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DEVELOPMENT AND ASSESSMENT OF THE SECOND GENERATION NATIONAL BUILDING STATISTICS DATABASE

Steven J. Burian[1], Nicholas Augustus[1], Indumathi Jeyachandran[1], and Michael J. Brown[2]

[1]*University of Utah, Department of Civil and Environmental Engineering*
[2]*Los Alamos National Laboratory*

1. INTRODUCTION

Mesoscale meteorological codes and transport and dispersion models are increasingly being applied in urban areas (Brown 2004). One challenge with such applications is representing the urban morphological characteristics necessary for accurate simulation of air flow, heating and cooling, and airborne contaminant concentrations in cities (Burian et al. 2004). The National Building Statistics Database (NBSD) was introduced in 2005 to address the need for building morphological characteristics nationally in the United States (U.S.). It provided an adequate first step by compiling 13 building statistics in gridded datasets for 17 of the most populous metropolitan areas in the country. This paper presents the *second generation* compilation of the National Building Statistics Database (NBSD2) recently developed by researchers at the University of Utah in collaboration with modelers at Los Alamos National Laboratory. NBSD2 contains the same set of building morphological parameters but has been expanded to cover 44 cities among the largest (in area and population) metropolitan areas in the U.S. One additional enhancement over the original NBSD includes the delivery of the data at 250-m and 1-km grid cell resolution. This paper describes the data and methods used to produce NBSD2, and reports interesting data characteristics and trends across cities.

2. BACKGROUND

In recent years two approaches to represent urban areas in models have evolved. The first involved adjusting parameter attributes associated with land use and other surface cover datasets to represent the altered morphological, reflective, and anthropogenic heating aspects of urban areas. The second approach involved modifying the model itself to account for the morphological, radiative, and anthropogenic effects that are different in urban areas compared to rural areas. Both approaches have been used to study a range of urban land-atmosphere processes, climate, and air quality issues, and both approaches have challenging drawbacks to overcome. For the land use based approach, the use of land use datasets may not be representative of the urban terrain. And for the modified model approach, the requirement for new and difficult to obtain morphological data presents a major challenge.

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

There have been efforts towards improving mesoscale meteorological and atmospheric dispersion models, however, two areas of needs have been lacking. First, the application of land use has not been adequately analyzed to show the need to move away from the use of existing land use datasets to more accurately represent morphological characteristics of cities. Second, a nationally consistent building morphological dataset has yet to be produced to supply the rapidly developing set of urbanized models. This paper addresses the second by introducing the NBSD2.

Currently, due to the expense and logistics of conducting detailed field surveys, building statistics have been derived for only small sections of a few cities. In most other cities, modeling projects rely on building statistics estimated from correlation to underlying land use using intuition and best guess techniques. There has been increasing emphasis in recent years to derive building statistics using digital building data or other data sources as a proxy for those data. Although there is a current expansion in public and private sector development of digital building data, at present there has not been an accumulation of this information at the national level in a consistent form of derived building parameters that are needed to run meteorological and transport and dispersion models.

3. BUILDING MORPHOLOGICAL DATABASE

The NBSD2 is comprised of building statistics computed from three-dimensional building datasets covering parts of 44 cities in the US. Figure 1 shows the distribution of the 44 cities contained in the NBSD2. The cities are distributed throughout the US, with 21 located west of the Mississippi River, 21 to the east and two along the Mississippi River (St. Louis and New Orleans). Regionally, 13 cities are in the west (8 in the Pacific West and 5 in the Mountain West), 8 are in the Midwest, 17 are located in the south, 4 of which are on the Gulf Coast, and finally 6 are found in the Northeast with 4 being in the Mid-Atlantic States and 2 being in New England. Table 1 lists the size of each metropolitan area and the population of the 44 main NBSD2 cities. These cities rank among the largest 46 metropolitan areas in the US (based on total population according to the 2000 Census). It should be noted that there is a large distribution of the size and population of the different cities and it can be assumed that these cities are representative of all major cities in the US.

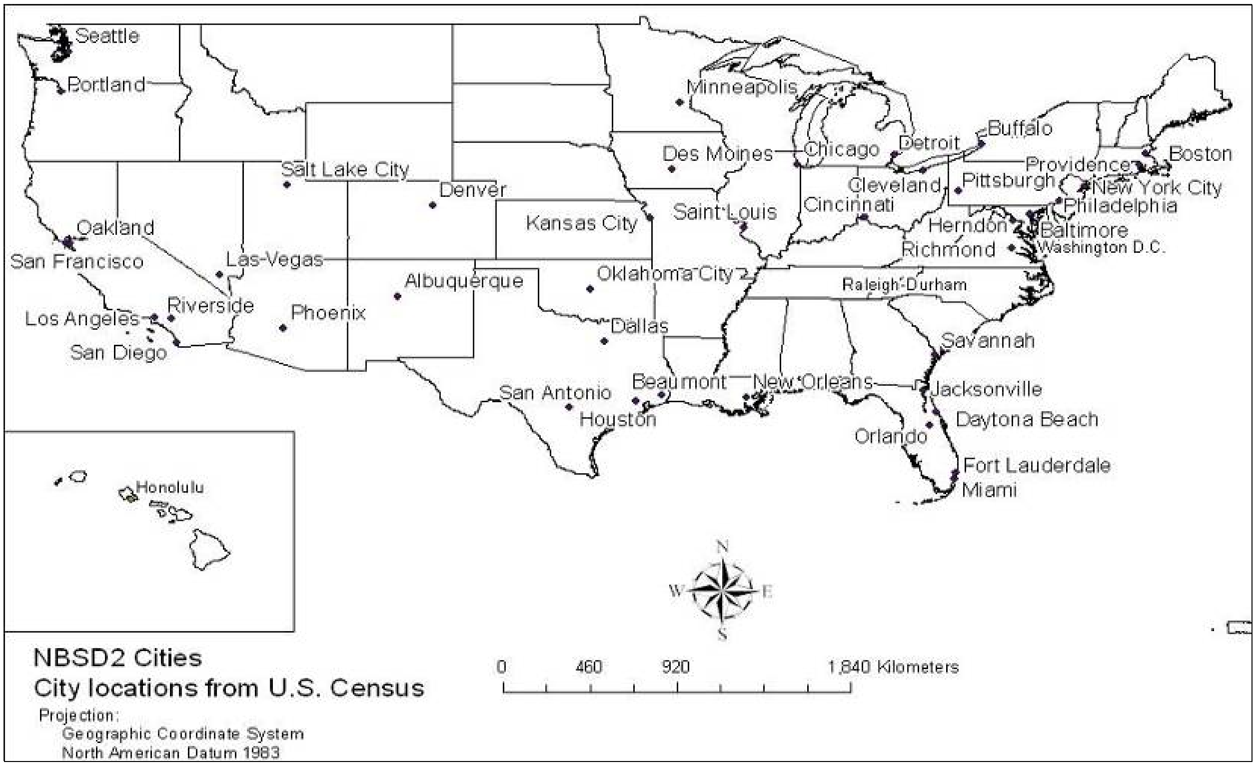

Figure 1. Cities in NBSD2

The characteristics of the building datasets used to derive the NBSD2 are contained in Table 2. All data extents are smaller than the complete metropolitan area (Table 1), but are centered on the important tall building districts. The majority of the datasets were either obtained from commercial vendors (e.g., i-cubed, Vexcel, Inc., Urban Data Solutions) or extracted from airborne lidar data by the National Geospatial-Intelligence Agency (NGA) using a set of tools created by Science Applications International Corporation (SAIC) in collaboration with the Defense Threat Reduction Agency (DTRA). The Houston dataset was derived by University of Utah researchers by modifying an existing building footprint dataset available from the city engineering department. The modification involved comparing the existing footprints to high-resolution digital orthophotos, deleting buildings that did not appear in the orthophoto and digitizing buildings that did appear. The building heights were then derived by overlaying the modified footprint coverage onto a 1-m full-feature DEM produced from airborne lidar data. Additional details of each building dataset are included in the individual city processing reports found on the NBSD2 CD.

The following building statistics are included in NBSD2:

- Mean building height
- Standard deviation of building height
- Plan-area-weighted mean building height
- Height histograms (at 5-m ht increments)
- Plan area fraction
- Plan area density (at 1-m ht increments)
- Building roof area density (at 1-m ht increments)
- Frontal area index
- Frontal area density (at 1-m ht increments)
- Building surface-to-plan area ratio
- Complete aspect ratio
- Height-to-width ratio
- Sky view factor

The processing of the three-dimensional building datasets is performed using the Urban Morphological Analysis Processor (UMAP) (Burian et al. 2005). UMAP is a tool developed for use with the ESRI ArcGIS 9 geographic information system (GIS) software package. UMAP computes building statistics at a user-defined horizontal spatial resolution. UMAP was designed to derive gridded surface parameter datasets corresponding spatially to an atmospheric dispersion modeling domain. Although effective to compute urban morphological characteristics for large areas, UMAP is a research grade tool. A brief overview of each building statistic and corresponding calculation method is provided below. Greater explanation of the parameter and explanation of the UMAP approach to computation can be found in the UMAP documentation.

Table 1. Characteristics of metropolitan areas *with building data* in NBSD2 (alphabetical).

City	Metro Area (km^2)	Population
Albuquerque, NM	15,461.8*	678,820[+]
Baltimore, MD	24,917.5*** [1]	2,491,254[+++]
Beaumont, TX	5,604.6*	376,256[+]
Boston, MA	16,779.4**	5,667,225[++]
Buffalo, NY	4,078.3*	1,142,121[+]
Chicago, IL	18,029.4***	8,885,919[++]
Cincinnati, OH	9,910.5***	1,960,995[+]
Cleveland, OH	9,398.3***	2,910,616[++]
Dallas, TX	23,685.5***	3,280,310[+++]
Daytona Beach, FL	4,138.7*	474,711[+]
Denver, CO	23,273.2***	2,417,908[++]
Des Moines, IA	4,494.5*	443,496[+]
Detroit, MI	17,080.9***	4,474,614[+++]
Fort Lauderdale, FL	8,204.0*** [2]	1,535,468[+++]
Herndon-Dulles, VA	24,917.5*** [1]	4,739,999[+++] [1]
Honolulu, HI	1,561.4*	864,571[+]
Houston, TX	20,048.7***	4,493,741[++]
Jacksonville, FL	6,856.4*	1,056,332[+]
Kansas City, MO	14,065.6*	1,755,899[+]
Las Vegas, NV	102,420.1*	1,381,086[+]
Los Angeles, CA	88,361.1*** [4]	16,036,587[++]
Miami, FL	8,204.0*** [2]	2,175,634[+++]
Minneapolis, MN	15,776.3*	2,872,109[+]
New Orleans, LA	8,843.4*	1,305,479[+]
New York, NY	26,445.6***	20,196,649[++]
Oakland, CA	19,169.1*** [3]	2,348,723[+++]
Oklahoma City, OK	11,049.7*	1,046,283[+]
Orlando, FL	9,081.4*	1,535,004[+]
Philadelphia, PA	15,442.3*	4,949,867[+++]
Phoenix, AZ	37,913.6***	3,013,696[+]
Pittsburgh, PA	12,028.9*	2,331,336[+]
Portland, OR	18,090.0***	2,180,996[++]
Providence, RI	2,448**	1,125,639[+]
Raleigh-Durham, NC	9,081.7*	1,105535[+]
Richmond, VA	7,660.8*	961,416[+]
Riverside, CA	88,361.1*** [4]	3,200,587[+++]
Salt Lake City, UT	4,207.9*	1,275,076[+]
San Antonio, TX	8,654.5*	1,564,949[+]
San Diego, CA	10,937.8*	2,820,844[+]
San Francisco, CA	19,169.1*** [3]	6,873,645[++]
Savannah, GA	3,542.2*	288,426[+]
Seattle, WA	18,791.6***	3,465,760[++]
St. Louis, MO	16,631.1*	2,569,029[+]
Washington, DC	24,917.5*** [1]	4,739,999[+++] [1]

* 1990 Metropolitan Statistical Area (MSA) (U.S. Census: www.census.gov/Press-Release/metro05.prn)
** New England County Metro. Area (NECMA) defined as of June 30, 1996; (www.census.gov/Press-Release/metro05.prn)
*** 1990 Consolidated MSA (CMSA) (www.census.gov/Press-Release/metro05.prn)
[+] 2000 MSA (www.census.gov/popest/archives/1990s/MA-99-01.txt)
[++] 2000 CMSA (www.census.gov/popest/archives/1990s/MA-99-01.txt)
[+++] 2000 Primary MSA (PMSA) (www.census.gov/popest/archives/1990s/MA-99-01.txt)
[1] Part of Washington, DC CMSA
[2] Part of Miami CMSA
[3] Part of San Francisco CMSA
[4] Part of Los Angeles CMSA

Table 2. Characteristics of building datasets used to derive NBSD2 (listed alphabetically).

City	Building Data Extent (km^2)	Tall Building District* Extent (km^2)
Albuquerque, NM	48.5	1.1
Baltimore, MD	383.5	4.6
Beaumont, TX	362.0	Not defined
Boston, MA	256.0	3.0
Buffalo, NY	24.3	3.1
Chicago, IL	154.1	9.8
Cincinnati, OH	506.3	2.9
Cleveland, OH	393.1	4.0
Dallas, TX	544.3	3.0
Daytona Beach, FL	439.1	Not defined
Denver, CO	141.4	5.9
Des Moines, IA	469.7	Not defined
Detroit, MI	506.6	10.5
Fort Lauderdale, FL	65.2	6.6
Herndon-Dulles, VA	287.7	Not defined
Honolulu, HI	375.4	Not defined
Houston, TX	1648.6	3.3
Jacksonville, FL	478.7	4.3
Kansas City, MO	357.0	8.9
Las Vegas, NV	200.0	10.6
Los Angeles, CA	262.8	2.5
Miami, FL	129.3	7.7
Minneapolis, MN	399.4	9.3
New Orleans, LA	26.1	3.7
New York, NY	321.2	32.5
Oakland, CA	54.8	Not defined
Oklahoma City, OK	27.0	0.7
Orlando, FL	491.9	Not defined
Philadelphia, PA	528.0	9.9
Phoenix, AZ	16.8	1.7
Pittsburgh, PA	544.8	5.9
Portland, OR	9.5	1.8
Providence, RI	503.0	4.2
Raleigh-Durham, NC	388.4	Not defined
Richmond, VA	443.8	Not defined
Riverside, CA	393.4	1.0
Salt Lake City, UT	140.0	1.6
San Antonio, TX	770.7	3.2
San Diego, CA	301.4	3.2
San Francisco, CA	185.2	4.5
Savannah, GA	395.1	Not defined
Seattle, WA	145.9	2.3
St. Louis, MO	433.9	4.1
Washington, DC	41.7	13.2

* Tall building districts were defined using digital orthophotos.
** The number in this column represents the number of features in the dataset. The data represent in some cases multiple buildings with a single feature or a single building with multiple features. Therefore, the number of buildings listed in the column is an approximation. Review of the data indicated that the number of misrepresentations is limited and the approximation should be fairly accurate.

3.1 *Building Height Characteristics*

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

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

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

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 average building height weighted by building plan area is calculated using the following equation:

$$\bar{h}_{AW} = \frac{\sum_{i=1}^{N} A_i h_i}{\sum_{i=1}^{N} A_i} \quad (3)$$

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 building height histograms are simply computed by summing the number of buildings with rooftop height falling within specified height increments. Height increments of 5-m were used.

3.2 *Building Plan Area Fraction (λ_p)*

The building plan area fraction (λ_p) is defined as the ratio of the plan area of buildings to the total surface area of the study region:

$$\lambda_p = \frac{A_p}{A_T} \quad (4)$$

where A_p is the plan area of buildings at ground level, i.e., the footprint area, and A_T is the total plan area of the region of interest, i.e., computational grid cell of UMAP. The computed value of the plan area fraction is dependent on the size of the area or the specific land use types included in the calculation. In most cases the plan area fraction will vary significantly from one city block to the next because of the heterogeneous nature of the urban landscape. The appropriate size of the calculation element should be chosen such that the characteristics of interest in the urban area are homogeneous and discernible.

3.3 *Building Plan Area Density ($a_P(z)$)*

The building plan area density ($a_P(z)$) is defined as the average building plan area within a height increment divided by the volume of the height increment:

$$a_p(z) = \frac{\frac{1}{\Delta z} \int_{z-\frac{1}{2}\Delta z}^{z+\frac{1}{2}\Delta z} A_P(z')dz'}{A_T \Delta z} \quad (5)$$

where, $A_p(z')$ is the plan area of buildings at height z', A_T is the plan area of the site, and Δz is the height increment for the calculation. Since A_T is not a function of height it can be brought into the integral in the numerator producing:

$$a_p(z) = \frac{\frac{1}{\Delta z} \int_{z-\frac{1}{2}\Delta z}^{z+\frac{1}{2}\Delta z} \frac{A_P(z')}{A_T} dz'}{\Delta z} \quad (6)$$

Knowing $\lambda_P(z') = A_P(z')/A_T$ and assuming that the building plan area does not change appreciably within a small height increment Δz, eq. (6) can be approximated by:

$$a_p(z) \cong \frac{\lambda_P(z)}{\Delta z} \quad (7)$$

3.4 *Roof Area Density ($a_r(z)$)*

The roof area density ($a_r(z)$) is defined as the rooftop plan area per height increment Δz divided by the volume of the height increment:

$$a_r(z) = \frac{A_r(z)}{A_T \cdot \Delta z} = \frac{A_p\left(z - \frac{\Delta z}{2}\right) - A_p\left(z + \frac{\Delta z}{2}\right)}{A_T \cdot \Delta z} \quad (8)$$

where A_T is the total area within which buildings are contained. The rooftop area within a height increment Δz can be approximated by the difference between the building plan areas at two heights:

$$A_r(z) = A_p\left(z - \frac{\Delta z}{2}\right) - A_p\left(z + \frac{\Delta z}{2}\right) \quad (9)$$

where $A_p(z)$ is the plan area of buildings at the specified height and a flat-roofed assumption has been made. Analogous to the leaf area index used in the plant canopy community, the integration of $a_r(z)$ from a specified elevation above ground (z) to the height of the canopy (h_c) is equal to the building area index ($L(z)$):

$$L(z) = \int_{z}^{h_c} a_r(z')dz' \tag{10}$$

The integration of $a_r(z)$ from ground elevation to the canopy height (h_c) is equal to λ_P:

$$L(0) = \lambda_P = \int_{0}^{h_c} a_r(z')dz' \tag{11}$$

3.5 *Building Frontal Area Index (λ_f)*

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

$$\lambda_f(\theta) = \frac{A_{proj}}{A_T} \tag{12}$$

where θ is the wind direction. The λ_f value for each grid cell is determined for northerly, northeasterly, easterly, and southeasterly winds.

3.6 *Frontal Area Density ($a_f(z)$)*

The frontal area density ($a_f(z)$) is defined as:

$$a_f(z,\theta) = \frac{A(\theta)_{proj(\Delta z)}}{A_T \Delta z} \tag{13}$$

where $A(\theta)_{proj(\Delta z)}$ is the area of building 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 study site. For a specified wind direction, the integral of $a_f(z)$ over the canopy height equates to λ_f.

3.7 *Complete Aspect Ratio (λ_C)*

The complete aspect ratio (λ_C) is defined as the summed surface area of roughness elements and exposed ground divided by the total plan area (Voogt and Oke 1997):

$$\lambda_C = \frac{A_C}{A_T} = \frac{A_W + A_R + A_G}{A_T} \tag{14}$$

where A_C is the combined surface area of the buildings and exposed ground, A_W is the wall surface area, A_R is the roof area, A_G is the area of exposed ground, and A_T is the plan area of the study site. A_C is calculated by summing the surface area of the buildings and the difference between the total plan area of the site and the plan area of buildings at ground level (i.e., the exposed ground surface). For dense urban areas with flat roofed buildings and without much vegetation, A_C can be approximated as the sum of the plan area of the site and the area of building walls (not including rooftops).

The rooftop surface area is calculated assuming the rooftops are flat, which introduces some error. Another source of error is the neglect of the surface area of trees and bushes. Grimmond and Oke (1999) found the surface area of trees and bushes to be an important component of the complete surface area, especially in residential areas. These limitations will be addressed in future revisions NBSD2.

3.8 *Building Surface Area to Plan Area Ratio (λ_B)*

The building surface area to plan area ratio (λ_B) is defined as the sum of building surface area divided by the total plan area:

$$\lambda_B = \frac{A_R + A_W}{A_T} \tag{15}$$

where A_R is the plan area of rooftops, A_W is the total area of non-horizontal roughness element surfaces (e.g., walls), and A_T is the total plan area of the UMAP grid cell. The computation is based on a flat-roof assumption.

3.9 *Height-to-Width Ratio (λ_S)*

The height-to-width ratio (λ_S) (also called the street aspect ratio) is calculated for two buildings by dividing the average height by the distance between the two buildings:

$$\lambda_S = \frac{(H_1 + H_2)/2}{S_{12}} \tag{16}$$

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). Figure 2 illustrates the measures used to compute λ_S. The calculation of λ_S is 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. For idealized arrangements of buildings, the calculation of an average λ_S can be approximated by taking the average building height divided by the average width between buildings (Grimmond and Oke 1999):

$$\overline{\lambda_S} \cong \frac{\overline{z_H}}{\overline{W}} \quad (17)$$

where $\overline{z_H}$ is the average building height and $\overline{W}$ is the average distance between buildings.

Due to the large number of buildings in real cities, an automated approach is warranted. Because of the complexity of the urban environments and the difficulty in estimating the average distance between two buildings, the simplified methodology described by eq. (17) was not used. Instead, λ_S was computed along linear traverses across the city at different angles using Eqn. (16). This calculation strategy involved converting the building database into a raster digital elevation model (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. Since this approach yields λ_S values in non-preferred directions (e.g., running along a street, not across a street), the matrices of traverses done at different angles were then superimposed, and the largest height-to-width ratio at each grid cell was selected to represent the value of the grid cell. Aggregation to UMAP grid cell resolution is accomplished by simple averaging.

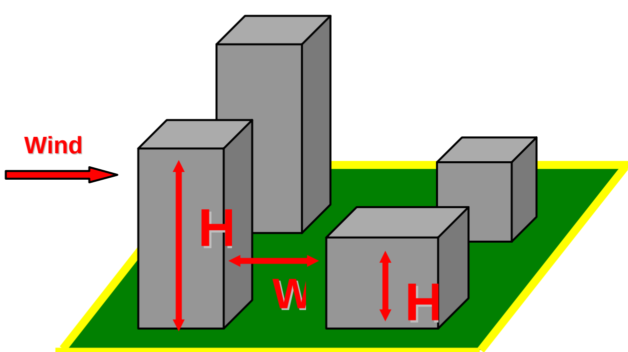

Figure 2. Illustration of height-to-width ratio parameter.

3.10 *Sky View Factor*

The sky view factor calculation involves sending out a ray at ground level searching for buildings. When a building is located, the angle created between the ground level and the top of the building at the point of interest is determined. The ray continues in the same direction encountering other buildings and calculating other angles. The largest angle encountered is selected for inclusion in the sky view factor calculation. Using the largest angle, the component of the sky view factor corresponding to the ray direction is calculated as follows:

$$\Psi_i = (\cos \beta_i)^2 \quad (18)$$

This equation accounts for the necessary weighting of the incoming radiation based on the angle with respect to the horizon. The sky view factor is then determined by finding the average of the results from equation 18 for a series of rays distributed 360° in the horizontal from the point of interest:

$$\Psi_{sky} = \frac{1}{n}\sum_{i=1}^{n}(\cos \beta_i)^2 \quad (19)$$

where i is the ray number, n is the total number of rays included in the calculation, and β_i is the maximum angle between a building top and the ground surface at the point of interest in the direction of ray i. The calculation approach is described in greater detail in the UMAP documentation.

3.11 *Aerodynamic Roughness Characteristics*

A common method used to calculate the displacement height (z_d) and roughness length (z_o) are simple rules-of-thumb (Grimmond and Oke 1999):

$$z_d = f_d \overline{z_H} \quad (20)$$

and

$$z_o = f_o \overline{z_H} \quad (21)$$

where $\overline{z_H}$ is the average building height and f_d and f_o are empirical coefficients. Approximations for urban values are 0.5-0.7 for f_d and 0.1 for f_o. Beyond the limitations of applying these equations to horizontally inhomogeneous urban areas, these equations also only hold for medium building density situations, as it is known that z_o and z_d vary with building spacing. Additional information can again be found in the UMAP documentation. The roughness length and displacement height morphometric equations presented by Rapauch (1994) and Macdonald et al. (1998) are also included in NBSD2.

4. RESULTS

The building datasets of the 44 cities were processed by UMAP to compute the building statistics at 250-m and 1-km horizontal spatial resolutions. Upon completion of processing, the resulting gridded building statistics were subjected to a quality assurance/quality control (QA/QC) process (Burian et al. 2007). The gridded building statistics datasets for all 44 cities were derived at both 250-m and 1-km resolutions and incorporated into the NBSD2 in shapefile, ESRI GRID (raster), ascii gridded, and

Excel tabular formats. These data are available from the authors on CD.

A few interesting insights can be obtained by a review of the data in NBSD2. For example, we noted a very high variation of mean building height in the Tall Building Districts (TBDs). This variation in height is key for differentiating cities – because it clearly shows using constant morphological parameters from city to city is not a correct approach. We also found the UCPs to vary across a given land use category (National Land Cover Dataset (NLCD) categories) consistent with earlier work by Velugubantla et al. (2004). Another interesting geographical observation was the location of the TBDs is within 3 miles of a major river or lake.

5. SUMMARY

This paper described the development of the NBSD2. The NBSD2 provides a comprehensive coverage of building morphological features for U.S. cities for use in mesoscale meteorological and dispersion models. The NBSD2 is available from the authors on a CD. Please contact us if you would like to be added to the mailing list, to receive a copy of the NBSD2, or to offer suggestions for future enhancements to the NBSD series.

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