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9.3 HIGH-RESOLUTION DATASET OF URBAN CANOPY PARAMETERS FOR HOUSTON, TEXAS

*Steven J. Burian[1], Stephen W. Stetson[2], WooSuk Han[1], Jason Ching[3], and Daewon Byun[4]

[1]Department of Civil & Environmental Engineering, University of Utah, Salt Lake City, Utah
[2]Global Environmental Management, Inc., Camden, Maine
[3]ASMD, ARL, NOAA, on assignment to U.S. Environmental Protection Agency
[4]Institute for Multi-Dimensional Air Quality Studies (IMAQS), University of Houston, Houston, Texas

1. INTRODUCTION

Mesoscale meteorological, 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 structures and surface cover properties requires much greater detail. To provide the most accurate surface characterization possible for an air quality modeling study of Houston, Texas, airborne LIDAR (Light Detection and Ranging) data were obtained at 1-m horizontal grid cell spacing for Harris County, Texas, an area of approximately 5800 km^2. The gridded dataset of full-feature elevation data was processed using GIS analysis techniques to determine more than 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 an effort to improve the efficiency and accuracy of the roughness length derivation, an alternative gridded dataset of roughness length was produced using satellite data collected by Synthetic Aperture Radar (SAR) instrumentation. The comparison of the SAR and morphometric (LIDAR) roughness lengths suggested an integration of the satellite and airborne LIDAR datasets may provide an efficient means to derive a more accurate roughness length gridded dataset. In this paper, we describe the high-resolution Houston UCP dataset, report on the variability of the UCPs across the Houston urban terrain, and present the comparison of the morphometric and SAR roughness lengths.

2. BACKGROUND

Urban canopy parameterizations have been used to represent urban effects in numerical models of mesoscale meteorology, the surface energy budget, and pollutant dispersion. The urban canopy parameterization accounts for the drag exerted by urban roughness elements, enhanced production of turbulent kinetic energy, and alteration of the surface energy budget (Brown 2000). Accurate representation of urban effects in numerical simulations using urban canopy parameterizations requires the determination of surface cover and geometric parameters describing the urban terrain (e.g., building height and geometry characteristics).

A handful of researchers over the years have pioneered the work on obtaining surface cover and morphological parameters for cities (e.g., Ellefsen 1990; Grimmond and Souch 1994; Voogt and Oke 1997; Cionco and Ellefsen 1998; Grimmond and Oke 1999). These studies have provided much useful information on building and vegetation parameters, focusing mostly on residential areas and, for a few cities, industrial and commercial areas as well. Past work involved detailed *in situ* studies, using visual surveys in an area encompassing a few city blocks and extrapolating the results to the entire city. With the recent availability of digital 3D building and vegetation datasets and high-resolution imagery, calculation of morphological and surface cover parameters has become automated using image processing and geographical information system (GIS) software allowing larger areas to be analyzed much more efficiently (e.g., Ratti and Richens 1999; Ratti et al. 2001; Burian et al. 2002; Long et al. 2003).

3. HOUSTON URBAN TERRAIN DATABASES

The CMAQ/MM5/DA-SM2-U modeling system was chosen for this neighborhood scale air quality modeling project. The modeling domain is centered on the Houston metropolitan area in southeast Texas (see Figure 1) and encompasses an 82,368-km^2 area covered by approximately two-thirds land surface and one-third water surface (primarily the Gulf of Mexico). The land use/land cover (LULC) for the modeling domain is based on the GIRAS LULC dataset for the conterminous U.S. at 1:250,000 available from the U. S. Environmental Protection Agency (EPA) and U.S. Geological Survey (USGS) (see Figure 2). The land use and cover information represented in the GIRAS LULC dataset dates to the late 1970s and early 1980s; therefore, to better represent current conditions the dataset was updated using high-resolution aerial photographs dating to 2000. Overall the land surfaces of the modeling domain are predominantly rural, consisting of significant fractions of Cropland & Pasture and Forest Land. The highest concentration of urban land use is the Houston metropolitan area located at the left center of Figure 2.

Most of the UCPs were derived by processing an airborne LIDAR full-feature digital elevation model (DEM) obtained from TerraPoint, LLC. LIDAR technology produces x, y, z representation of topography via airborne lasers. TerraPoint provided the

**Corresponding author address*: Steve Burian, 122 S. Central Campus Dr., Suite 104, Salt Lake City, UT 84112; E-mail: burian@eng.utah.edu

DEM as a distribution of data points according to an evenly spaced grid at 1-m resolution (i.e., a raster dataset). Horizontal accuracy of the DEM was 15 to 25 cm, while the vertical accuracy was approximately 10 cm. The DEM represented all terrain elements including buildings and vegetation, but did not differentiate between elements.

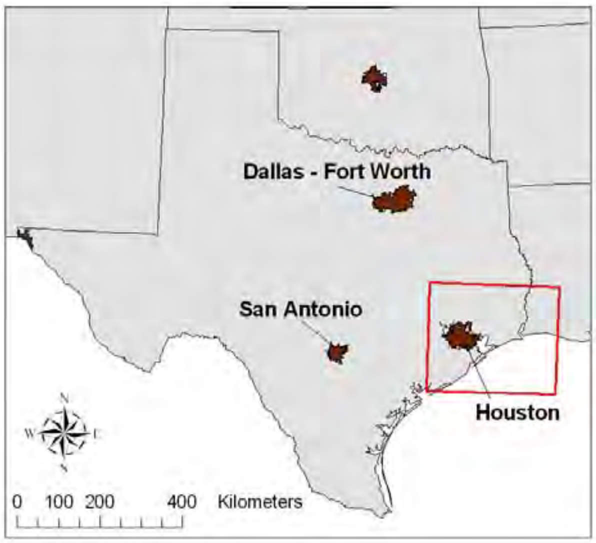

Figure 1. Houston metropolitan area vicinity map and modeling domain. The inner grid of the modeling domain is shown as a red box.

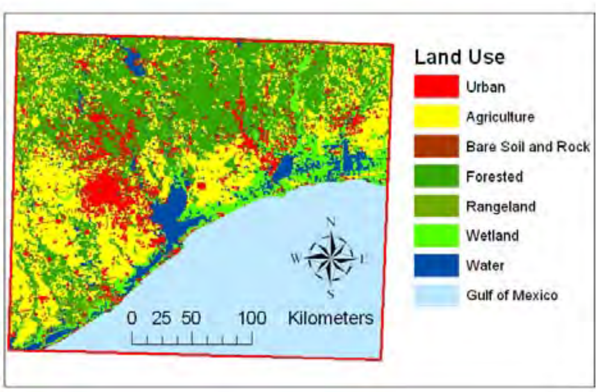

Figure 2. Land use and land cover of modeling domain.

The LIDAR DEM only covered 5800 km^2 of the modeling domain, the left central part of the domain containing the Houston metropolitan area. At 1-m resolution the uncompressed dataset in its various forms was immense (accumulated it was hundreds of gigabytes) and caused numerous data management and processing issues working as described by Burian et al. (2003). To define the UCPs outside of the DEM coverage an extrapolation approach was devised based on the correlation between the UCPs and land use type within the 5800 km^2 DEM coverage. The extrapolation method and the accuracy of the results are described later.

One other dataset used for the derivation of surface roughness was Synthetic Aperture Radar, or SAR, data collected from the ASAR instrument aboard the European Space Agency's satellite, ENVISAT. The ASAR instrument is an all-weather, day-and-night, high-resolution imaging instrument that provides radar backscatter measurements indicative of terrain structure, surface roughness, and dielectric constant. The surface roughness measured by the ASAR instrument is defined as the variation of surface height within an imaged resolution cell (see Figure 3). A surface appears rough to microwave illumination when the height variations become larger than a fraction of the radar wavelength. The fraction is qualitative, but may be shown to decrease with incidence angle. The SAR data was processed to remove anomalies due to cross-scene illumination differences due to incidence angle as well as to remove anomalies associated with data spikes and drop-out values.

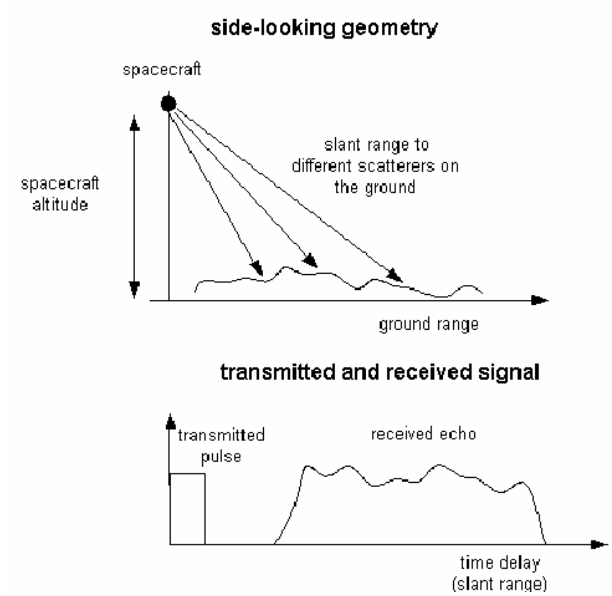

Figure 3. Illustration of SAR data collection concept.

For this project UCPs were defined for full canopy morphology (buildings and vegetation), building-only morphology, and vegetation-only morphology. Therefore, the raster DEM had to be intersected with another dataset that would differentiate between buildings and vegetation. The dataset chosen to differentiate buildings and vegetation was a digital building footprint layer obtained from the City of Houston (COH). The COH building footprint dataset is based on 1983 aerial photographs with small updates in the mid 1990s, not adequate for this project since the LIDAR data represent November 2001 conditions. The COH building dataset was therefore modified by overlaying it onto a series of high-resolution aerial photos covering the Houston metropolitan area collected in 2000. Buildings shown in the aerial photo but not contained in the COH dataset were added and buildings in the COH dataset not shown in the aerial photos were removed. This tedious process was performed using the ESRI

ArcGIS software package for a 1653 km^2 area containing most of the defined Houston metropolitan area and large tracts of outlying rural, forested, and agricultural regions. The original COH dataset contained 523,920 building footprints, while the modified dataset contains 664,861 building footprints. The building footprints defined the DEM cells representing buildings and all other DEM cells were assumed to be vegetation or non-building structures (e.g., roadway overpasses). Further details about the datasets used to derive the UCPs are provided by Burian et al. (2003).

4. URBAN CANOPY PARAMETER DATASET

This project required the calculation of the following canopy, building, vegetation, and other UCPs:

Canopy UCPs:
- Mean canopy height
- Canopy plan area density
- Canopy top area density
- Canopy frontal area density
- Roughness length
- Displacement height
- Sky view factor

Building UCPs:
- Mean building height
- Standard deviation of building height
- Building height histograms
- Building wall-to-plan area ratio
- Building height-to-width ratio
- Building plan area density
- Building rooftop area density
- Building frontal area density

Vegetation UCPs:
- Mean vegetation height
- Vegetation plan area density
- Vegetation top area density
- Vegetation frontal area density

Other UCPs:
- Mean orientation of streets
- Plan area fraction surface covers
- Percent directly connected impervious area
- Building material fraction

Calculation procedures were based on the GIS approach described by Burian et al. (2002). The mean orientation of streets was determined for each grid cell within the modeling domain, the canopy only UCPs were determined for the 5800 km^2 DEM coverage, the building and vegetation specific parameters were determined for the 1653 km^2 area covered by building footprints. Within the 5800 km^2 DEM coverage and 1235 km^2 of the 1653 km^2 building footprint zone the average UCP values for each USGS Level 2 land use type were determined (the other 418 km^2 of the 1653 km^2 building footprint zone was used for extrapolation validation as described below). The USGS land use in these regions was updated based on the year 2000 aerial photographs. The mean UCP values per land use type were then extrapolated to areas outside the data coverage using an area-weighted average based on underlying land use amounts within each grid cell.

The accuracy of the extrapolation process was assessed for most of the UCPs for a 418 km^2 area within the 1653 km^2 building footprint coverage. The relative similarity of the 418 pairs of "calculated" and "extrapolated" UCPs was measured using bias, root mean square error (RMSE), and cumulative relative error (CRE) statistics and visualized using scatter plots:

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

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(UCP_i - \overline{UCP_i}\right)^2} \qquad (2)$$

$$\text{CRE} = 100 \cdot \frac{\sum_{i=1}^{n}\left|UCP_i - \overline{UCP_i}\right|}{\sum_{i=1}^{n}\overline{UCP_i}} \qquad (3)$$

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). Table 1 contains the accuracy assessment statistics for the building height UCPs. On average the extrapolation will produce higher building height parameters, with the most significant error associated with the standard deviation of building height estimate. Table 2 contains a comparison of the average UCPs per land use type calculated in the derivation (1253 km^2) area and the validation area (418 km^2). The Residential and Industrial land use types have the greatest differences.

Table 1. Building height UCP accuracy assessment statistics.

	Bias	RMSE	CRE
Mean Building Height	1.02 (+23%)	1.64	28%
Standard Deviation of Building Height	1.47 (+75%)	1.84	83%
Footprint Area-Weighted Mean Height	1.15 (+23%)	2.39	34%
Wall-to-Plan Area Ratio	0.009 (+9%)	0.05	31%
Height-to-Width Ratio	0.004 (+11%)	0.02	37%

Scatter plots of extrapolated versus calculated UCPs were created using data for the 418 grid cells in the defined validation area. These plots were meant to identify limitations of the extrapolation process and define future enhancements. Figure 4 contains the scatter plot for mean building height. One readily apparent observation is the "floor" limiting the lower end of the extrapolation values. This observation was expected because the use of the average value prevents the accurate prediction of extremely low or high values in the distribution of parameter values. Possible remedies to this limitation are to incorporate (1) other base data layers into the extrapolation process that can be correlated to morphological parameters (e.g., population) or (2) the variability of the parameter into the extrapolation. Both of these remedies are being evaluated in other work.

Table 2. Comparison of mean building height per land use type in the derivation and validation zones.

USGS Level 2 Land Use Name	Mean Building Height (m) – Derivation Zone	Mean Building Height (m) – Validation Zone
Residential	5.70	4.74
Commercial & Services	6.05	5.85
Industrial	6.09	4.95
Transportation, Communications, Utility	4.81	4.17
Other Urban or Built-Up Land	4.95	4.68
Cropland & Pasture	5.02	4.94
Deciduous Forest Land	7.32	5.67

The summary statistics (bias, RMSE, and CRE) were determined and scatter plots created for most of UCPs included in the dataset. The complete results of the assessment are too extensive to include in this paper, but are summarized in more detail by Burian et al. (2003). More will be described in the presentation. Several noteworthy observations regarding the UCP gridded dataset for Houston are:

- All UCPs were over-estimated on average by the extrapolation, except the UCPs that were determined as a function of height.
- Upper and lower limits to the estimated UCP values caused by the extrapolation were noted for many of the UCPs (as was described above for the mean building height)
- Morphometric roughness length extrapolation was less accurate than the morphometric displacement height extrapolation. This is initially addressed below with an alternative method to derive roughness length using satellite data and continues to be addressed in on-going work.
- The range of errors is significant and in some cases the errors resulting from the extrapolation can be quite large, but on average the magnitudes of the errors are moderate (within the 30-50% range predominantly).

The final UCP dataset for the Houston modeling domain contained more than 80 million parameter values corresponding to grid cells with specified coordinates. Overall, the UCPs contained in the gridded dataset were concluded to be more accurate and representative of surface properties than could have been obtained by simply using literature values correlated to land use type and have been shown to improve model results (e.g., Dupont et al. 2004).

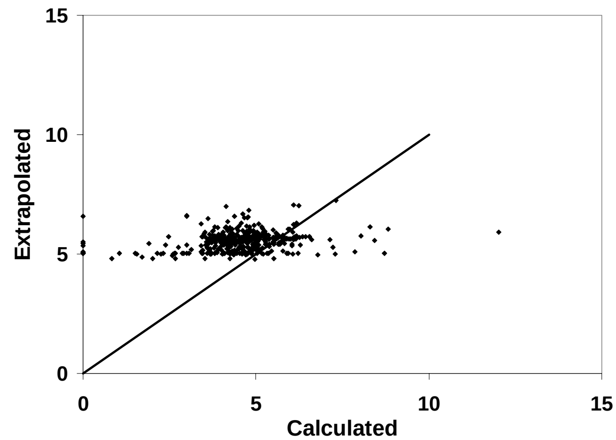

Figure 4. Scatter plot of extrapolated versus calculated mean building height (m) for the 418 grid cells in the validation area.

5. UCP VARIABILITY

The initial Houston UCP dataset extrapolation using the mean UCP value correlated to land use provides reasonable estimates, but improvements can be made. In an effort to develop an improved method to perform the extrapolation, the variability of the UCPs for the land use types was quantified. The motivation for this effort was to use the quantified UCP variability as a function of land use type in an enhanced extrapolation that incorporated the variability using a stochastic approach. The first step of quantifying the variability is reported here.

The same updated land use and building datasets covering the 1653-km^2 area that were used to derive the gridded UCP coverage described above were also used to quantify the parameter variability for selected land use types (see Figures 5 and 6). The study area has a large fraction of Residential land use (38%), with smaller amounts of Commercial & Services, Industrial, Cropland & Pasture, and Forest Land.

The UCP variability was determined for the following seven land use types: Residential; Commercial & Services; Industrial; Transportation, Communication, Utility; Other Urban or Built-up; and Cropland & Pasture. These land uses were selected because they had sufficient coverage in the study area to provide adequate samples to quantify variability. The land use dataset of the study area is divided into 5779 polygons, each representing one land use type. Of the 5779 total polygons, 5447 represent the seven land use types included in the study. Table 3 lists the summary characteristics of the 5447 polygons.

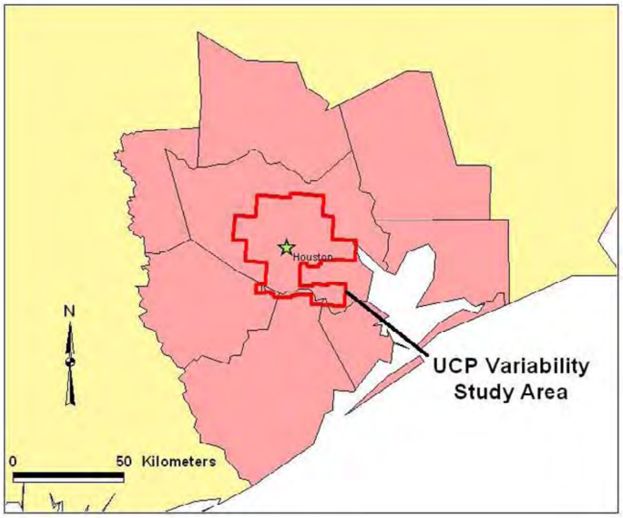

Figure 5. Location and extent of UCP variability study area.

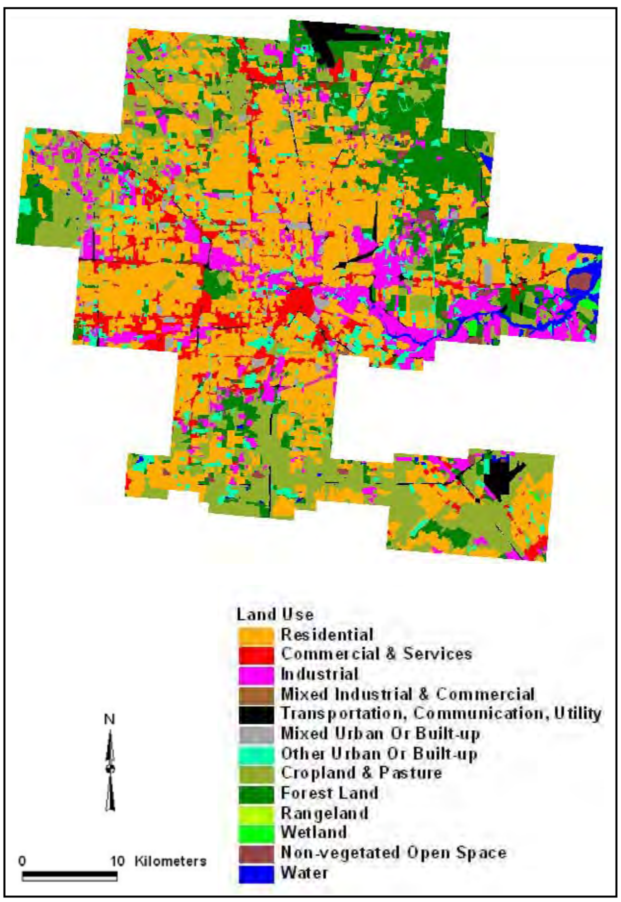

Figure 6. Land use of UCP variability study area.

Table 3. Summary characteristics of the land use polygons included in the UCP variability analysis.

Land Use	Number	Avg. Size (ha)	Median Size (ha)
Residential	1450	44	29
Commercial & Services	762	15	8
Industrial	690	23	11
Transportation	290	21	12
Other Urban Or Built-up	818	11	7
Cropland & Pasture	762	39	17
Forest Land	675	33	16

All seven land use types have a sufficient number of samples to derive meaningful statistics and perform scientific visualizations to quantify and express the relative variability of the UCP values. The majority of land use samples are Residential, which also have the largest average size. The Other Urban or Built-up land use has the smallest average polygon size. The minimum land use sample size is slightly smaller than 0.5 hectares, while the largest size is 1268 hectares. The 1268 hectare polygon is a relatively unique sample because it represents the Bush Intercontinental Airport.

For each land use sample polygon, the set of UCPs were calculated and the variability of the UCPs was then quantified for each land use type by calculating a series of statistics representing the central tendency and spread of the distribution of values. The following UCPs were included in this analysis:

- Number of buildings per hectare
- Mean building height
- Standard deviation of building height
- Plan-area-weighted mean building height
- Plan area fraction of buildings
- Building frontal area index
- Building height-to-width ratio
- Roughness length (simple & Raupach) – based on buildings and canopy
- Displacement height (simple & Raupach) – based on buildings and canopy
- Mean canopy height
- Standard deviation of canopy height
- Plan area fraction of canopy

Summary statistics for the UCP values for each land use type were determined. Table 4 contains the statistics for the Residential land use type. The summary of the other UCPs and land use types are too extensive to include in this paper; complete results are available in Burian (2004). The summary statistics for all land use types indicated three general observations:

- The coefficient of variation (C_V) suggests the Residential land use has the smallest UCP variability of the seven land uses studied, while the Transportation, Communication, Utility land use has the largest.
- UCP values equal to zero indicated no buildings

(or canopy) were present in the sample polygon. This was uncommon for the Residential, Commercial & Services, and Industrial categories, but was common for the Other Urban or Built-up, Transportation, Cropland & Pasture, and Forested land use types.

- Of the three primary urban land use types (Residential, Commercial & Services, and Industrial) the Commercial & Services had the highest UCP variability.

Table 4. Summary UCP statistics for Residential land use samples.

UCP	Mean	Median	Standard Deviation	C_V
No. of Buildings per hectare	9.01	8.64	5.12	0.57
Mean bldg ht. (m)	5.45	5.42	1.13	0.21
St. dev. bldg. ht. (m)	2.24	2.18	1.02	0.46
Plan-area-weighted mean bldg. ht. (m)	5.32	5.26	1.10	0.21
Bldg. λ_P	0.17	0.17	0.10	0.59
Bldg. ht-to-width	0.05	0.05	0.02	0.40
Bldg. λ_F	0.07	0.07	0.04	0.52
Roughness length (simple; bldgs) (m)	0.55	0.54	0.11	0.21
Displacement ht. (simple; bldgs) (m)	2.72	2.71	0.56	0.21
Roughness length (Raupach; bldgs) (m)	0.32	0.31	0.18	0.56
Displacement ht. (Raupach; bldgs) (m)	2.01	2.01	0.69	0.35
Mean canopy ht. (m)	6.38	6.20	1.76	0.28
St. dev. canopy ht. (m)	4.46	4.43	1.19	0.27
Canopy λ_P	0.61	0.62	0.11	0.19
Roughness length (Simple; Canopy) (m)	0.64	0.62	0.18	0.28
Displacement ht. (Simple; Canopy) (m)	3.19	3.10	0.88	0.28

The first observation would be expected in most cities because residential development is guided by fairly uniform building codes and builders will typically follow a small number of plans when constructing new houses in a subdivision. The uniformity of most subdivisions significantly reduces the UCP variability from one location in a subdivision to another, but also limits the variability from one residential location to another. The third observation also would be expected in other cities because Commercial & Services is a broader definition and will not contain as uniform building types and site layouts as Residential and Industrial land uses. Direct comparison of the coefficients of variation of each UCP for all land uses was conducted by extracting the numbers from the tables and creating bar chart plots. Figure 7, for example, shows the plot for the mean building height UCP (all plots available in Burian (2004)). The plots support the observations derived from the analysis of the UCP summary statistics for each land use type.

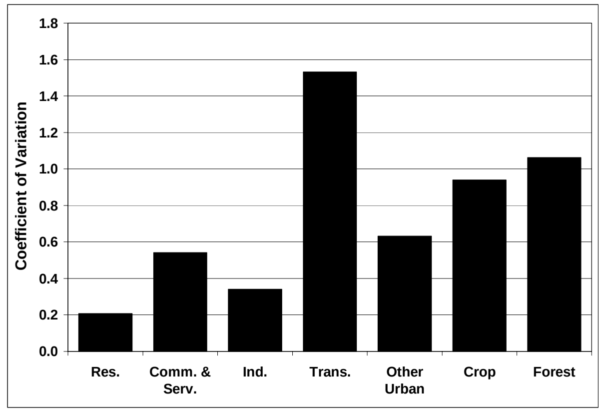

Figure 7. Plot of coefficients of variation for the mean building height UCP.

6. ROUGHNESS LENGTH DERIVATION

The representation of surface roughness is a critical first step in many meteorological, wind engineering, and atmospheric dispersion modeling activities. It provides an estimate of the drag and turbulent mixing associated with the underlying surface. The roughness length (z_o) is a key parameter in the logarithmic velocity profile based on similarity theory and is commonly used in many models to specify boundary conditions above built-up areas. The roughness length is directly related to the overall drag of the surface. Mathematically, it represents the distance above the displacement height plane at which the velocity goes to zero.

z_o is difficult to estimate with certainty by experiment or theory. Grimmond and Oke (1999) reviewed methods to calculate the z_o of urban areas based on building and vegetation morphology. They compared the predictions of the morphological methods to those obtained from wind measurements in urban areas and found significant differences. However, collecting and analyzing wind measurements to determine the roughness length for a large number of model grid cells covering a heterogeneous urban area is not practical. Even collecting measurements for representative urban land use types is not feasible for most modeling projects. Methods must be developed that can efficiently and accurately produce gridded coverage of roughness parameters.

For the Houston UCP database five morphological estimates of z_o were used and three were compared to investigate the relative differences between the methods. Unfortunately, there is no "true" roughness length dataset to make comparisons to determine which method is the most accurate and under what circumstances. Manual interpretation of the relative differences can however provide useful observations and potential recommendations for deriving more accurate roughness parameter data layers.

The first morphological technique used to derive the roughness length coverage for the 82,368-km^2 inner modeling domain is a simple approach that defines the roughness length to be one-tenth of the mean height of roughness elements (buildings and vegetation). The second technique is based on morphometric equations introduced by Raupach (1994):

$$\frac{z_d}{\overline{z_H}} = 1 - \left\{ \frac{1-\exp\left[-\left(c_{d1} 2\lambda_f\right)^{0.5}\right]}{\left(c_{d1} 2\lambda_f\right)^{0.5}} \right\} \qquad (4)$$

and

$$\frac{z_o}{\overline{z_H}} = \left(1-\frac{z_d}{\overline{z_H}}\right)\exp\left(-k\frac{U}{u_*}+\psi_k\right) \qquad (5)$$

where

$$\frac{u_*}{U} = \min\left[\left(c_S + c_R\lambda_f\right)^{0.5}, \left(\frac{u_*}{U}\right)_{max}\right] \qquad (6)$$

and z_d is the displacement height, $\overline{z_H}$ is the mean canopy height, λ_F is the frontal area index, 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. Using these values, a von Kármán constant (k) of 0.4, and the values computed for the mean building height and the frontal area index for a north wind direction the roughness length was determined.

The third approach computes the surface roughness using data collected from satellite using Synthetic Aperture Radar (SAR) instrumentation (Stetson 2004). The SAR sensors provided backscatter measurements indicative of surface roughness at 150 m resolution. Following the data calibration, a surface roughness coefficient for each ground sample, or pixel, was generated based on the range of SAR values within each separate LULC class. The roughness coefficient for each pixel was then applied to the standard roughness-length value associated with each LULC class using a look-up-table derived from peer-reviewed literature sources. For each 150 m pixel, the roughness coefficient was generated as the quotient of the individual pixel's SAR value divided by the mean SAR value for its respective LULC class. Within each LULC class the roughness coefficient was used to derive the roughness length:

$$z_o = RC * z_{o*} \qquad (7)$$

where RC is the roughness coefficient and z_{o*} is a standard roughness length for the given land use or cover class obtained from the literature. The final step was to resample the 150 m resolution roughness to 1-km to correspond to the model domain. It should be noted that the derivation of the SAR roughness coverage used a newer and improved LULC dataset than that used to derive the other roughness length values, although the differences in the dataset are not significant in the metropolitan area.

The study area for comparison of the derived roughness lengths was centered on Houston, Texas (see Figure 8). The study area encompasses eight counties of the Texas Gulf Coast covering an area of approximately 23,100 km^2. Note that Harris County shown in the figure contains the Houston metropolitan area.

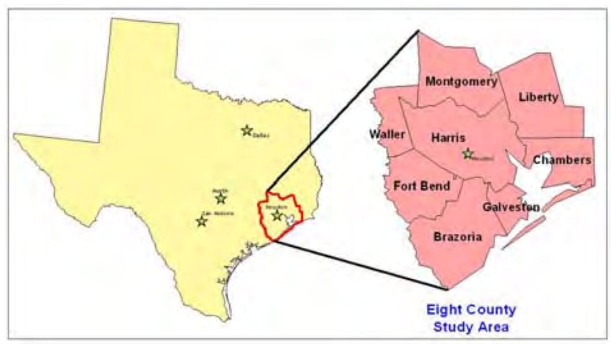

Figure 8. Location of roughness length calculation comparison study.

The three roughness length coverages were first compared by calculating summary statistics for the entire study area (see Table 5). The DEM methods (simple ratio and Raupach) have mean and maximum values that are approximately two times the values for the SAR method. The minimum's are all the same (nearly zero) and are correctly assigned to water and flat non-vegetated areas by the three approaches. Interestingly, the measure of variability of values across the study area (standard deviation) is identical for all three estimation techniques. The maximum values are important because for both the simple method and the Raupach method the values correspond to the location of the downtown core area, while the maximum values for the satellite data do not.

Figure 9 shows histograms of the roughness length values for the three estimation methods. In this form, one notes the weight of the distribution of the values based on the satellite estimation method is towards 0.0 – 0.5. In fact, 60% of the 1-km^2 grid cells are estimated from the satellite data to have a roughness length in this range; while less than 20% of the grid cells fall within this range for the simple method and the Raupach method. More than 99% of the roughness lengths estimated from the satellite data are less than 1.0, but approximately 20% of the values estimated using the DEM data (both methods) are greater than 1.0.

Table 5. Summary statistics for entire study area comparing roughness length calculation methods.

	Satellite	DEM – Simple	DEM – Raupach
Mean (m)	0.41	0.70	0.73
Standard Deviation (m)	0.32	0.32	0.32
Minimum (m)	0.00	0.00	0.00
Maximum (m)	1.20	2.90	2.90

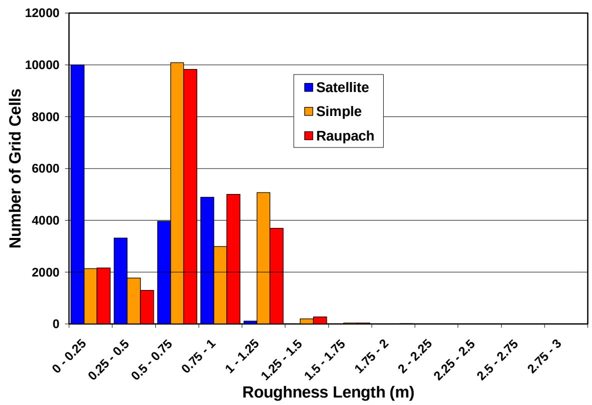

Figure 9. Comparison of roughness length histograms.

The second phase of the roughness length comparison focused on smaller areas and specific locations with selected land use samples. One location of interest was the downtown core area of Houston. The street network in the downtown area is angled off of the north-south : east-west directions. The west end of the downtown contains the dense high-rise buildings. Equally as dense, yet shorter buildings occupy the east and south ends. The major sports facilities are located on the eastern end. The roughness lengths using the three techniques for six 1-km resolution grid cells covering the downtown area were computed. The DEM-based roughness lengths (simple and Raupach) are much higher in the tall building region of the downtown than the satellite method. The satellite roughness of 0.97 m for the grid cell containing the tallest buildings is at the upper end of the range of values for the satellite, suggesting that the satellite data may be correctly identifying a location of a relative maximum, although it does not identify it as the absolute maximum in the dataset. The values predicted by the DEM procedures (2.9 m) are more consistent with values calculated using morphology and wind profile measurements for the downtown core areas of other cities (Burian et al. 2003).

Similar comparisons were made for several other locations for multiple land use types (urban and non-urban). A summary comparison of the roughness length values estimated per land use and cover type was also determined and is shown in Table 6. The synthesis of results suggests that the gridded fields of roughness lengths produced by the three techniques are predominantly similar for Residential, Industrial, Transportation, and Other Urban or Built-up land uses. The most noteworthy difference corresponded to Commercial land use types, while Cropland & Pasture and Forested land uses also exhibited significant differences.

Table 6. Comparison of roughness lengths per land use and cover type.

Land Use	Mean z_o (m) Satellite	Mean z_o (m) Simple	Mean z_o (m) Raupach
Residential	0.72	0.72	0.80
Commercial & Services	0.65	0.74	0.85
Industrial	0.47	0.62	0.65
Mixed Industrial & Commercial	0.47	0.74	0.83
Transportation, Communication, Utility	0.41	0.69	0.74
Mixed Urban Or Built-up	0.62	0.74	0.80
Other Urban Or Built-up	0.67	0.69	0.76
Cropland & Pasture	0.25	0.44	0.47
Forest Land	0.67	0.94	0.93
Rangeland	0.16	0.57	0.51
Wetland	0.25	0.42	0.44
Non-vegetated Open Space	0.59	0.29	0.39
Water	---	---	---

7. SUMMARY

The project described in this paper involved the processing of high-spatial resolution digital terrain datasets using GIS and image processing software and other computational tools. The objective was to derive an accurate gridded set of urban canopy parameters for use in the CMAQ/MM5/DA-SM2-U modeling system. The first generation dataset has the following characteristics:

- 16 UCPs required 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 meters to 297 meters) 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 the land use fraction has 29 values per grid cell **[2,388,672 total values]**

The total number of UCPs in the first generation dataset is more than 80 million, not including the multiple roughness length values and other derivative products.

The UCP variability assessment indicated that the Residential land use has the least amount of parameter variability across the Houston metropolitan area, while the Commercial & Services land use type had the greatest. The comparison of the three roughness length derivation approaches indicated that methods to estimate roughness length have a significant degree of variability and the accuracy of any method is questionable because a gridded dataset of true values does not exist for comparison. The new satellite approach to estimating roughness lengths introduced by Stetson (2004) was found to be a promising technique because it produced comparable results to the methods based on morphometric equations even using standard values from the literature. Possible future improvements to the satellite approach include incorporating a calibration step and using city-specific morphometric estimates of roughness lengths per land use class in the extrapolation process. As future work improves the accuracy of the UCP values, the Houston database will be updated.

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