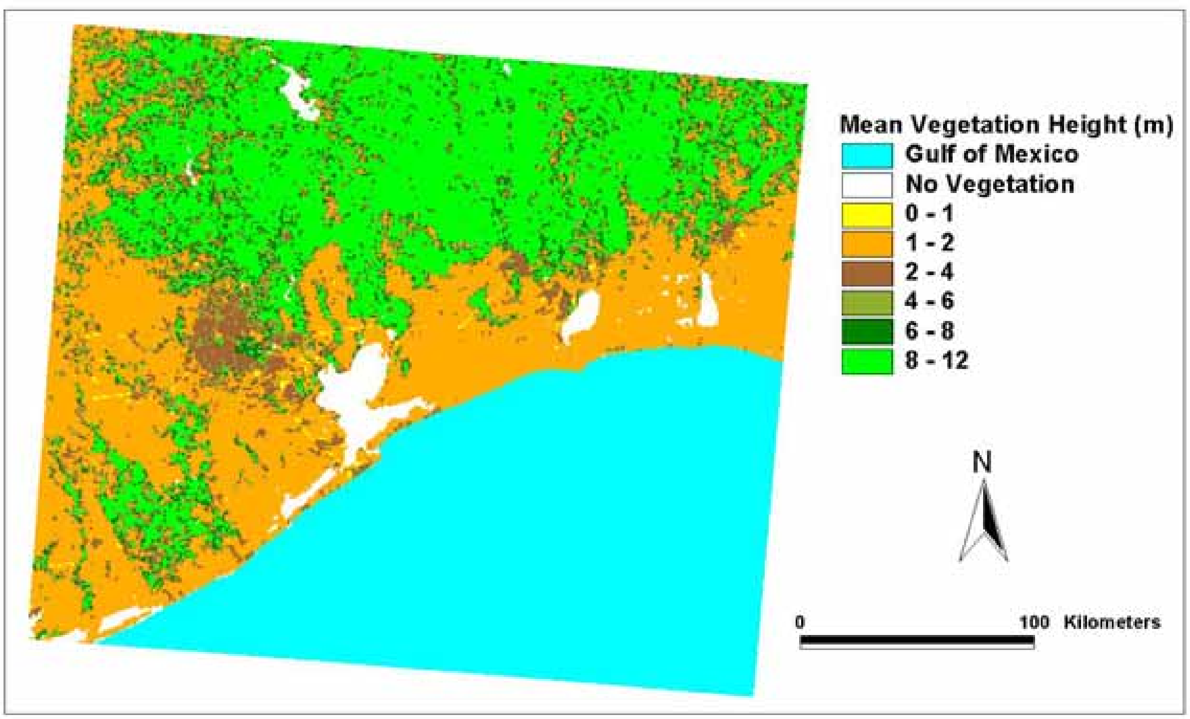

Figure 39. Spatial distribution of mean vegetation height in the modeling domain.

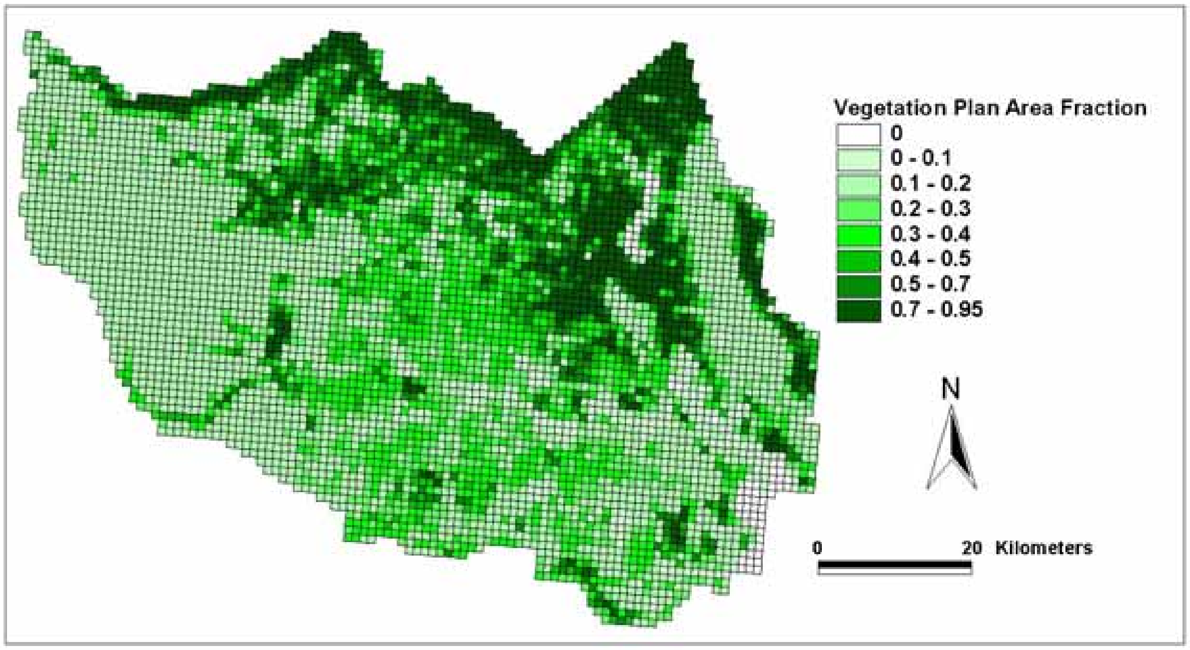

Figure 40. Spatial distribution of vegetation plan area fraction in Harris County.

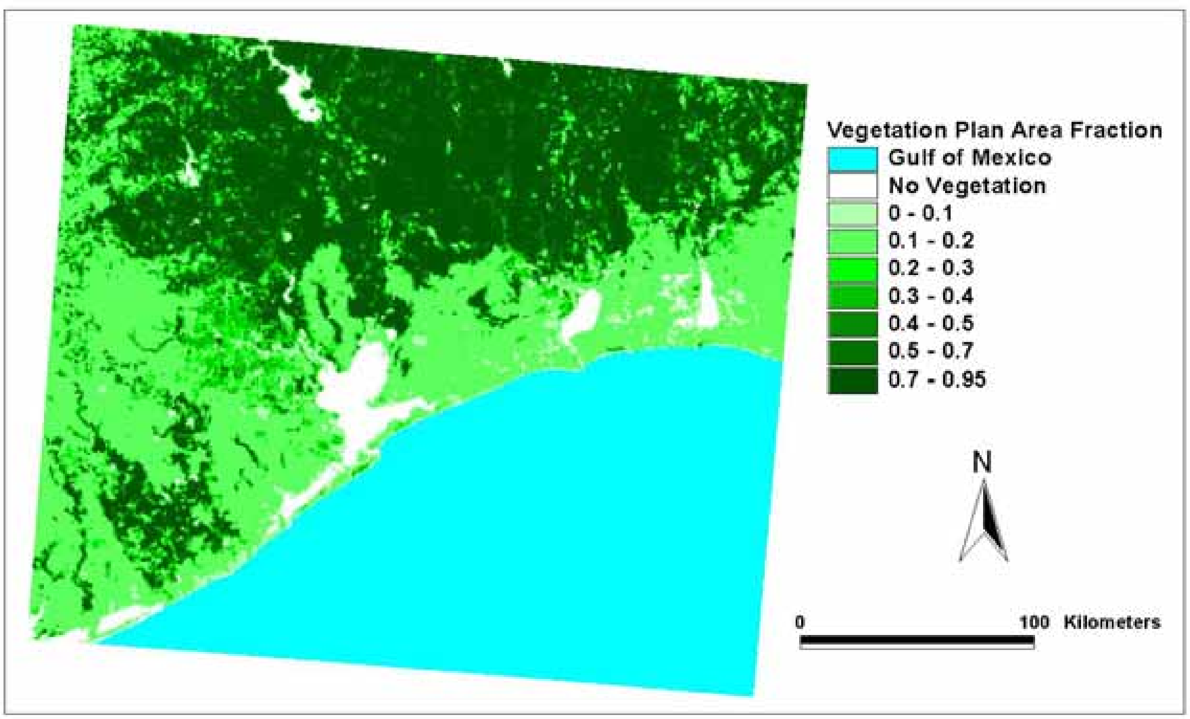

Figure 41. Spatial distribution of vegetation plan area fraction in the modeling domain.

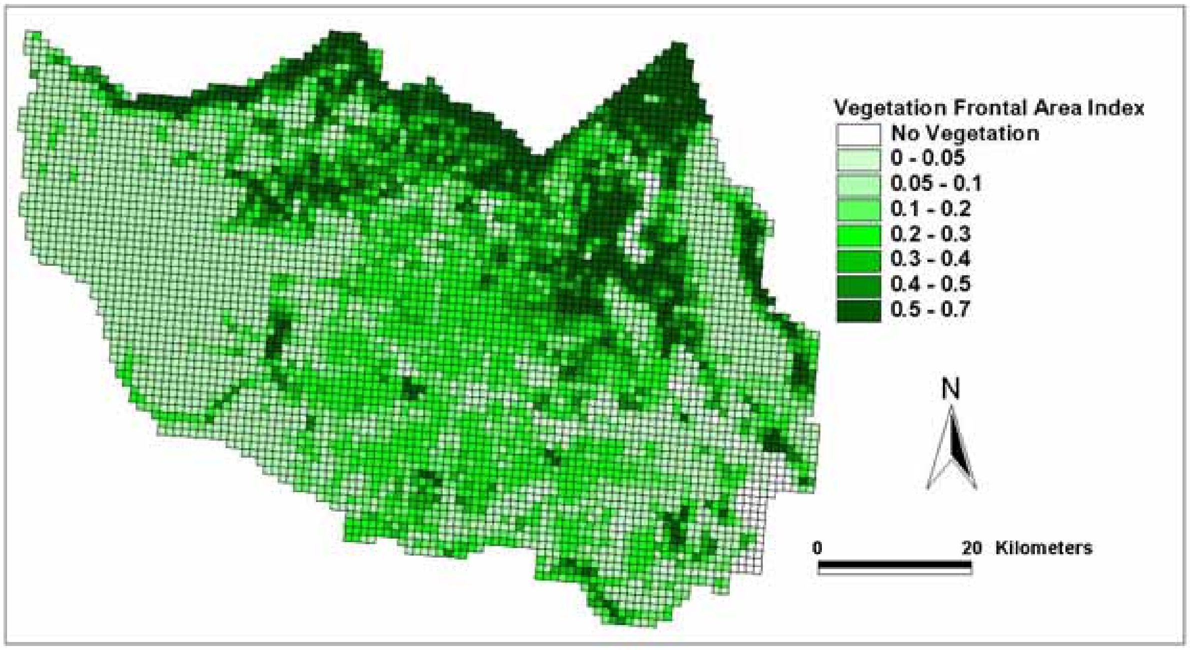

Figure 42. Spatial distribution of vegetation frontal area index in Harris County.

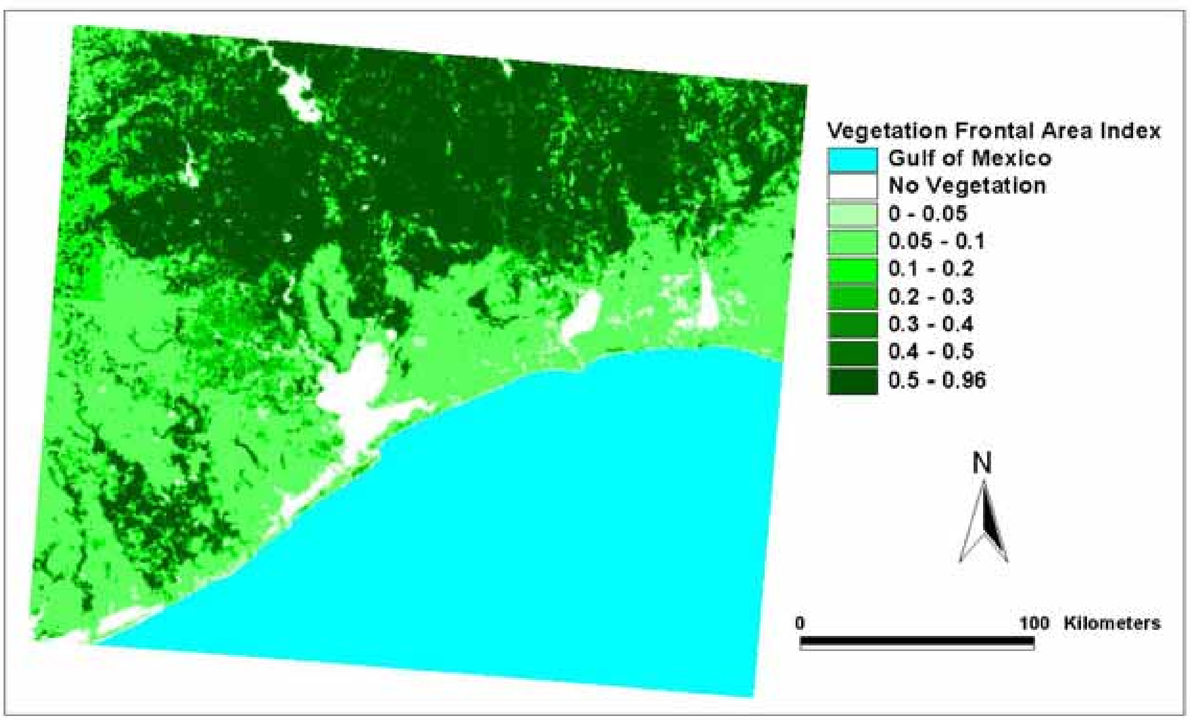

Figure 43. Spatial distribution of vegetation frontal area index in the modeling domain.

5.3 Canopy Height Characteristics

Figures 44 to 49 contain graphics of the spatial distribution of the mean canopy height, canopy plan area fraction, and canopy frontal area index parameters for Harris County and the modeling domain. An important observation from the canopy data distribution is the spatial heterogeneity in Harris County. This can be attributed, first of all, to the spatial heterogeneity of the urban terrain but also likely is partially because of the fact that the canopy parameters in Harris County were calculated based on actual data, whereas the parameters outside Harris County are based on the area-weighted average extrapolation. As noted earlier, the extrapolation will tend to reduce the heterogeneity of the parameter across the modeling domain.

5.4 Displacement Height and Roughness Length

The displacement height (z_d) and roughness length (z_o) were calculated using three sets of equations: (1) Macdonald et al. (1998), (2) Raupach (1994), and (3) Bottema (1997). Figures 50-61 display the roughness length and displacement height for the three calculation methods in both Harris County and the modeling domain. Comparison of the results of the three techniques indicates that there is considerable variability from one method to another. The investigation of the variability between the three morphometric techniques will be part of a separate study and will be reported in the future.

5.5 Sky View Factor

Figure 62 shows the spatial distribution of the sky view factor for Harris County. The grid cells containing mostly open space, including grid cells within the ship channel and near Galveston Bay, have the highest sky view factors. The forested areas at the north end of Harris County have the lowest sky view factors. Sky view factors are similar in urban areas and forest areas; therefore, the urban area is not distinguished in the figure as it is for other parameters. Figure 63 shows the distribution of the sky view factor for the modeling domain. Areas near the coast have sky view factors near 1.0, whereas the forested areas to the north are mostly in the range of 0.6 to 0.7.

5.6 Percent Directly Connected Impervious Area

Figure 64 shows the spatial distribution of the fraction of DCIAs for Harris County. The downtown core area has the highest values (approaching 90% impervious area directly connected to the stormwater drainage system), with slightly lower values in adjacent Residential, Commercial and Services, and Industrial areas. Outside of Houston, the fraction DCIA values are very close to zero (shown in gray in the figure) for most areas. Figure 65 shows the distribution of the fraction DCIA for the modeling domain. The Houston metropolitan area is clearly delineated, as are the major interstate highways (I-10 is the east-west line and I-45 runs north out of Houston). Other smaller cities also are shown. Water bodies other than the Gulf of Mexico are shown as contiguous white areas. White areas to the north of the modeling domain include lakes, forested land, and wetlands.

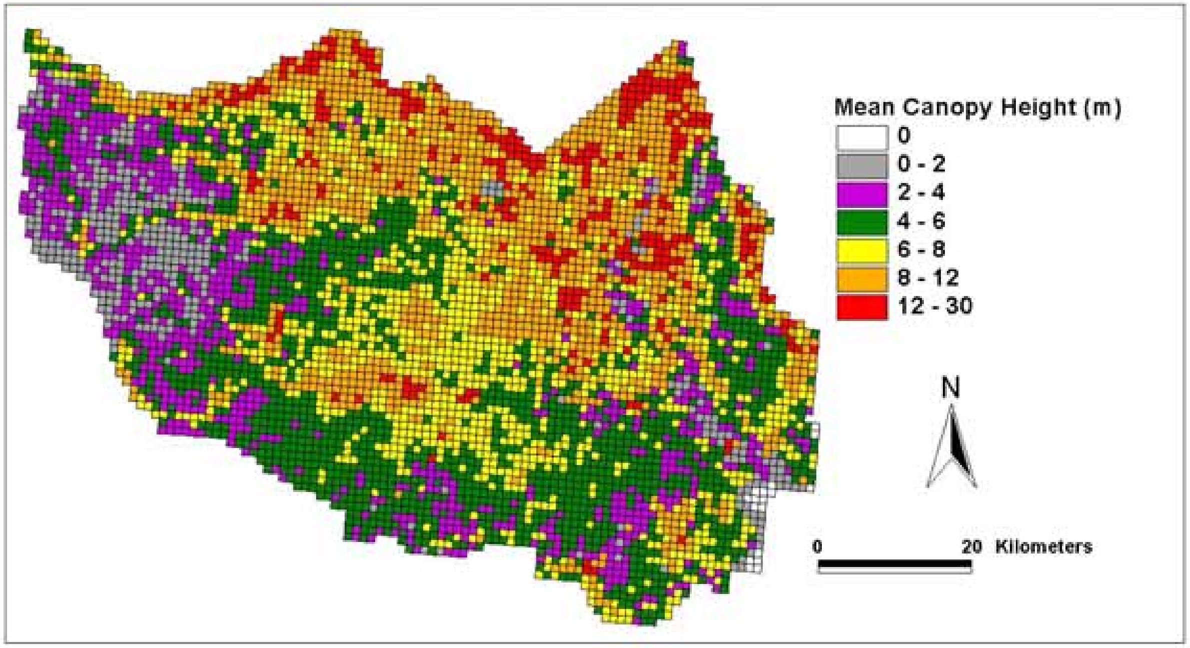

Figure 44. Spatial distribution of mean canopy height in Harris County.

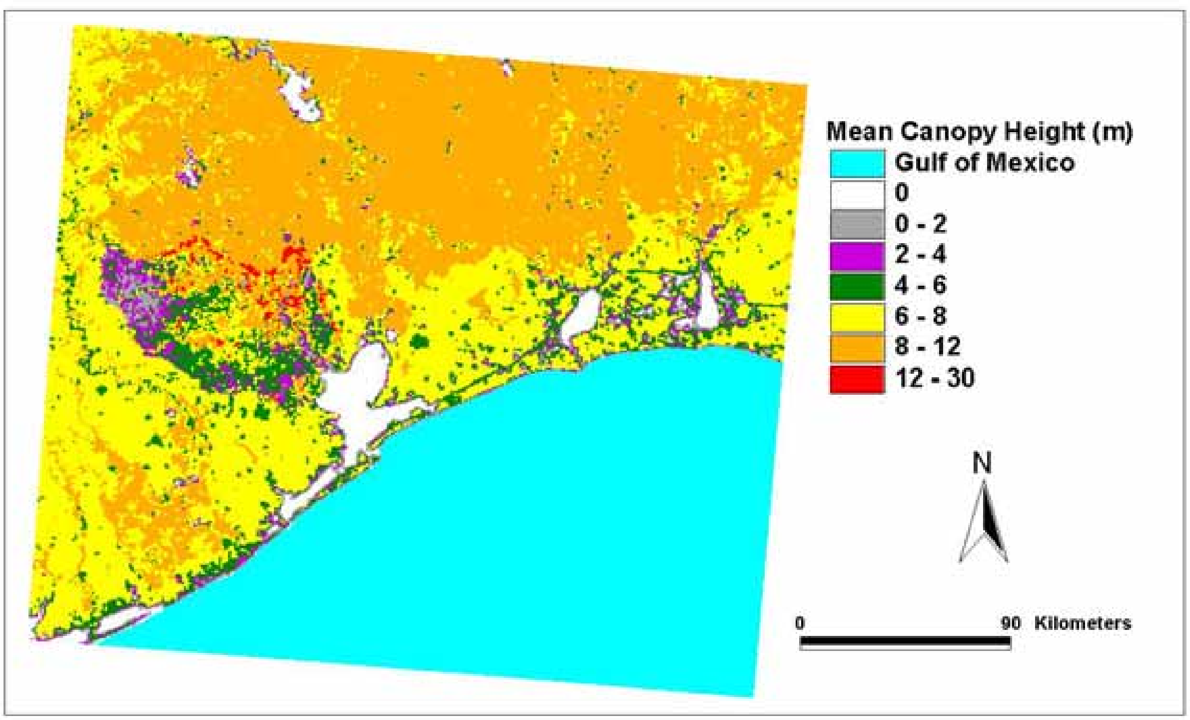

Figure 45. Spatial distribution of mean canopy height in the modeling domain.

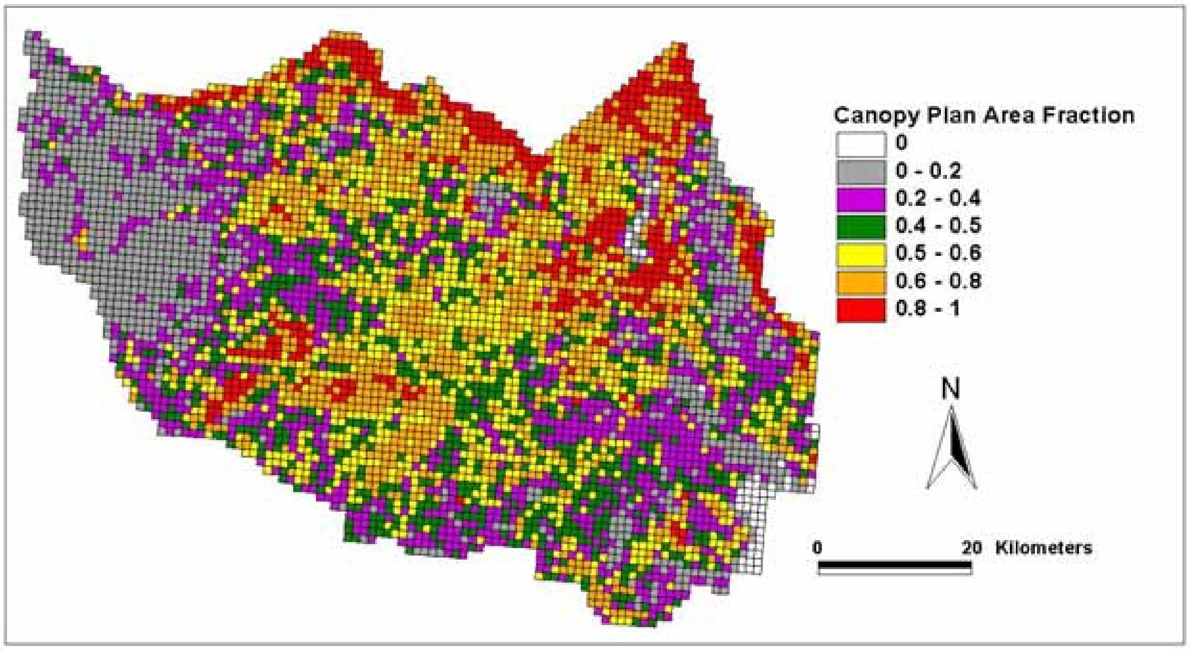

Figure 46. Spatial distribution of canopy plan area fraction in Harris County.

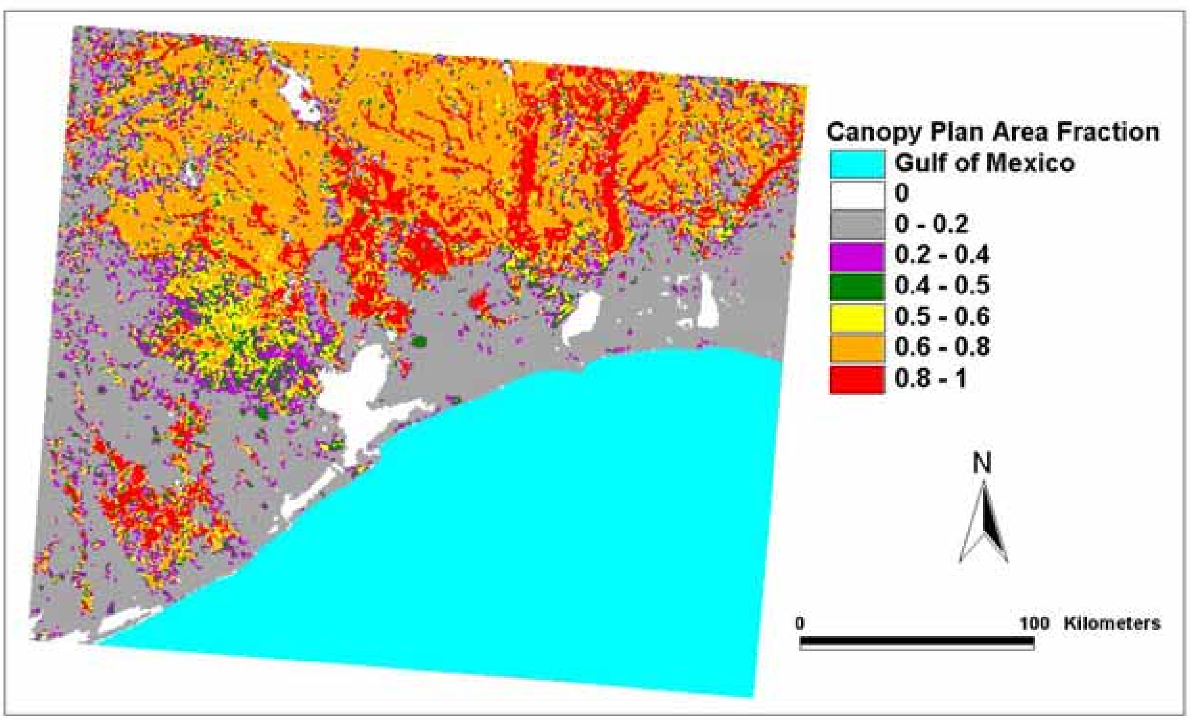

Figure 47. Spatial distribution of canopy plan area fraction in the modeling domain.

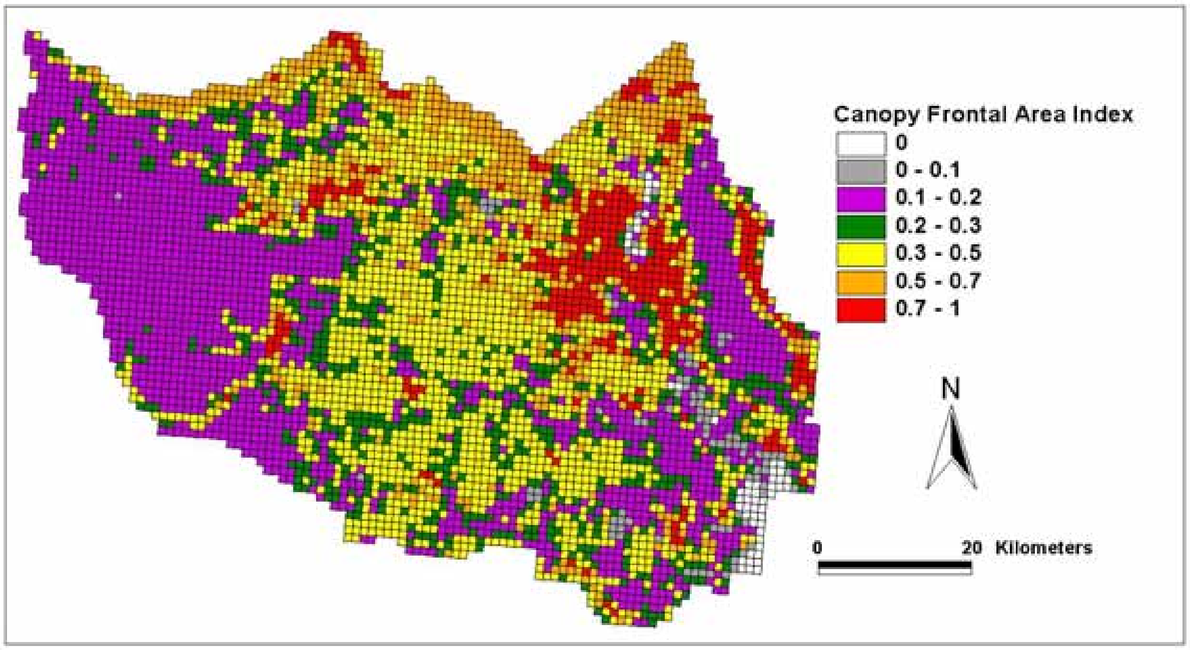

Figure 48. Spatial distribution of canopy frontal area index in Harris County.

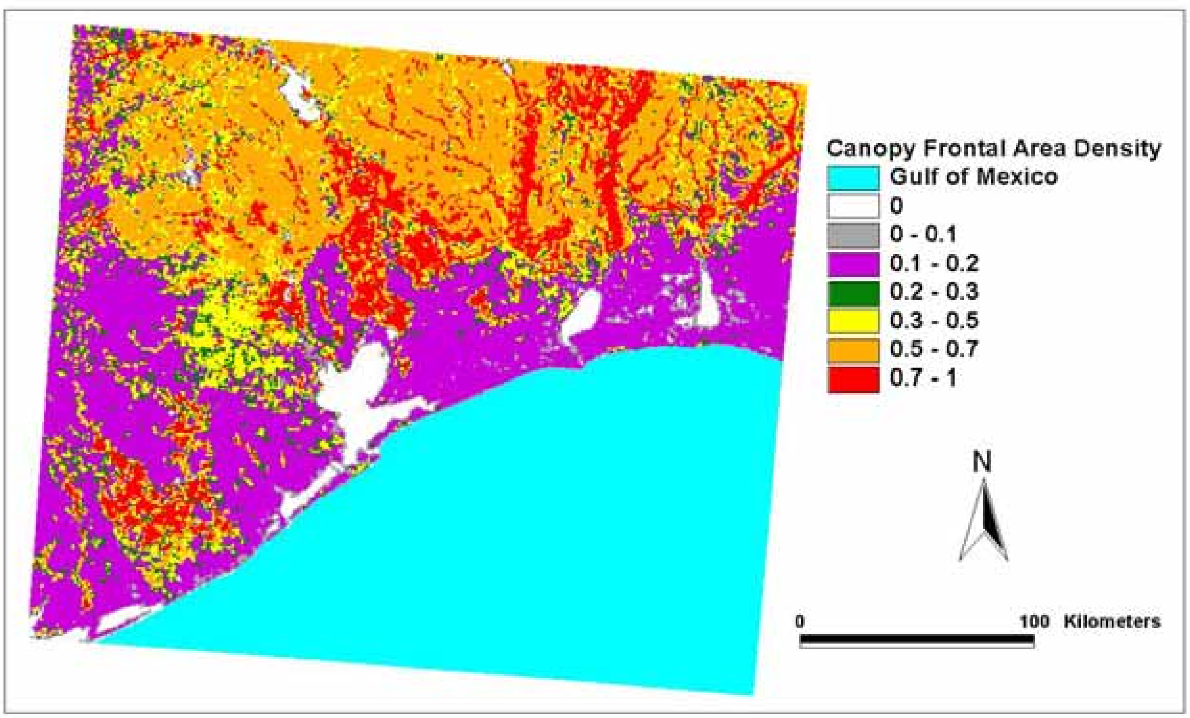

Figure 49. Spatial distribution of canopy frontal area index in the modeling domain.

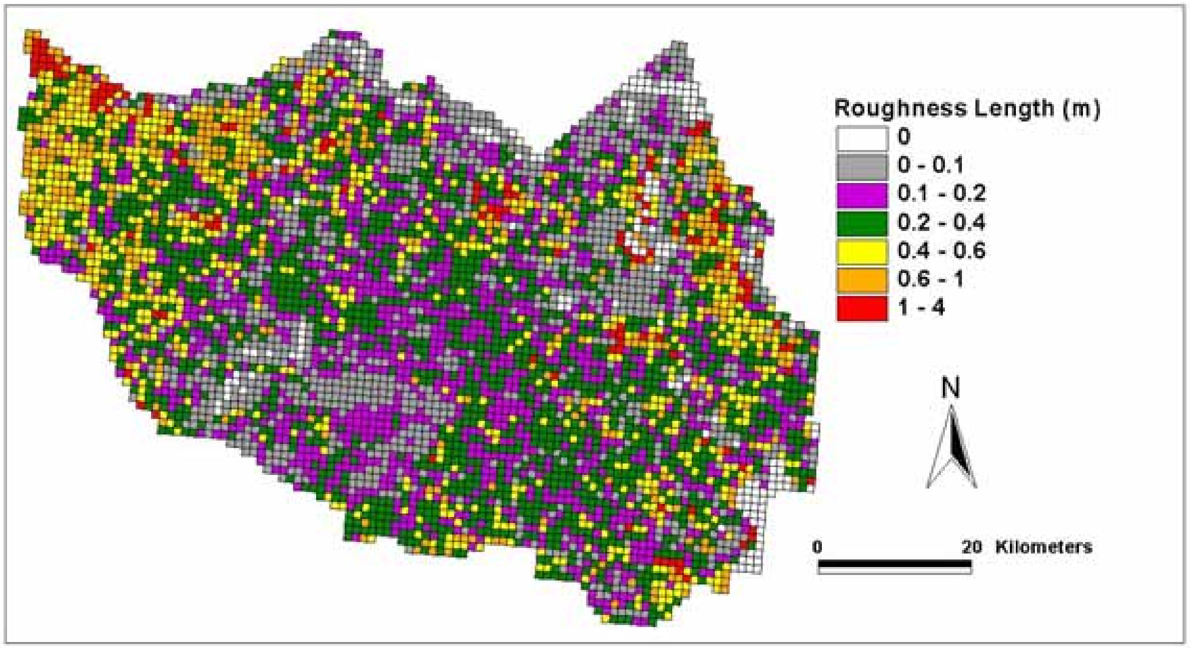

Figure 50. Spatial distribution of roughness length in Harris County calculated using the Macdonald et al. (1998) set of equations for a north wind azimuth.

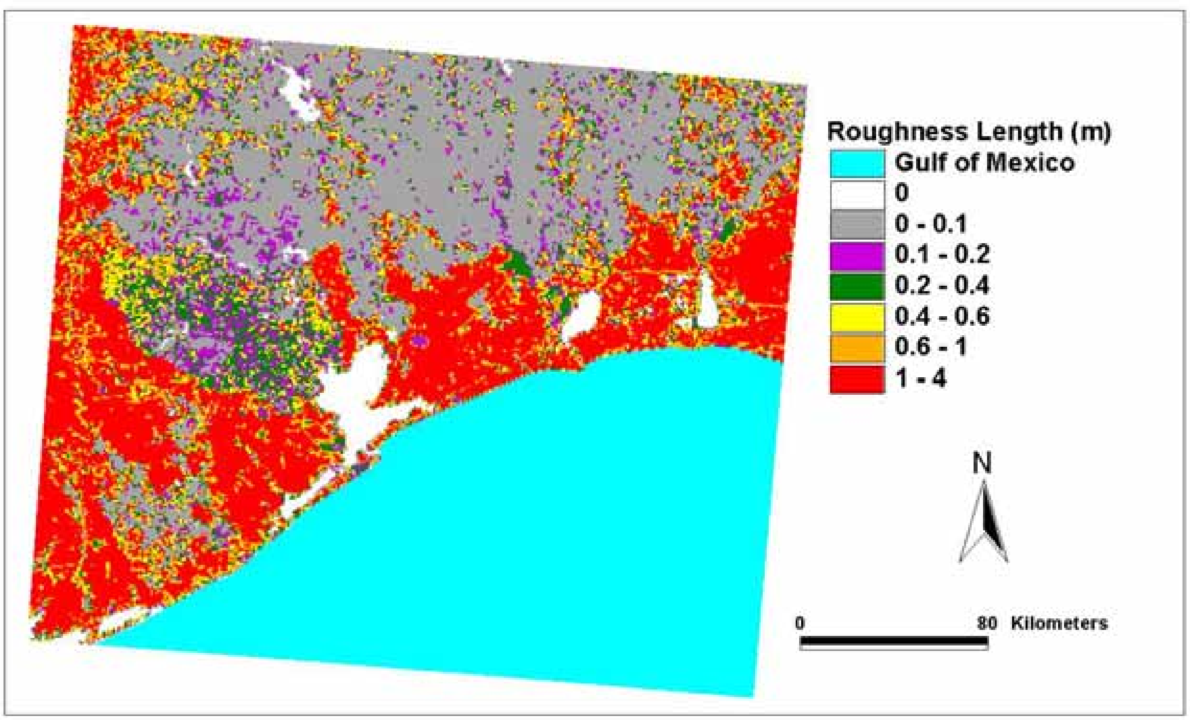

Figure 51. Spatial distribution of roughness length in the modeling domain calculated using the Macdonald et al. (1998) set of equations for a north wind azimuth.

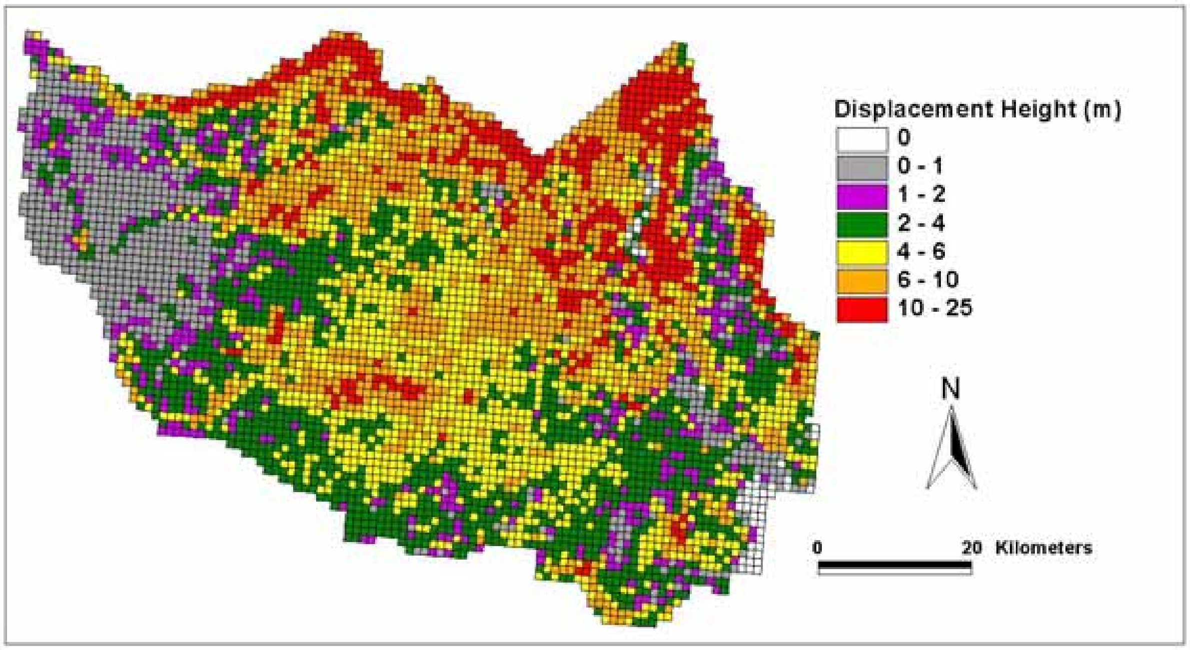

Figure 52. Spatial distribution of displacement height in Harris County calculated using the Macdonald et al. (1998) set of equations for a north wind azimuth.

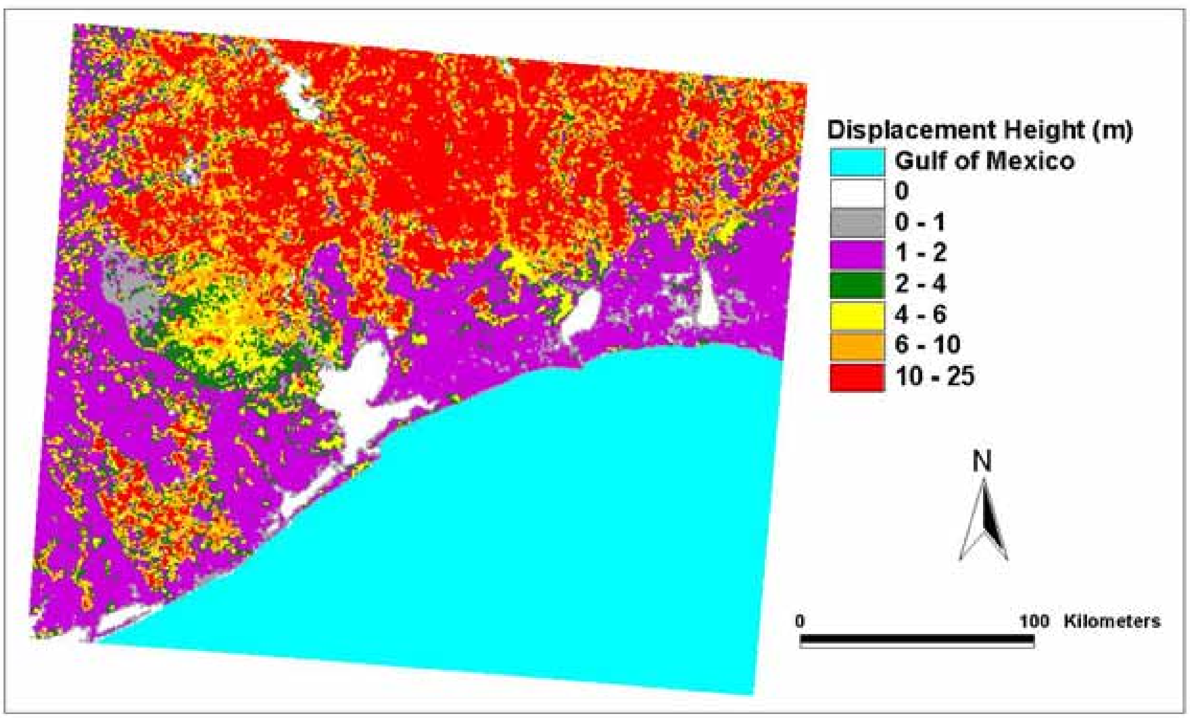

Figure 53. Spatial distribution of displacement height in the modeling domain calculated using the Macdonald et al. (1998) set of equations for a north wind azimuth.

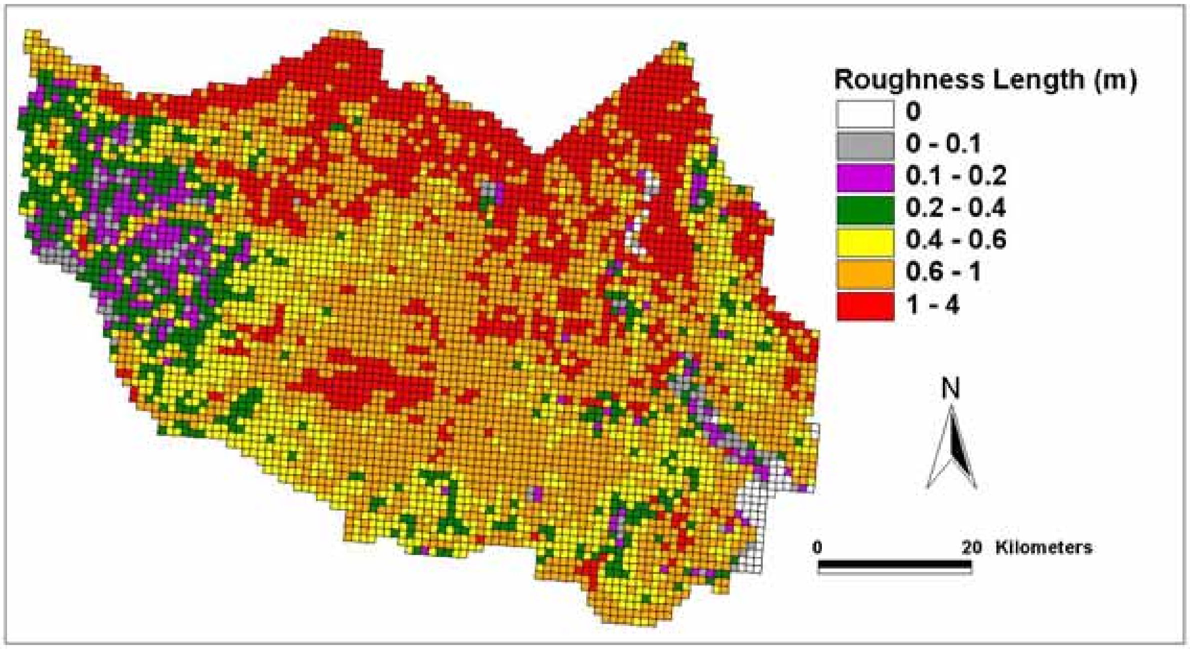

Figure 54. Spatial distribution of roughness length in Harris County calculated using the Raupach (1994) set of equations for a north wind azimuth.

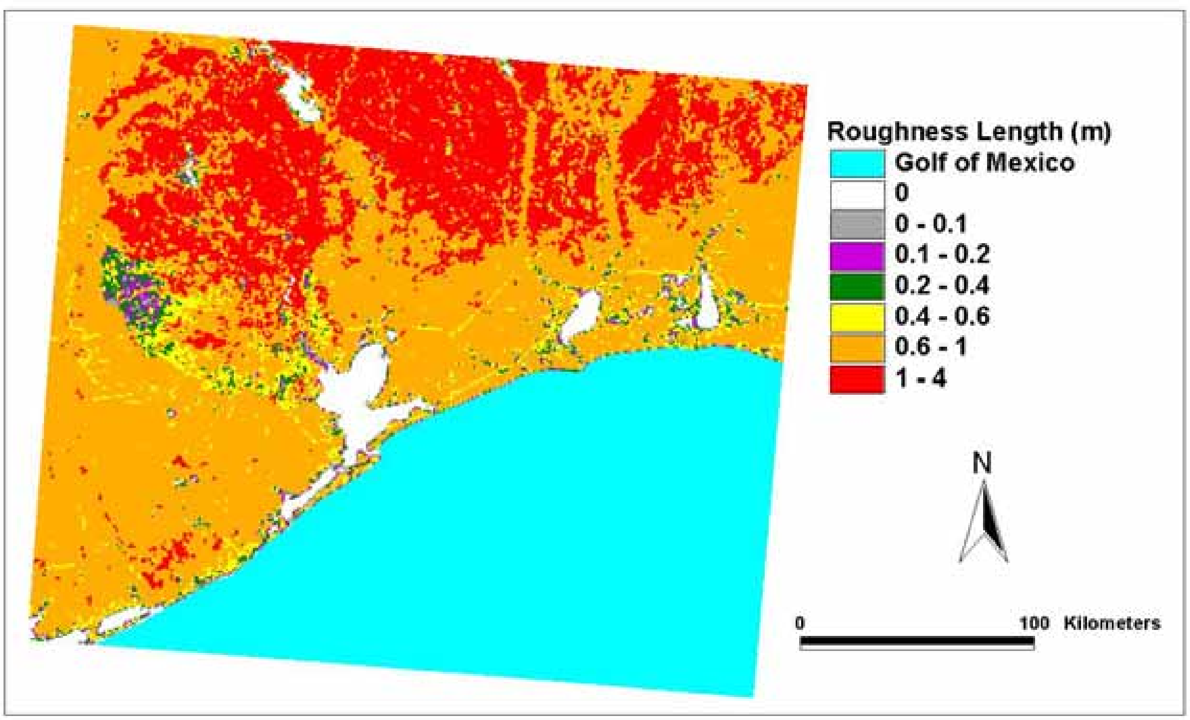

Figure 55. Spatial distribution of roughness length in the modeling domain calculated using the Raupach (1994) set of equations for a north wind azimuth.

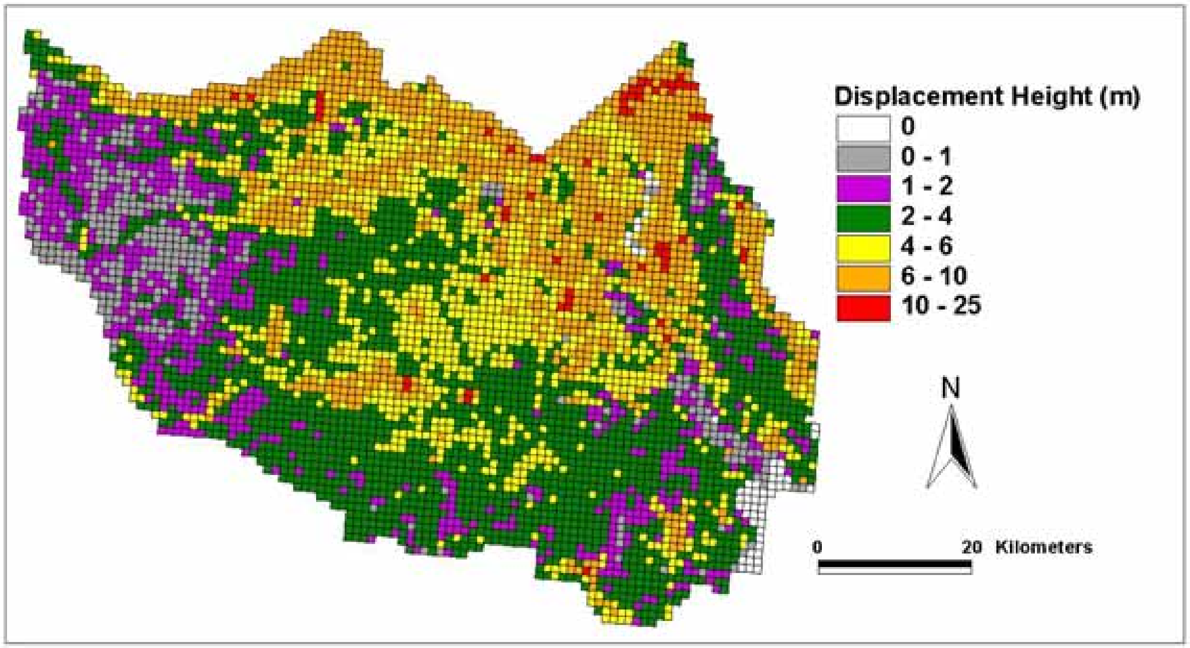

Figure 56. Spatial distribution of displacement height in Harris County calculated using the Raupach (1994) set of equations for a north wind azimuth.

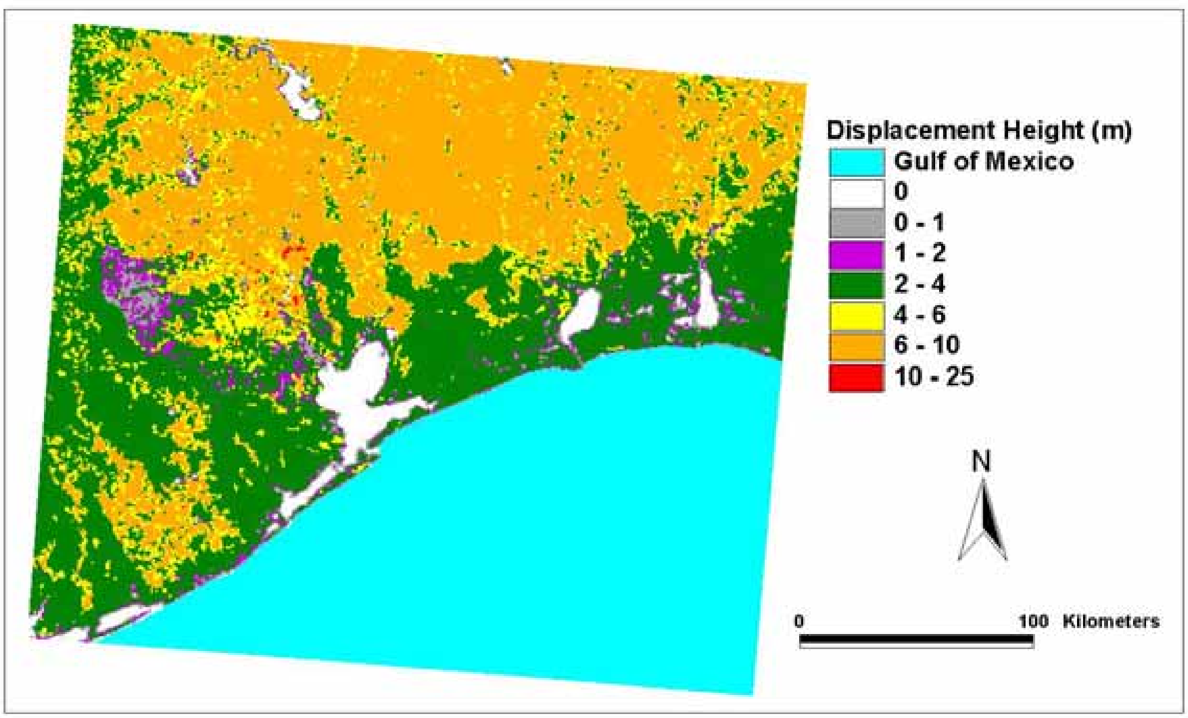

Figure 57. Spatial distribution of displacement height in the modeling domain calculated using the Raupach (1994) set of equations for a north wind azimuth.

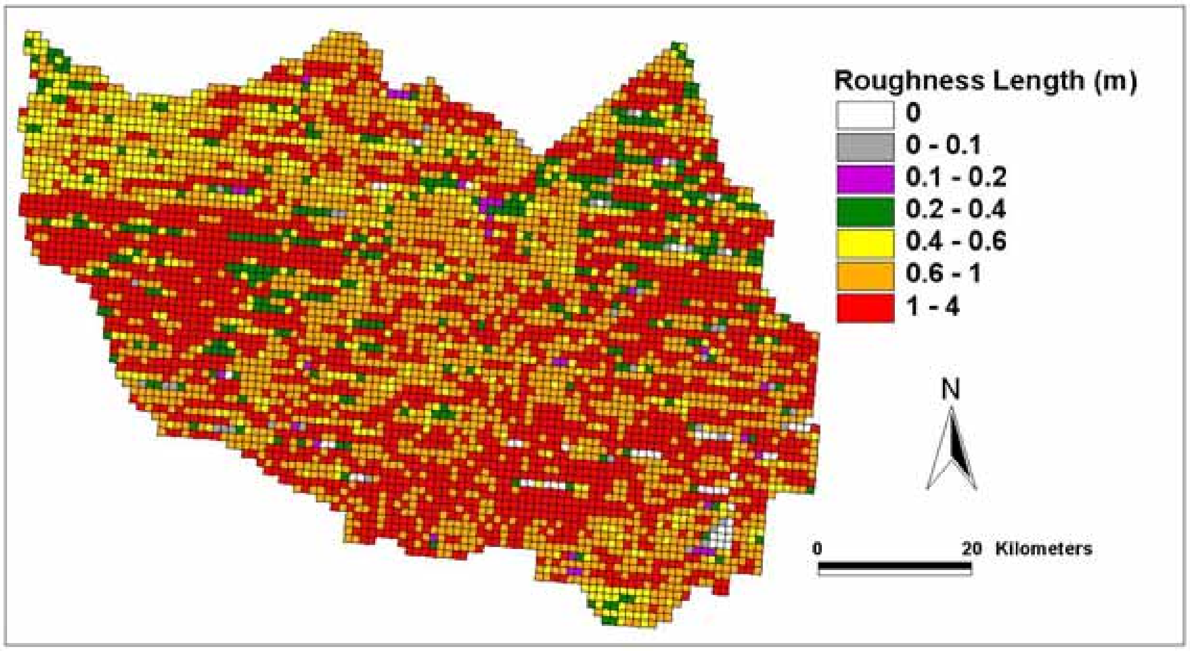

Figure 58. Spatial distribution of roughness length in Harris County calculated using the Bottema (1997) set of equations for a north wind azimuth.

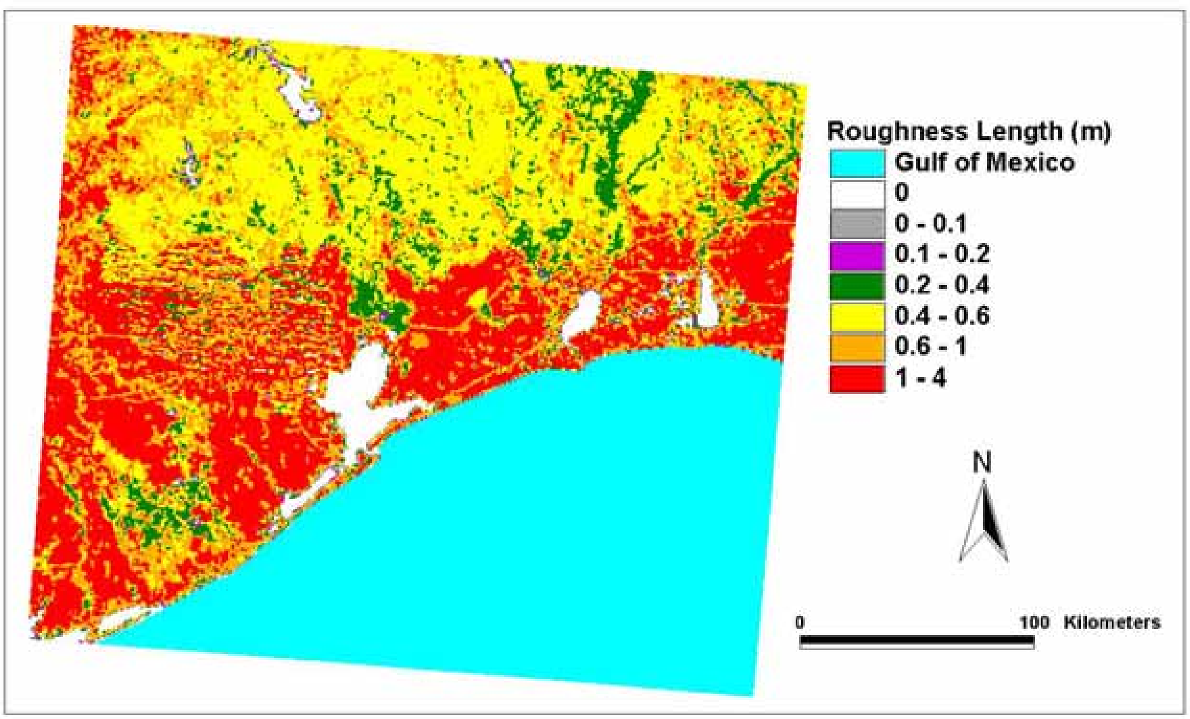

Figure 59. Spatial distribution of roughness length in the modeling domain calculated using the Bottema (1997) set of equations for a north wind azimuth.

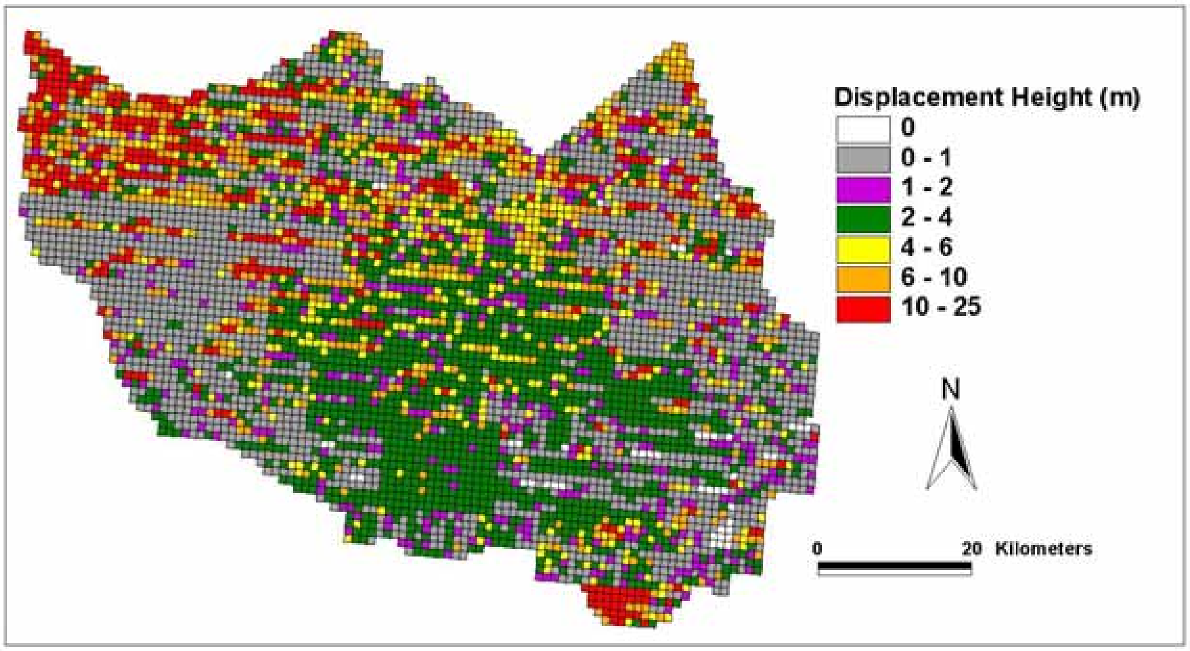

Figure 60. Spatial distribution of displacement height in Harris County calculated using the Bottema (1997) set of equations for a north wind azimuth.

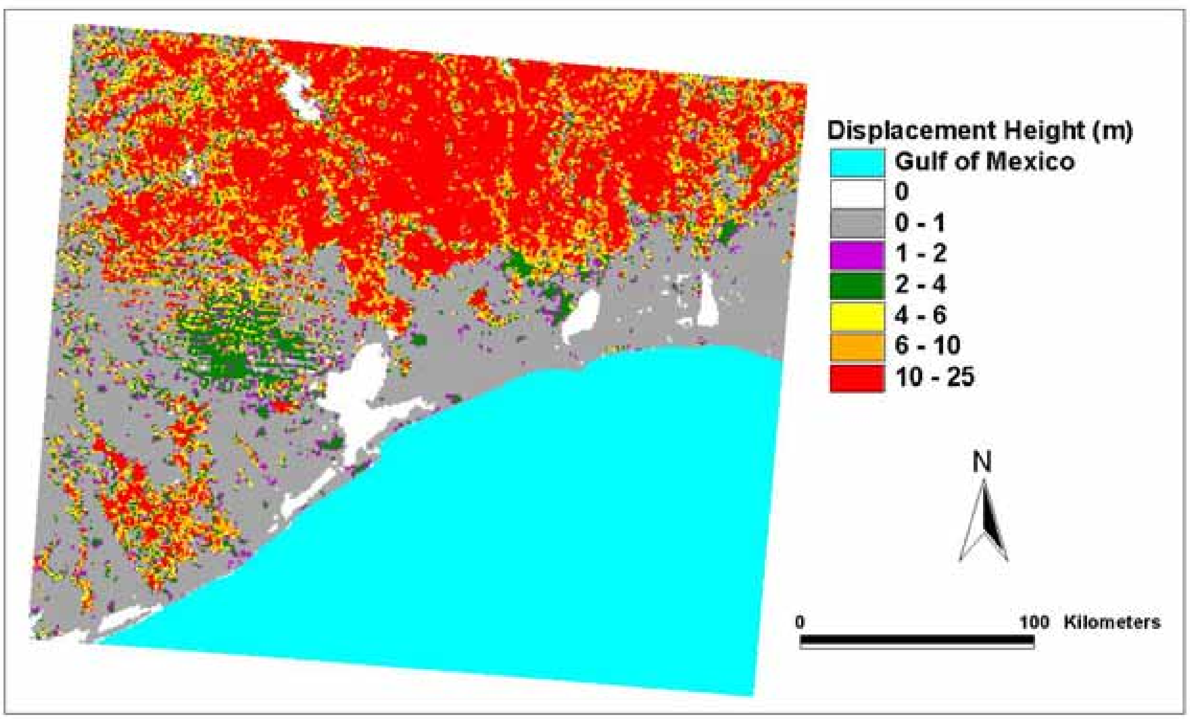

Figure 61. Spatial distribution of displacement height in the modeling domain calculated using the Bottema (1997) set of equations for a north wind azimuth.

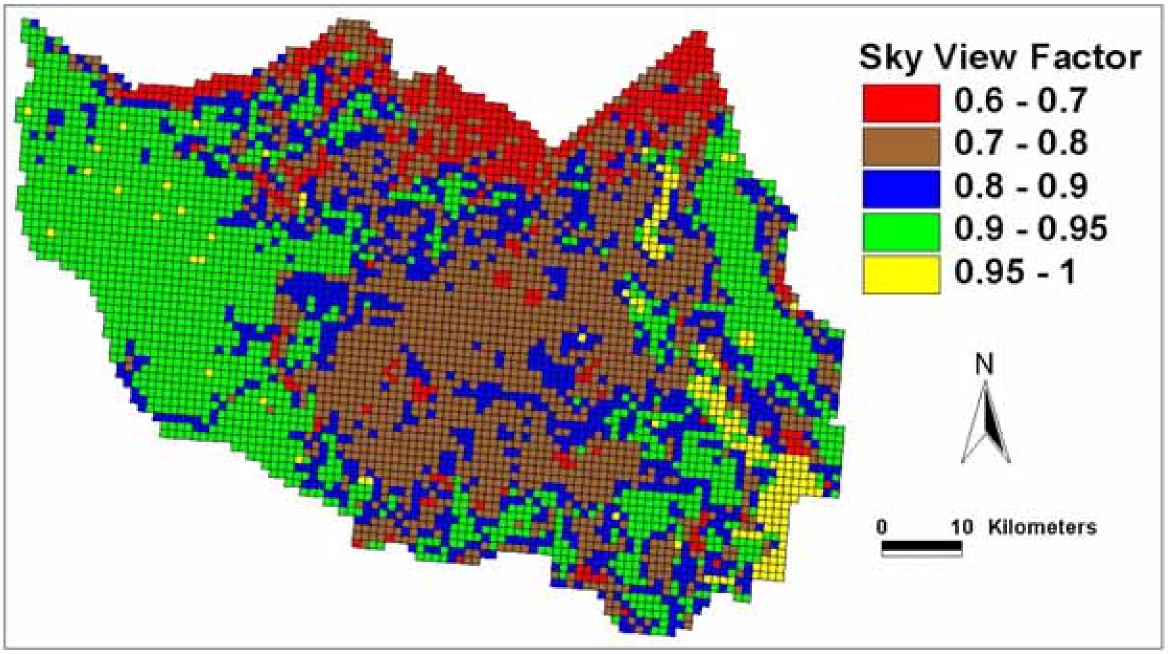

Figure 62. Spatial distribution of sky view factor in Harris County.

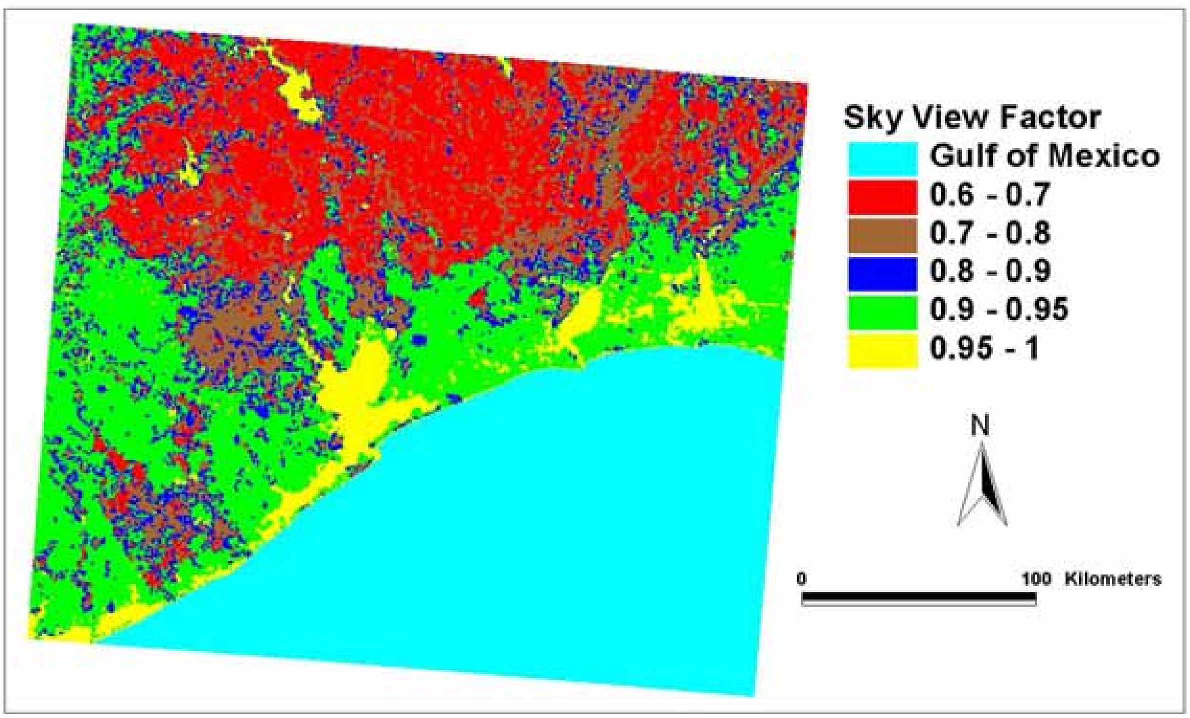

Figure 63. Spatial distribution of sky view factor in the modeling domain.

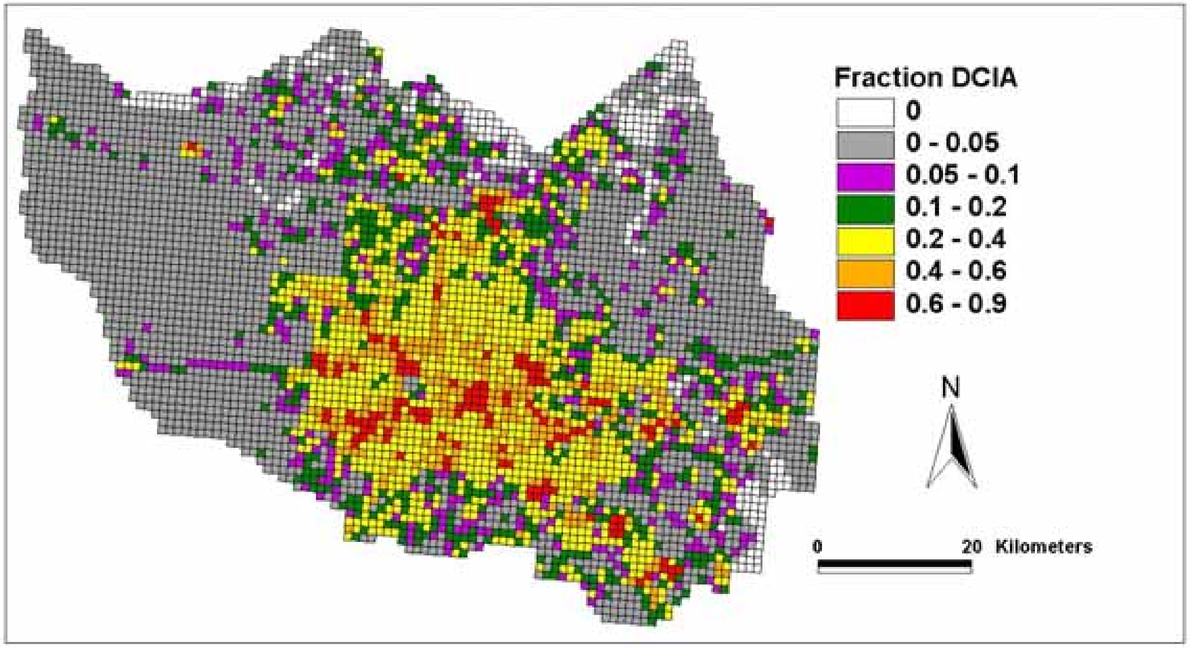

Figure 64. Fraction of each grid cell in Harris County that is directly connected impervious area (DCIA).

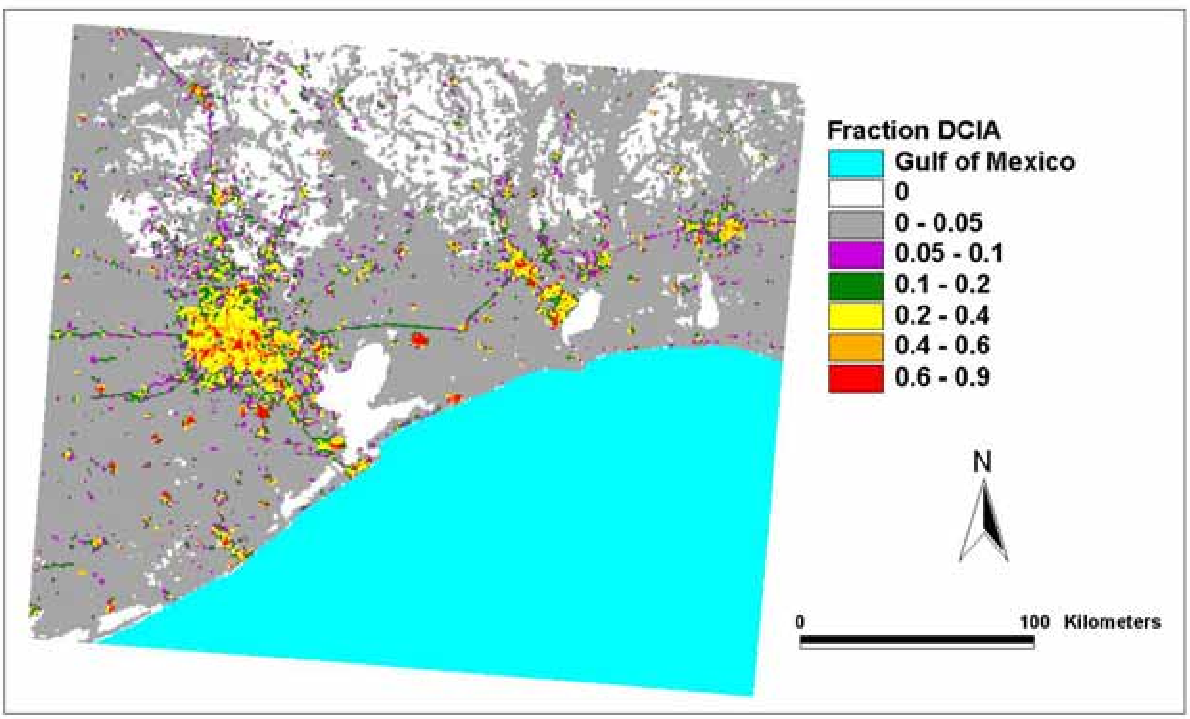

Figure 65. Fraction of each grid cell in the modeling domain that is directly connected impervious area (DCIA).

6. Summary

The project described in this report involved the processing of a high-spatial-resolution digital terrain dataset using GIS and other computational tools. The objective was to compute a gridded set of urban canopy parameters for use in the CMAQ/MM5/DA-SM2-U modeling system. The set of derived UCPs for each land use, the UCPs used for extrapolation, and the final gridded dataset are included in the spreadsheets accompanying this report. The final dataset contains the following number of UCPs:

- 16 UCPs required only one value per grid cell; 82,368 grid cells *[1,317,888 total values]*;
- 9 UCPs (Plan Area Densities, Top Area Densities, and Frontal Area Densities) are given as a function of height (one value per meter for a range of 33 to 297 m) for each grid cell *[~74,000,000 total values]*;
- 2 UCPs (Land Cover Fraction and Building Material Fraction) have five values per grid cell *[823,680 total values]*;
- 1 UCP (Building Height Histograms) has 62 values per grid cell (62 height increments) *[5,106,816 total values]*; and
- and the land use fraction has 29 values per grid cell *[2,388,672 total values].*

In total, the results spreadsheets contain approximately *84 million UCP values!* Because of the voluminous amount of UCPs, a comprehensive summary and presentation is not possible. Instead several figures displaying the data spatially were prepared. The Excel spreadsheets contain the entire set of UCPs.

7. References

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